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## The GridShare solution: a smart grid approach to improve service provision on a renewable energy mini-grid in Bhutan

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# The GridShare solution: a smart grid approach to improve service provision on a renewable energy mini-grid in Bhutan

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## Abstract

This letter reports on the design and pilot installation of GridShares, devices intended to alleviate brownouts caused by peak power use on isolated, village-scale mini-grids. A team consisting of the authors and partner organizations designed, built and field-tested GridShares in the village of Rukubji, Bhutan. The GridShare takes an innovative approach to reducing brownouts by using a low cost device that communicates the state of the grid to its users and regulates usage before severe brownouts occur. This demand-side solution encourages users to distribute the use of large appliances more evenly throughout the day, allowing power-limited systems to provide reliable, long-term renewable electricity to these communities. In the summer of 2011, GridShares were installed in every household and business connected to the Rukubji micro-hydro mini-grid, which serves approximately 90 households with a 40 kW nominal capacity micro-hydro system. The installation was accompanied by an extensive education program. Following the installation of the GridShares, the occurrence and average length of severe brownouts, which had been caused primarily by the use of electric cooking appliances during meal preparation, decreased by over 92%. Additionally, the majority of residents surveyed stated that now they are more certain that their rice will cook well and that they would recommend installing GridShares in other villages facing similar problems.

**Keywords:** smart mini-grid technology, micro-hydro, demand-side management, brownouts, renewable energy, rural electrification, South Asia

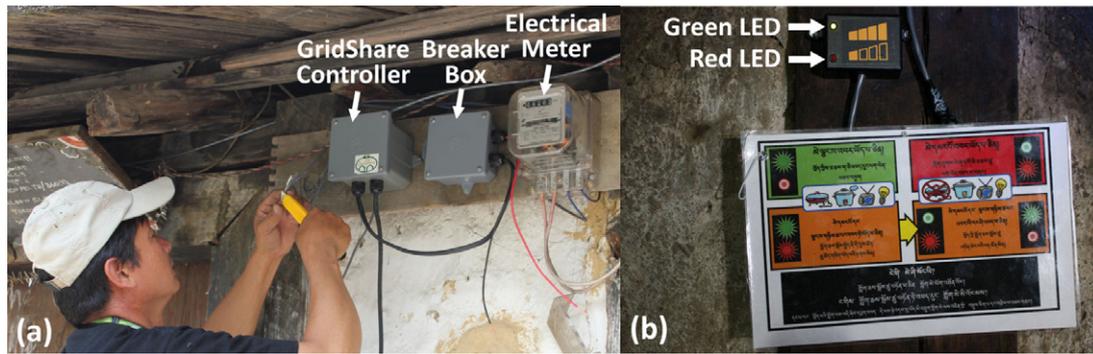
 Online supplementary data available from [stacks.iop.org/ERL/8/014018/mmedia](http://stacks.iop.org/ERL/8/014018/mmedia)

## 1. Introduction

Renewable energy mini-grids are estimated to serve over 50 million households worldwide (Martinot *et al* 2002).

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Though these systems provide a valuable electrical service, many are faced with a common problem of brownouts during times of peak demand. To address this issue, a team from Humboldt State University (HSU) developed GridShare, an approach to alleviating brownouts caused by peak power consumption on isolated, village-scale electrical systems through technology, education and village-scale collaboration. With the support of Schatz Energy Research Center, the Bhutan Power Corporation, Ltd (BPC), and the



**Figure 1.** BPC electrician installs a GridShare and breaker box near the electrical meter (a). LED indicator lights with an instructional sign are installed near the rice cooker (b). Borrowing from familiar power-indicating graphics on cell phones, the yellow bars next to the green LED remind users that when the green light is lit, the grid is at ‘full power’ and any appliances may be used, while the empty bars next to the red LED suggest that the red light means the grid electricity is limited and only low power appliances can be used.

Bhutan Department of Energy (DoE), this system was piloted in Rukubji, Bhutan, a village of approximately 90 households connected to a micro-hydroelectric system rated at 40 kW.

In Rukubji, like many other mini-grids, the power supply is sufficient during off-peak times. However, during preparation of morning and evening meals, the use of high-power kitchen appliances regularly causes electrical demand of the village to exceed the available supply and brownouts to occur. The lowered voltage that characterizes a brownout causes lights to dim, televisions to flicker, and electrical appliances, such as rice cookers, not to function properly; the corresponding drop in frequency may cause flickering in magnetic-ballast fluorescent lights and reduced speed in electric motors (refrigerators, power tools).

The GridShare system involves installing a device in every household and business connected to the mini-grid that provides two mechanisms to alleviate brownouts: indication of the current state of the grid and an enforcement mechanism to limit load when the grid is overburdened (figure 1). The implementation of this project in Rukubji has provided a more reliable electrical service to the village.

## 2. Literature review: mini-grid issues and demand-side management

Isolated mini-grids deliver electricity service to populations that are inaccessible by centralized electrical grids due to rough terrain and/or remote locations (ESMAP 2000, Martinot *et al* 2002, Terrado *et al* 2008, Modi *et al* 2005, REN21 2005, Palit and Chaurey 2011). Because mini-grids have finite generation resources, when consumers have unrestricted access, overloading and brownouts are common (Dorji 2007, Greacen 2004, Dorji *et al* 2012). This problem occurs worldwide; for example, in a survey of Thai mini-grid systems, respondents in 48 of 59 villages surveyed complained of low voltages (Greacen 2004).

Hydroelectric mini-grid systems are a common source of electricity in rural Bhutan, with 10 such systems in operation and the potential for more (Chhetri 2012, Dorji *et al* 2012, Uddin *et al* 2007). In some of these systems, rice cookers and

electric water boilers account for 50%–70% of the peak load (Dorji 2007). Primarily due to these appliances, the electrical load of these villages exceeds the power generated for a few hours each day. During all other times, the hydroelectric generator supplies excess power, which is often rejected as heat via a dump load.

Increased generation capacity or the addition of energy storage, as with batteries, could be effective solutions to alleviating brownouts but are frequently cost prohibitive at the village-scale. Alternatively, several demand-side management solutions have been developed to manage loads on mini-grids. A non-technological solution is to restrict the number or types of appliances that customers are allowed to use, although enforcement is usually impractical (ESMAP 2000). Additionally, encouraging the use of energy efficient appliances and light fixtures, such as compact fluorescent lamps (CFLs), can reduce demand on mini-grids, just as on utility-scale grids (Casillas and Kammen 2011). Load-limiting devices, including fuses, miniature circuit breakers (MCBs), and positive temperature coefficient thermistors, are also commonly used, often in conjunction with power-based tariffs (ESMAP 2000, Smith 1995)<sup>4</sup>. However, inexpensive MCBs can be unreliable, and load-limiting devices can easily be bypassed or tampered with (ESMAP 2000). In the past, load limiters installed in Bhutan were commonly bypassed (Dorji 2007). Additionally, load limiters restrict users even at off-peak times when a surplus of power is available. Alternatively, installing meters and charging a tariff based on usage, rather than a flat rate or power-based tariff, can encourage energy conservation and reduce peak loads (Casillas and Kammen 2011). For meters to encourage conservation, however, tariffs must be high enough to send an appropriate price signal, and ideally, either real-time pricing or time-of-use pricing would be instituted to reduce demand

<sup>4</sup> Power-based tariffs are billing systems in which consumers are charged a fixed monthly fee for use of electricity up to a specified power limit. Energy usage is not metered and consumers are not charged based on the kilowatt hours they consume. This billing system is commonly used on micro-hydroelectric mini-grids where power is a limited commodity during peak periods, but surplus energy is produced throughout the day.

during peak periods (Borenstein 2005, Orans *et al* 2010). More advanced devices combine energy metering and load limiting and may include prepayment features allowing users to purchase energy or peak power as needed (INENSUS GmbH 2011, Soto *et al* 2012, Briganti *et al* 2012, Rolland and Glania 2011).

### 3. The GridShare concept

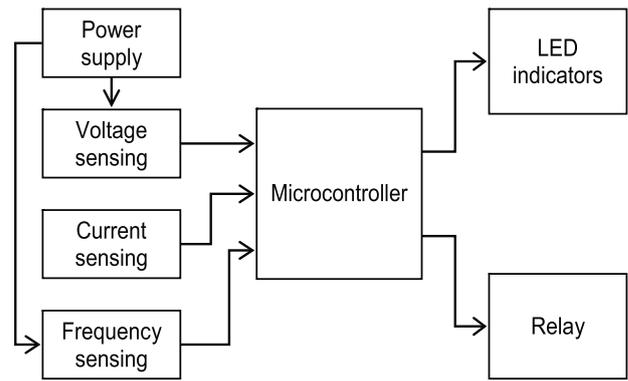
The GridShare system is designed to restrict electricity use only when the demand on the system exceeds the supply. This adaptive approach offers a distinct advantage over simple load limiters, which is particularly important for hydroelectric mini-grids, where the power produced throughout the day is relatively constant while demand varies greatly. In addition, unlike simple load limiters, the GridShare provides information to users about the status of the grid and whether they are being restricted. By combining these features with an education program focused on load-shifting, the GridShare enables more efficient use of the available generation resource.

The GridShare technology is part of a three-pronged approach to demand-side management of mini-grids, comprising indication, enforcement, and education. Indication about the state of the mini-grid is provided by red and green light emitting diodes (LEDs) (figure 1(b)) installed prominently inside each residence. The state of the mini-grid is determined by measuring the voltage. The green LED is lit when the voltage of the mini-grid is within the normal operating range, while the red LED indicates that the voltage is low. Enforcement prevents the use of large electrical draws during periods of peak demand. Any resident who tries to use a large appliance will momentarily lose power to their house until their load is reduced. This enforcement seeks to prevent 'severe' brownouts by restricting consumption during peak use periods<sup>5</sup>. Education was a significant component of this pilot's success. The GridShare team engaged the community through village meetings, surveys and informational material, translated into the native language, which started a two-way discussion on why brownouts occur, what the GridShare indicator lights mean, and how residents can alter their electricity usage to reduce brownouts. Feedback from these meetings informed the design, education, and implementation processes.

#### 3.1. GridShare components and operation

The GridShare device is installed at the electrical service entrance of every residence and business connected to the mini-grid, while the LED indicator box is installed indoors near the high-power cooking appliances. Each GridShare device acts independently; there is no communication between devices or with the utility.

The GridShare consists of circuitry to measure the voltage and current entering the home, LED indicators to



**Figure 2.** Functional block diagram of the GridShare device. (Reproduced from Quetchenbach (2011).)

provide the user with information about the status of the power grid, a relay to switch the power to the home, and a Microchip PIC microcontroller to process the inputs and control the output devices (figure 2). A linear power supply using a low-dropout voltage regulator keeps the cost of the GridShare low while allowing it to operate over a wide range of voltages. For this pilot project, the cost of each individual GridShare device, including the circuit board, circuit breaker, enclosures, and cables, was US\$ 93.<sup>6</sup> Materials from Quetchenbach (2011), summarized in the supplementary material (available at [stacks.iop.org/ERL/8/014018/mmedia](http://stacks.iop.org/ERL/8/014018/mmedia)), describe the GridShare design in more detail.

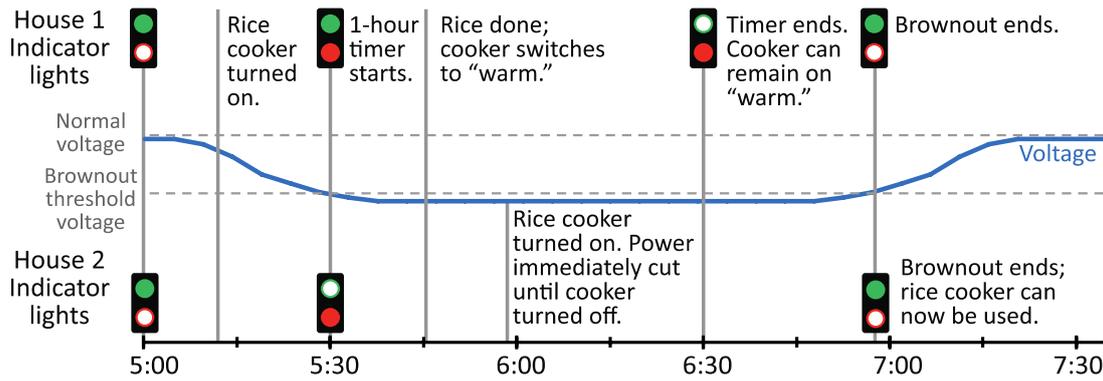
When the supply voltage is above a programmable threshold (200 V), the GridShare is in normal mode and only the green light illuminates. When the voltage drops below the threshold, if no large appliance (above 400 W at the nominal 230 V) is in use, the GridShare enters brownout mode and only the red light illuminates. If a large appliance is in use when the voltage drops, the GridShare allows the customer to continue cooking with no power restriction for 1 h before entering brownout mode. During this 'timer mode', both lights are on.

When the GridShare is in brownout mode, if the current exceeds the large-appliance threshold, the relay opens, disconnecting power from the house for 30 s. The relay then closes for 10 s to allow the GridShare to make another current measurement. If the current has dropped below the threshold, indicating that the large appliance has been turned off, the relay remains closed; otherwise, the power is disconnected for another 30 s and the process repeats. Since the peak load is mainly resistive, the current threshold is computed as the current at which a resistive load would dissipate 400 W at 230 V.

During brownout mode, if the grid voltage recovers beyond a second programmable threshold (208 V), the GridShare resumes normal mode. The hysteresis (the difference between the 200 V brownout threshold and the

<sup>5</sup> Severe brownouts are defined in this study as times when the voltage drops below 190 V on the 230 V nominal system.

<sup>6</sup> Costs for assembly and installation are not included because much of this labor was donated for the pilot. It is expected that producing GridShare devices on a large scale would significantly decrease per-unit costs.



**Figure 3.** A hypothetical timeline of two homes in a brownout to clarify the indication and enforcement aspects of the GridShare. A rice cooker is a ‘large appliance’ unless on warming mode, which for a typical 600 W rice cooker requires approximately 40 W.

208 V recovery threshold) in the transition between brownout and normal modes is intended to prevent GridShares from cycling rapidly between brownout and normal modes if the voltage remains near the threshold. The 208 V value was selected based on the logged voltage data to provide sufficient hysteresis while also ensuring a sufficiently fast response to the end of a brownout event. Random delays are associated with the decision to enter and exit brownout mode and timer mode to reduce the probability of large numbers of GridShares entering or leaving brownout mode simultaneously.

All voltage thresholds, power limits and timers on the GridShare are programmable for flexibility. The thresholds mentioned in this letter are those used in the Rukubji pilot project. Reprogramming the GridShare microcontroller requires a computer and a compatible microcontroller programmer. Though modifying the software requires advanced knowledge of computers and programming, microcontroller chips can be programmed off-site and delivered to a local technician to install in each GridShare, or local technicians or engineers can be trained to program the microcontrollers with compiled code provided by an off-site software developer.

Figure 3 illustrates the action of the GridShare in two hypothetical households, one in which a rice cooker is already in use when the grid enters a brownout (House 1) and a second in which the users turn on the rice cooker during a brownout (House 2). The GridShare in House 1 enters timer mode, illuminates both the red and green lights, and allows the rice cooker to finish cooking. In House 2, the users attempt to turn on the rice cooker during a brownout while the red light is on. All power is immediately cut to the house until the rice cooker is turned off. After the brownout ends, only the green light is lit and residents of both houses can use high-power appliances.

#### 4. Project implementation: applying the three-pronged approach

The GridShare pilot project site is the village of Rukubji, along with the neighboring villages of Tsenpokto and Bumiloo, which are all connected to the Rukubji micro-hydro power plant. The villages lie near the eastern border of

Wangdue Phodrang district of central Bhutan, a journey of about 125 km (80 miles) or 6 h by car from the national capital, Thimphu. In June of 2011, GridShare devices were installed to assess the effectiveness of the GridShare and residents’ satisfaction with the system.

##### 4.1. Pilot project site

The three villages participating in the pilot consist of approximately 90 households. Typical houses in the villages vary from single-room thatch structures to three-story homes of traditional rammed earth construction. Household size ranges from 1 to 11 people, averaging 3.7 people in the summer and 4.8 people in the winter. Every household uses electric lighting; throughout the study, over 70% of the light bulbs in use were CFLs, while fluorescent tube lights and incandescent bulbs composed the remaining light sources<sup>7</sup>. All but one household owns at least one electric rice cooker. Other commonly owned appliances include water boilers, curry cookers, televisions, radios, blenders, and non-electric appliances, such as liquefied petroleum gas (LPG) stoves and wood stoves. Several businesses are also present in the village, including a restaurant, a milk-processing plant, and three small in-home shops.

The village hydroelectric generator has a nominal capacity of 40 kW but typically produces between 24 and 30 kW. The mini-grid has three distribution substations connected by a 6.6 kV line. Though the generator produces 3-phase power, all customers (except the milk-processing plant) have 230 V single-phase service. Customers have energy meters and, prior to and throughout the study, were billed monthly on a per-kWh basis. Though electricity in the village is metered, existing tariffs do not seem to provide

<sup>7</sup> The number of CFLs increased from 326 bulbs in June 2010 to 424 bulbs in January 2012 and the number of incandescent bulbs reciprocally decreased from 94 bulbs in June 2010 to 47 bulbs in January 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.

enough of a price incentive to encourage conservation<sup>8</sup>. Additionally, the electromechanical meters in use do not enable time-of-use or real-time pricing; thus, no price signals are in place to stimulate load-shifting. A village agreement prohibits electric space heaters and immersion water heaters<sup>9</sup>. As demonstrated by the high proportion of CFL bulbs in use in the village, prior to the study, utility-sponsored programs successfully promoted energy efficient CFL bulbs. Despite instating metered electricity, village-wide restrictions and apparent conservation measures, prior to the GridShare installation, the village regularly experienced brownouts in the mornings and evenings, primarily due to the use of electric rice cookers and water-boiling kettles.

#### 4.2. In-country partnerships

Successful implementation of the pilot installation in Rukubji required partnerships with the DoE of Bhutan, the BPC and the village of Rukubji. The DoE helped identify the pilot village and provided advisory and logistic support throughout the pilot. The BPC owns and maintains the micro-hydro system and mini-grid in Rukubji.

BPC engineers and electricians provided technical support for the installation and continue to oversee monitoring and maintenance of the GridShares. Additionally, the BPC employs an operator who lives in the village and performs system maintenance and other operational tasks, including repairing power lines, installing meters for new customers, reading meters, distributing bills, and collecting payments.

The support of the Rukubji community for the pilot project was secured through verbal agreements with each household and a signed agreement with the village leaders.

#### 4.3. Implementation approach

In January of 2010, the implementation in Rukubji began with an initial visit to the village to introduce the GridShare concept and determine residents' interest in the project. Following the villagers' positive response, the team returned in July of 2010 and held community meetings, surveyed each household, and installed voltage and current loggers to monitor the electric system for the duration of the project. Additionally, an installation and monitoring agreement was signed with the village leaders during this visit. Each household verbally agreed to participate prior to the July 2010 survey and all subsequent surveys.

In June of 2011, the team returned to install 90 GridShare devices on 81 houses and two businesses. Every village household and in-home business received a GridShare. In cases where multiple households lived in a single house

<sup>8</sup> 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<sup>-1</sup> (~US\$0.02 kWh<sup>-1</sup>). 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.

<sup>9</sup> From observation in the village, most households abided by this village agreement, though a few owned electric space heaters.

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. Both preceding and following the installations, community meetings were held to educate residents about the GridShare program and answer questions. During and after installations, the team talked with members from each household to ensure they understood how the GridShare worked and who to contact if they had questions or problems with the device. Bilingual posters, pamphlets and visual aids helped communicate concepts.

Following the GridShare installation, DoE and BPC representatives visited the village several times to monitor the system, ensure GridShares were operating properly, and inspect for signs of tampering. The team returned in January of 2012 to perform an initial assessment of the project through surveys and a final community meeting. The project continues to be managed by the BPC.

## 5. Data collection and processing

The methods of collecting and processing the aggregate electrical data and household surveys are detailed below. Additional information was collected through community meetings, electrical data logging in three individual households, billing data and data downloaded directly from GridShares; these additional results are not presented here<sup>10</sup>.

#### 5.1. Electrical data logging methods

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 data loggers. Data were collected in 5 min intervals. Since neither power factor nor real power (kW) were recorded, 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.

All data were processed using a script written in the R programming language. This program compared data from the 'before' period, from 22 July 2010 to 9 June 2011, to the 'after' period, from 22 July 2011 to 9 June 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

<sup>10</sup> These results will be available in Harper (2013), a forthcoming Master's Thesis for Humboldt State University.

the generator was offline and days with excessive missing data<sup>11</sup>. Additionally, prior to the installation, 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. For more details on the data selection process, see the supplementary material (available at [stacks.iop.org/ERL/8/014018/mmedia](http://stacks.iop.org/ERL/8/014018/mmedia)). The pre-processed datasets consisted of 77 130 observations (38 463 before, 38 667 after) and 270 days (135 before, 135 after).

Minutes of brownout were calculated 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 because testing indicated that rice cooked fully and lights did not noticeably dim above this voltage.

### 5.2. Survey methods

In total, three surveys were administered to households connected to the mini-grid during the course of the study. The first survey was given in June of 2010 to all households to assess the community's interest in participating in a pilot GridShare installation and to establish a baseline for average electricity use and cooking patterns. A second survey was administered to a representative subset consisting of 33 households in July of 2011 to re-establish the baseline data and to gather additional data related to the frequency with which residents used their lights and appliances for a pre-installation and post-installation comparison. The third survey was given to all households in January 2012 to assess behavioral changes related to the GridShare and residents' satisfaction with the GridShare program<sup>12</sup>.

Surveys were administered verbally in the national language, Dzongkha, to each household by a team member. In cases where the team member administering the survey was not a native Dzongkha speaker, a Bhutanese translator assisted. 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). The initial survey was offered to any adult household member without respect to gender or household role. When possible, the same member of the household was surveyed in each subsequent survey.

## 6. Results

Results from electrical data logging and in-home surveys suggest that the GridShares were effective in reducing the occurrence of severe brownouts and that residents benefited from the information provided by the GridShares regarding the status of their electrical grid.

### 6.1. Electrical data logging

Data logged at the powerhouse show that there were over 92% fewer days with severe brownouts after the GridShares were installed (figure 4). This reduction occurred on all three phases of the grid, though only results from one phase are presented here due to space limitations. (See the supplementary material available at [stacks.iop.org/ERL/8/014018/mmedia](http://stacks.iop.org/ERL/8/014018/mmedia) for results from all three phases.) This decrease in days with brownouts is statistically significant for two of the three phases (2-proportion *z*-test, 1-tailed,  $p < 0.001$ ; see supplementary material available at [stacks.iop.org/ERL/8/014018/mmedia](http://stacks.iop.org/ERL/8/014018/mmedia) for details)<sup>13</sup>.

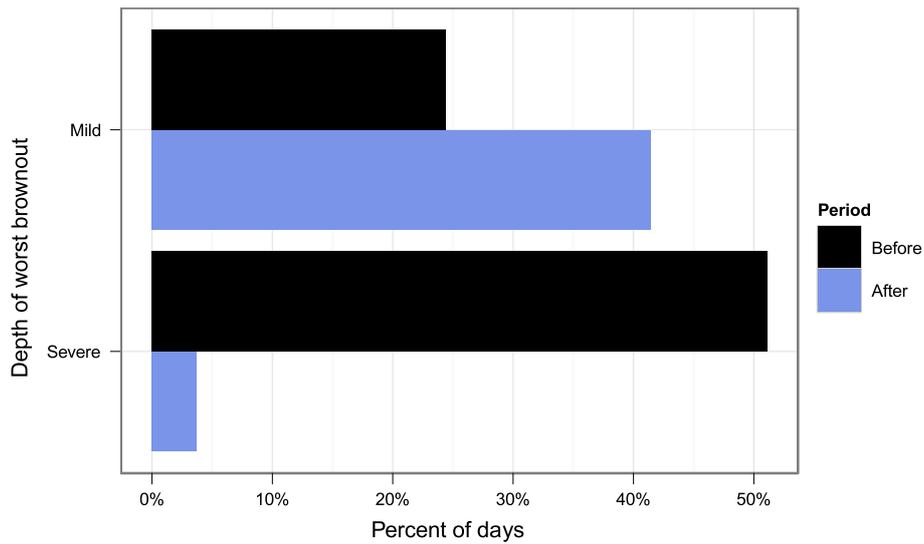
After the GridShare installation, although severe brownouts occurred much less frequently, the number of days with mild brownouts increased (figure 4). Additionally, the daily duration of both mild and severe brownouts significantly decreased (figure 5). Before the GridShare installation, customers experienced an average of 45 min of brownout conditions per day, of which 30 min were spent in severe brownout. After installation, the daily average decreased to 8 min, of which only 1 min was spent in severe brownout. The decreases in both total minutes of brownout and minutes of severe brownout were significant across all three phases (1-tailed Wilcoxon rank-sum test,  $p < 0.001$ ).

Though the occurrence, depth and length of brownouts were all reduced, the timing of brownouts was similar before and after the GridShare installation. The data did not indicate a substantial shift in the time that residents used electricity. The probability of experiencing a brownout decreased after the GridShare installation, but the time that the brownout was likely to occur remained the same and corresponded to times when residents typically cook rice for breakfast and dinner (figure 6). The graph of median load power consumption throughout the day similarly suggests that there is very little change in the daily load profile between the before and after periods (figure 7). The graph indicates a very slight shift in the timing of the load, suggesting that some residents may be starting to cook earlier in the morning and later in the evening. Additionally, it appears that after the installation of the GridShare, the peaks of the total connected load are slightly shorter.

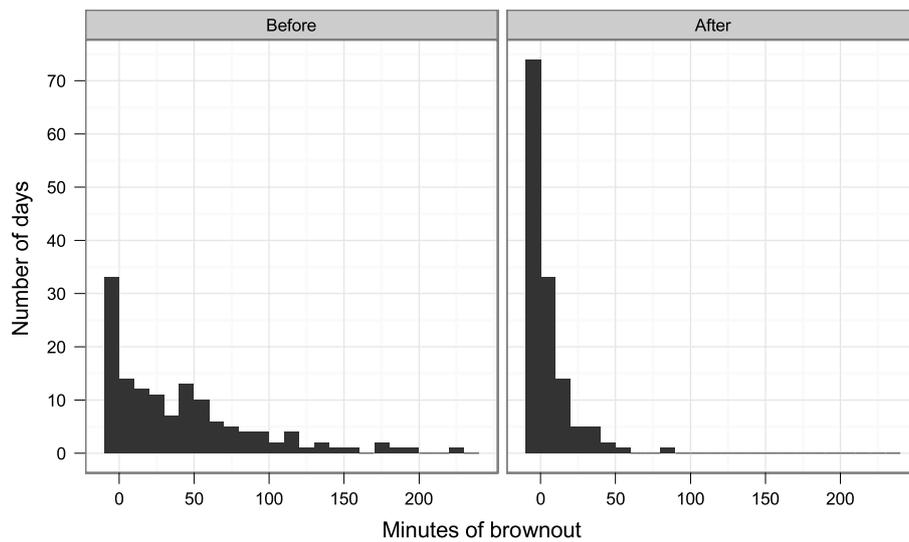
<sup>13</sup> Due to uneven loading of the grid, one of the phases rarely experienced brownouts before and after the GridShare installation. Because of this small sample size, data from this phase did not meet the assumptions of the statistical test.

<sup>11</sup> 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 system. Periods of low generation often surrounded the blackouts, so at least 30 min of data after each blackout were also discarded.

<sup>12</sup> This final survey is included for reference in the supplementary material (available at [stacks.iop.org/ERL/8/014018/mmedia](http://stacks.iop.org/ERL/8/014018/mmedia)).



**Figure 4.** Percentage of days with mild and severe brownouts before and after installation of the GridShare devices. After the GridShare installation, Rukubji still experienced periods with voltage drop, but there were fewer severe brownouts (voltages less than 190 V) and more mild brownouts (voltages between 190 and 208 V). For this plot, a day has a severe brownout if at least two (not necessarily consecutive) 5 min measurements are less than 190 V.



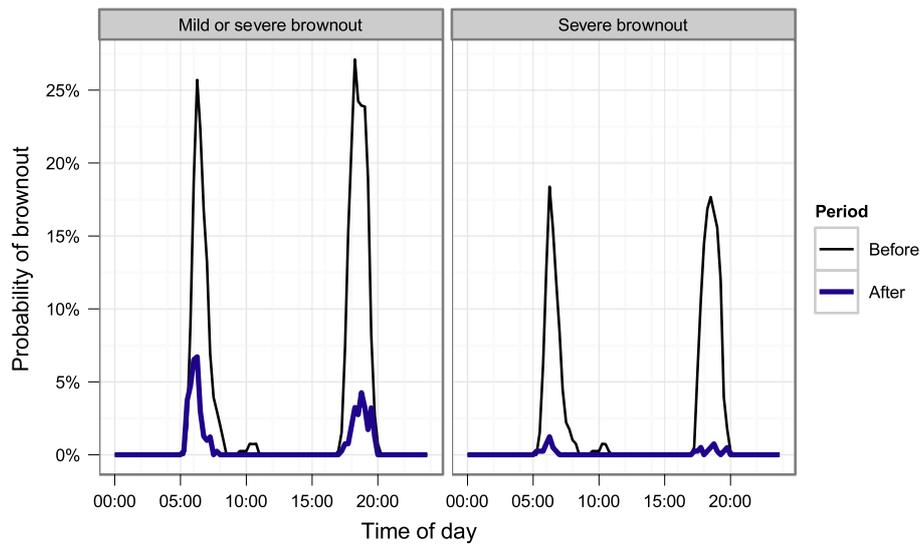
**Figure 5.** Histograms of total daily brownout durations before and after the GridShare installation (bin width 10 min). After the GridShare, Rukubji experienced more days with no brownouts and fewer days with long periods of brownout.

6.2. Surveys

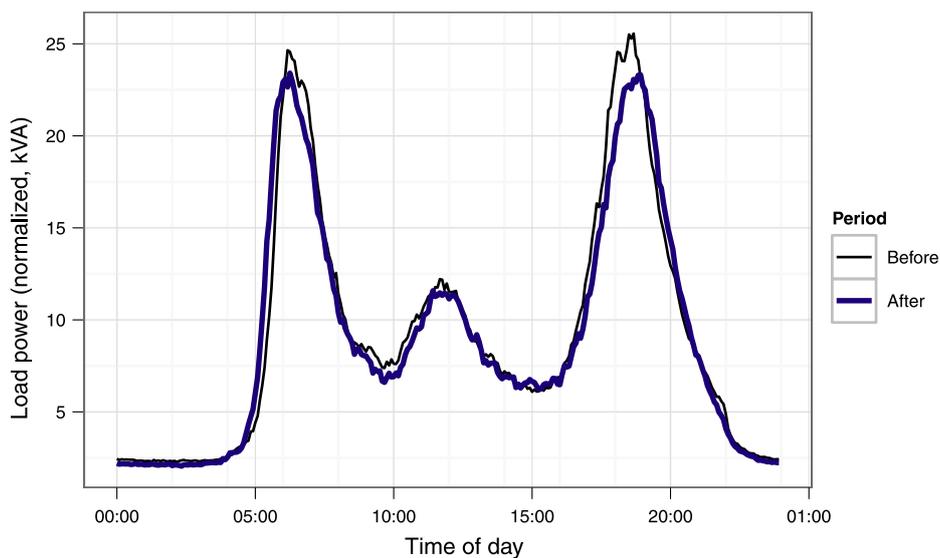
The survey results presented customer perceptions that supported the results from the data logging and provided insight as to whether the benefits of the GridShare outweighed its inconveniences in terms of customer satisfaction. The surveys also helped identify ways to improve the GridShare and the program implementation.

6.2.1. Customer perceptions of brownout frequency and behavior change. The follow-up survey results confirmed the expectation that residents would see the red light frequently, but that the occurrence of severe brownouts in which their lights dimmed and rice cooked poorly would be greatly reduced after the GridShare installation. 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 78% of respondents stated that they saw the red light occasionally. This finding complements the electrical data that suggested mild brownouts, which would trigger the red light, still commonly occurred on the grid. Prior to the GridShare installation, 99% of respondents stated that they experienced impacts associated with severe brownouts; after the GridShare installation, 54% reported that they experienced these conditions. As the electrical data suggest that days with severe brownouts were reduced by 92% and the average duration of a severe brownout was reduced to approximately one minute, it is both unsurprising and affirming that fewer respondents would report experiencing these conditions following the GridShare installation. The



**Figure 6.** The probability of a mild or severe brownout occurring on a given day before and after the GridShare installation. The probability of a brownout occurring is much higher during times when people cook their rice for breakfast and dinner. After the GridShare, the probability of a brownout decreased substantially, but still existed during the same time periods. The probability of severe brownouts (voltages below 190 V) decreased to less than 2%.



**Figure 7.** Median load power consumption throughout the day before and after the GridShare installation. 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.<sup>14</sup> 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.

combination of residents seeing the red light and 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.

<sup>14</sup>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. The normalized power cannot be calculated as  $IV_{nom}$  because during a brownout, when the voltage drops, the corresponding current that is drawn by a resistive load must also drop according to Ohm's law ( $V = IR$ ).

One would expect that these results were accompanied by either load-shifting or fuel-switching to explain the decrease in brownouts. In the case of load-shifting, one would expect to see wider and shorter peaks in the daily average load curve after the GridShare installation; these changes should be observable in both the electrical data and the reported time of day that the respondents cooked. On the contrary, load curves from the electrical data showed only very slight change after the GridShare installation and aggregate data based on the time of day respondents stated that they cooked before and after the installation do not provide a discernible pattern of time-based load-shifting. Despite the lack of evidence for

load-shifting, 42% of respondents stated they intentionally cooked either earlier or later than their normal cooking time at least once a week. In the case of fuel-switching, one would expect to see shorter peaks in the daily average load curve and expect respondents to report decreased use of electric appliances and increased use of alternative cooking methods. Though the normalized load curve from the electrical data does display slightly shorter peaks, the surveys administered to a representative subset of households ( $n = 33$ ) indicate that households used their electric rice cookers with the same or greater frequency than before the installation. Moreover, the responses indicate a decrease in the use of LPG, a common alternative cooking fuel in the villages.

Given the lack of evidence to suggest substantial load-shifting or fuel-switching occurred, an alternative 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 the reduction in brownouts along with the lack of substantive change in the daily load curve and use of electric appliances.

**6.2.2. Customer satisfaction.** Given the promising results from the electrical data, it was expected that most customers would express increased satisfaction with the quality and efficacy of their electricity. Indeed, after the GridShare installation, 92% of respondents stated that if they plugged in their rice cooker when the green light was on, they felt more confident that their rice would cook properly. Additionally, 52% of respondents thought that their rice took less time to cook. When asked about the benefits of the GridShare, many residents stated that they now knew when to cook and plug in devices, which improved the quality of their rice and the predictability of cooking. Additionally, several respondents stated that they felt their lighting quality and TV service had improved after the GridShare installation due to the more stable electricity supply.

Though, as noted above, reactions to the GridShare system expressed in survey responses were largely positive, residents did describe some disadvantages of the GridShare. A number stated frustration with the red light and the enforcement. They stated that it was difficult to cook when one was in a hurry, particularly in the mornings when they needed to send children to school. Although there was no detectable increase in aggregate LPG usage, some respondents stated that when faced with a long red light they would switch to LPG to cook their rice. Some residents were also worried that having their power turned on and off might damage appliances, which is a valid concern for fluorescent lights and some electronic appliances. These survey results provide both advantages and concerns that should be taken into account by mini-grid developers and operators and communities considering installing GridShares.

**6.2.3. Assessment of the education component.** The surveys also provided insight into ways to improve the education component of the GridShare program. Education took place through pamphlets, presentations, community meetings, and in-home visits, with most households identifying in-home visit as the most effective way to learn about the program. While residents generally understood how the GridShare worked, survey responses identified the need to more fully explain why residents should not plug in during a red light and why their power will be cut off if they do. Additionally, the explanation of the purpose and indication of 'timer mode' needed to be clarified in the education materials and in-home visits. Despite these two shortcomings, many respondents volunteered to say that the education program was clear and helpful, and 96% reported that everyone in their family had learned about the GridShare.

## 7. Conclusion and recommendations

The pilot installation of GridShares in Rukubji, Bhutan was successful in reducing the occurrence, depth and duration of severe brownouts. The response from the community, as assessed through surveys and community meetings, was largely positive, though surveys indicated some frustration and confusion regarding the enforcement mechanism. The community and the BPC asked to keep the GridShares installed and will continue to monitor the devices and their impact on the electrical system. This pilot project demonstrates that the GridShare offers a feasible demand-side management solution for power-limited mini-grids.

Though this success implies that mini-grid operators should consider GridShares in the development of existing and future projects, care should be taken to understand that this technology may not be applicable for all remote mini-grids. GridShares are particularly suited for mini-grid systems that operate continuously (such as micro-hydro and some diesel generators) and thus provide a constant power resource throughout the day. 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 that justify the cost of the GridShare system.

Even where the GridShare approach is technically feasible, the size and organization of the community may play a role in promoting compliance and satisfaction with the GridShare system. Rukubji and the surrounding villages are relatively small communities with established community leadership and a history of village agreements and cooperative decision-making, all of which greatly aided the process of gaining and maintaining community support. In addition,

customer satisfaction in the case of Rukubji may have been higher in part because the village had been suffering from brownouts for many years prior to the installation. A community may be less receptive to the restrictions imposed by the GridShare without first experiencing the alternative negative effects of brownouts. With these conditions in mind, when replicating the installation of GridShares in a different community, it would be valuable to identify limitations of Gridshares in this different context and key objectives of the education campaign.

From the experience gained in Rukubji, several potential improvements to the GridShare device were identified, including.

- Incorporating the circuit breaker and GridShare into one enclosure to reduce costs and installation time.
- Adding remote-monitoring capability to the GridShare, for example by using the mobile phone network.
- Including logic in the GridShare software to prevent users from increasing their load during timer mode (the 1 h grace period that allows residents to continue to use appliances in use when the system enters a brownout).

Opportunities for improving the education aspect of the GridShare approach were also identified. As mentioned, the surveys revealed that not everyone fully understood the purpose of the GridShare and most did not fully understand the timer mode. Both of these issues must be addressed in revisions to the education materials and may also call for a design change to the GridShare, such as adding a third LED to more clearly indicate timer mode.

Nearly all types of mini-grids face restrictions of limited and/or intermittent generation, constrained storage and poor demand-side management, but these systems nonetheless provide a valuable resource to isolated communities. While several academic studies, technical designs and practical implementations related to mini-grid design and management are in progress, more work is needed to better understand and address these issues and how creative demand-side management strategies can be used to increase access to high-quality, reliable electricity.

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<sup>15</sup>Note that single names are common in Bhutan, such as Phuentsho and Kinley.

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