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Review of Strategies and Technologies for Demand-Side Management on Isolated Mini-Grids

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Note: This document 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. Additionally, it should be noted that the author of this review was on the team that developed and pilot tested the GridShare, which is one of the devices described in this report. Despite this affiliation, all efforts have been made to objectively describe the strategies and technologies presented herein.

Introduction

This review provides an overview of strategies and currently available technologies used for demand-side management (DSM) on mini-grids throughout the world. For the purposes of this review, mini-grids are defined as village-scale electricity distribution systems powered by small local generation sources and not connected to a main grid.[1] Mini-grids range in size from less than 1 kW to several hundred kW of installed generation capacity and may utilize different generation technologies, such as micro-hydro, biomass gasification, solar, wind, diesel generators, or a hybrid combination of any of these. This review will primarily refer to AC mini-grids, though much of the discussion could apply to DC grids as well. Many mini-grids include energy storage, though some rely solely on real-time generation.

Often, mini-grids offer a more economical option for rural electrification than grid extension (ESMAP 2000, Flavin and Aeck 2005, Rolland and Glania 2011). Some types of mini-grids can provide a higher level of energy service than individualized solar home systems, thus enabling commercial and industrial end-uses (Kirubi et al. 2009). Despite these advantages, limited power generation and constrained or nonexistent energy storage present restrictions for users of these rural grids. Peak loads, or periods of high electricity demand, can exceed the power generation capacity of the mini-grid and cause brownouts, or times where the voltage and frequency drop, causing lights to dim and appliances to not work properly. On mini-grids with intermittent renewable energy sources, energy storage is often provided in the form of flooded lead-acid 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 spread load over time to preserve mini-grid reliability and ensure that electricity is equitably shared among the mini-grid users.

As mini-grids differ substantially in generation type, size, and financial support, appropriate strategies and technologies for DSM vary. As described above, 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, whereas on energy-limited grids, such as wind and solar, effective management requires regulating daily energy consumption as well. As noted in Table 1, this review first provides examples of

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[1] In this review, a solar home system (SHS) is not considered a mini-grid, unless the system provides power to multiple households. Additionally, battery charging models, such as EGG Energy (http://egg-energy.com/), are not covered in this review. This review discusses some technologies that make mini-grids more affordable and manageable, such as prepaid meters and pay-as-you-go financing schemes. Many of these prepaid models exist for solar home systems as well, including products and programs created by Hessex, Simpa Networks, Mobisol , Azuri, Econet Solar, M-KOPA Solar, Solar Gem, Bright Solar Power, Angaza, Stima, Off-Grid: Electric, Grundfos. A list of these products and similar products for mini-grids can be found at http://bennu-solar.com.

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 report.

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

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 either 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.[2] Investments in energy efficiency on an existing project can help to accommodate load growth without investing in additional capacity.

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[2] While efficiency measures can result in energy savings, the degree of cost savings for the customers depends upon the electricity tariff structure.

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).[3] 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 et al. 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 et al. (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 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.[4] 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 et al. 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 et al. 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.[5]

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[3] To maximize efficiency gains from fluorescent lighting, tube lights should be power-factor corrected with a capacitor. Similarly, CFLs should either be high-quality bulbs that come with power-factor correction, or correction should be added during installation. Though electronic ballasts for fluorescent tube lights are typically more energy efficient, on mini-grids that are subject to voltage fluctuations, magnetic ballasts are still recommended as the ballast protects the light against high voltages.

[4] The organization TopTen (www.topten.info) is just one organization that provides lists of the most efficient appliances available on the European, US and Chinese markets. This information is more difficult to attain for other markets, but referencing these lists can provide comparative values to assess locally available appliances.

[5] Companies manufacturing DC appliances include, but are not limited to: Clean Chill (www.cleanchill.com), Promethean Power Systems (www.coolectrica.com), SunDanzer (www.sundanzer.com), SunFrost

To complement the use of efficient appliances, groups such as ITDG[6] have designed low-power "heat storage cookers" for mini-grids with restricted power but excess energy production throughout the day (Holland et al. 2002). 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). 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).

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 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. In a similar manner, in the village of Rukubji, Bhutan, a milk processing facility only runs its large equipment during off-peak mid-morning and afternoon hours and the local restaurant aims to use its large rice cookers before and after the morning peak loads (Quetchenbach et al. 2013). 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.

Reducing non-essential commercial loads can also substantially lower operating costs on hybrid mini-grids. On a PV-diesel hybrid mini-grid in rural Canada, Pelland et al., (2012) found that reducing the non-

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(www.sunfrost.com), TrueEnergy (www.trueenergy.com), Steca (www.steca.com), Lenjoo (www.lenjoo.com), Minus 40 (www.minus40.co.za), Invenio (www.inveneo.org), SolarLEAP (www.solarleap.org/), and BBox (www.bboxx.co.uk).

[6] ITDG stands for the Intermediate Technology Development Group; this organization is now called Practical Action.

essential commercial loads that had been acting essentially as "dump loads" for an over-sized 95 kW diesel generator allowed for the installation of a second 30 kW diesel generator.[7] After installation of the smaller generator, non-essential loads were turned off on nights and weekends and the larger generator was only run during commercial hours, reducing fuel use of the mini-grid by over 20,000 L/year, or by approximately 20%.

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 primarily for lighting loads and, by default, restrict the use of other appliances. Systems currently being installed in villages in Uttar Pradesh, India, by a company called Mera Gao use 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 of use is a more difficult task and often requires technical intervention in addition to a verbal agreement. 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, and no verbal or written agreements regarding maximum allowable power were in place. As a result, households attempted to use high-power appliances, which subsequently over-loaded the system and may have contributed to burning out the generator (ESMAP 2000). In the village of Ura, Bhutan, the mini-grid operator banned the use of large appliances, such as electric rice cookers and water boilers, but had no mechanism for enforcement. Consequently, the majority of consumers owned at least one rice cooker and approximately 30% owned water boilers, the use of which resulted in regular brownouts (Dorji 2007). In Rukubji, Bhutan, rice cookers were permissible, though space heaters and water heaters were banned by village agreement (Quetchenbach et al. 2013). Despite the agreement, several households still owned and used electric space heaters, though many in the village expressed displeasure that others were violating the agreement not only on principle, but also because their over-use led to frequent and long-lasting brownouts. In another case study in Indonesia, a village agreement was instated to limit individual power use to 40 W. 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.

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[7] The system was originally sized to meet the peak load of 75 kW with capacity for expansion, but the average load during non-business hours was only 30 kW. System managers felt that to prolong the life of the 95 kW generator, non-essential commercial loads should be left on so that the generator was operated close to its rated capacity.

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. In response to the difficulties of regulating electricity use by village agreement, over the past decade, practitioners have developed more advanced metering systems which control both power demand and energy use. Some of these systems are discussed later in this document.

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).[8] 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.[9] 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, Rolland and Glania 2011, Casillas and Kammen 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

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[8] Note that in this report and in the context of mini-grids, the concept of a capacity-based tariff refers to a flat fee charged based on a pre-arranged power limit. Though demand metering, such as that used for most larger commercial and industrial customers on utility-scale grids, could technically be labeled a capacity-based tariff, it is excluded from the definition in this context. Demand meters could be installed for larger commercial and industrial customers on mini-grids as an augmentation to a consumption-based tariff, but this practice is uncommon due to the added cost and complexity.

[9] Current limiters will be discussed in greater detail later under the DSM Technologies section.

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). 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.[10] 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).[11] 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 this document, 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 (Briganti et al. 2012, INENSUS 2012a, CAT Projects 2011, SharedSolar 2012, Powerhive 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

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[10] An inverted block rate refers to the tariff structure in which the price per kWh increases with increasing usage. These rate changes are assigned to tiers or blocks of usage. Typically, the rate of the first tier will be set deliberately low (below the marginal cost) to ensure that low income consumers can afford sufficient electricity.

[11] This economic analysis was presented in the context of setting appropriate water tariffs in the developing world; however, these same theories could be applied to the mini-grid context.

costs, as well as any amortized capital costs (Rolland and Glania 2011).[12] 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 (Rolland and Glania 2011, Bushlight 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 this report 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

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[12] In many countries, tariffs on mini-grids are also subject to regulatory approval, as discussed in more depth in Deshmukh, Carvallo and Gambhir (2013) "Sustainable Development of Renewable Energy Mini-grids for Energy Access: A Framework for Policy Design," available from http://cleanenergysolutions.org/.

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.

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.

Current 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 (ESMAP 2000; Smith 1995; Smith and Ranjitkar 2000; Smith et al. 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 biomass, may benefit from metering in addition to current

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

limiting depending on their intermittency, the efficiency curve of the generator, and the marginal cost of electricity.

The characteristics of different types of current limiters are presented in Table 2. A more thorough description and discussion of current 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 limiters (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

*Thermal MCBs rated to limit currents greater than 6 A are widely available; the availability of smaller MCBs is more limited.

**Thermistors with higher current ratings are available on the market, but have not been documented in use on mini-grids.

Though any of the above devices may be installed on mini-grids, in research conducted for this review, only two current 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 current at levels between 0.031A and 0.4 A, depending on the model (Aartech 2012).[14] The device comes in two form factors, one enclosed in a short segment of PVC pipe to enable weather-proof 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;

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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.

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 have been 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 et al. 2003). Additionally, an electronics manufacturer in Thailand suggested they could produce similar electronic breakers for approximately US$ 5 each (Greacen 2004). Note that these prices have not been adjusted from their reported prices quoted in literature in 2000 and 2004, respectively.

Though initially effective, current limiters can degrade over time from exposure to the elements – such as salty air at coastal installations – or after a high number of resets and have been found to be commonly bypassed or fraudulently replaced with limiters with higher current ratings (ESMAP 2000, Dorji 2007). Additionally, current 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.

GridShare: A "Smart" Current Limiter

GridShare is a technology designed and piloted by a group from Humboldt State University that acts as a "smart" current limiter, enabling consumers to use high-power appliances, such as rice cookers and water boilers, when ample power is available, but restricting electricity use when power is limited (Quetchenbach et al. 2013).[15] As such, the device effectively captures consumer welfare that would have otherwise been lost due to brownouts or static current limiting restrictions. GridShares use red and green LED lights to alert residents to voltage drop on the grid and use a circuit-driven relay to regulate use of large appliances before severe brownouts occur. If the system voltage is normal, the green light is lit and the resident can use any appliance. If the system voltage falls below a threshold, the GridShare enters brownout mode. In brownout mode, users are restricted to only using smaller loads, such as lighting, a small TV, or a rice cooker on the low-power "warm" setting. 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. 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.[16]

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[15] The author of this review was on the Humboldt State University team that developed and pilot tested the GridShare.

[16] In the GridShare pilot project, the brownout threshold was set to 200 V and the timer mode was set to one hour to allow rice cookers ample time to finish cooking. In hindsight, this time limit should likely have been shortened.

The combination of the enforcement in brownout mode and 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.

GridShare technology is still in the pilot phase. The team of undergraduate and graduate students from Humboldt State University worked in coordination with partners at the Bhutan Power Corporation (BPC), Department of Energy of Bhutan, and the Schatz Energy Research Center to design, build, and field-test GridShares in the village of Rukubji, Bhutan. Prior to the installation, the village faced daily brownouts when everyone plugged in their large appliances, such as rice cookers and water boilers, to cook breakfast and dinner. In 2011, the team installed GridShares in every household and business connected to the Rukubji micro-hydro mini-grid. The installation was accompanied by an extensive education and monitoring program, which included hosting community meetings, conducting in-home visits and surveys prior to, during, and after the installation, and monitoring the current and voltage profile of the electrical system starting a year before the installation.[17] Following the installation of the GridShares, the occurrence of severe brownouts decreased by over 90%. Additionally, the majority of residents surveyed stated that after the GridShare installation, they are more certain that their rice will cook well. The community of Rukubji decided by consensus to keep the GridShares installed, and the BPC continues to support the effort. This pilot project indicates that user-interactive DSM strategies, such as the GridShare, can be effective at reducing brownouts on micro-hydro mini-grids. Though individual installations (including external hydraulic-magnetic circuit breakers) cost just under US$ 100 for this pilot project, the creators think that these costs could be substantially reduced with design revisions and increased production volume, but that the price point would still be higher than a simpler current limiter.

Distributed Intelligent Load Controller

Distributed intelligent load controllers (DILCs) are another technology devised to address the need to limit peak demand but still enable use of the excess energy produced off-peak.[18] DILCs are designed to monitor the frequency of the electrical system to determine the availability of electricity and to cut off power to large, dispensable loads when electricity is limited. Smith et al. (2003) describe using the combination of current limiters and DILCs to better manage a limited electric supply 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

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[17] Additional information was presented to the community through bilingual posters, pamphlets, and visual aids as well as through presentations and activities at the local school.

[18] 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.[19] 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. 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 types of grids, if meters are installed, the best practice is to use meters in conjunction with either a current 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) and create ongoing costs for meter readers.[20] Additionally, it is important to consider the power consumption of the energy meter itself with respect to the size of the generation

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[19] PowerProvider brand electronic circuit breakers were used as current limiters for this case study.
[20] Note that retail price information was not collected from all companies and was quoted for quantities of 100 units.

and loads on the mini-grid. 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. Additionally, low-income consumers that do not fully understand how their use of electricity can affect their bills can receive bills that are beyond their means to pay.

Prepaid Meters

Since the late 1980s, prepaid meters have risen in popularity for use on both mini-grids and utility-scale grids (Ghanadan 2009, Nefale 2004, Ruiters 2009, van Heusden 2009, Tewari and Shah 2003). 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.[21] 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. In recent years, many rural customers have already become accustomed to prepayment systems thanks to the widespread use of prepaid mobile phones. For prepaid electric meters, 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 payments from customers.[22] An additional cost or opportunity that accompanies 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 current 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 current-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 will be described in the next section.

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[21] 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 in South Africa (van Heusden 2009, Tewari and Shah 2003). 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 (Ruiters 2009, Nefale 2004). 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 (Ruiters 2009, Ghanadan 2009).

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

Though prepaid meters have been in use on mini-grids for years, several recent mini-grid installations have highlighted their use of prepaid meters. As part of their renewable energy mini-grids, the recent social energy start-up Devergy uses a prepaid metering system (Devergy 2012). Users buy scratch-off cards and send an SMS message with a credit code to the payment system to add electricity to their meters. Devergy states that though most of the initial installation costs of the mini-grid and generation are covered by donation, each user is charged a small fee at the time of connection. The entire system is remotely monitored for faults and has been tested in an initial pilot project in Matipwili, Tanzania. Earthspark International has also chosen to pioneer the use of prepaid meters with additional current limiters in their mini-grid installation in Les Anglais, Haiti (Archambault 2012). This will be the first use of prepaid meters in Haiti, though consumers have already experienced prepaid systems through their mobile phone providers.

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. Though they are all relatively new, some of these systems have undergone successful field trials; these include the Circutor Electricity Dispenser, INENSUS Micro Utility Solution, CAT Project's Bushlight India and SharedSolar. Other systems, including Powerhive and Gram Power's Smart Microgrid, are currently undergoing their early pilot or demonstration projects. An additional start-up, Lumeter, is in the process of creating and field-testing their first prototypes.

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 devices. 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.[23] 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.[24] Each of these advanced metering systems is summarized in Table 3 and described in more detail below.

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[23] Just as with the prepaid meters, price information was not collected from all companies. When collected, these prices were quoted as retail prices for small quantities. As many of these systems are still refining their meters and currently using small production runs, these prices may decrease in the future.

[24] Tariff regulations for mini-grids vary by country and may or may not allow for this financing strategy.

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 the meter	-Power limit -Energy usage limited to pre-set rate -Enables loadshedding -Can use "pricing" signals to encourage DSM	Cape Verde, Morocco, Ecuador, and soon in 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-set quantity -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 -Energy usage limited to pre-set quantity -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 to account. System uses centrally-located meters.	-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. System uses centrally-located meters.	-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 electricity credits from local vendors who provide a code that can be programmed into the meter. Back-end accounting enables project developers to be reimbursed based on electricity purchases.	-Power limit -Pre-paid metering -Enables loadshedding	Soon to be installed in Peru

Circutor Electricity Dispenser

Circutor is a Spanish electrical and energy efficiency company that offers an alternative take on the prepaid meter by controlling both power and energy use. In this system, users purchase a monthly subscription to a maximum power limit and associated "flow" of energy, described as the user's Energy Daily Allowance (EDA) (Vallvé et al. 2000, Circutor 2012a, Briganti et al. 2012).[25] Each user starts their service with three EDAs, which are equivalent to three days of a pre-determined amount of daily energy consumption based on the mini-grid's generation capacity and community's load profile. Throughout the day, energy credits are constantly added to the dispenser at a set rate equivalent to one EDA per day. If a user maintains their consumption at a similar rate, the user's balance will remain at approximately three EDA. If a user consumes at a slower rate, the meter records the electricity savings and the EDA balance may increase up to a maximum of six EDA, which can be used at a later time. If users consume at a faster rate, their balance will decrease. If the balance reaches zero, the meter will disconnect all supply to the household. Because the EDA credits are constantly being supplied at a set rate, power will automatically restore after a few minutes, once the balance is positive. If disconnection was caused because the current limit was exceeded, power has to be restored by the user by pressing a reset button on the meter.

The monthly EDA rate and power limit are programmed onto a card by a local vendor and the card is then used to activate the household meter. The meters are also designed to allow users to transfer EDA credits from their meter to a neighbor's meter or a meter at a community center using their cards (Circutor 2012b). This process and other information are communicated to the user through a small digital display that can be programmed to display in several languages.

Circutor Electricity Dispensers may be installed as separate units with no central communication, or may be connected to a supervisory control module that monitors the status of both generation and battery storage. When communicating with the supervisory control module, the Circutor Electricity Dispenser can provide additional DSM by encouraging the use of surplus energy when generation is high and storage is full and discouraging the use of energy when battery state of charge is low. These signals are provided through LED indicator lights on the meter, and result in EDA being consumed at a slower rate to encourage surplus energy use, or a faster rate to discourage energy use. To enable loadshedding, the Circutor Electricity Dispenser includes an additional auxiliary relay that can be wired to automatically turn on or off deferrable loads based on signals from the energy management supervisory control module.

Circutor Electricity Dispensers and their prototypes have been installed on isolated grids in Spain, Senegal and Morocco and were most recently installed in conjunction with a solar-diesel hybrid mini-grid in Monte Trigo, a village of approximately 80 households in Cape Verde (Briganti et al. 2012). Community meetings, practical trainings and demonstrations were conducted with both consumers and system technicians during and after the installation. After several months, the residents reported being

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[25] Prototypes of the Circutor Energy Dispenser were originally designed and tested by Trama Tecno Ambiental (TTA) in the late 1990's in villages in Spain under the name *TApS - energy dispenser / meter*.

satisfied with the service and the system managers registered consistent on-time payments for the service. Additionally, the state of charge of the system battery bank was maintained at nearly 90% and the inverters always operated within their optimum range, suggesting that the metering system provided effective DSM.

INENSUS Micro Utility Solution

Created by the German off-grid energy company INENSUS, the Micro Utility Solution also allows users to purchase a monthly subscription in the form of "electricity blocks" (INENSUS 2012a). An electricity block is a standard unit of available energy that allows 28 hours of electricity consumption per week at a maximum power of 50 W, for a maximum consumption of 1.4 kWh per week. If a consumer uses less than their allotted electricity in a week, the balance is forfeited at the end of the week, while if a consumer uses all of their allotted energy in the week, the meter disconnects power to the household until the beginning of the next weeklong block (ArcFinance 2012). Customers pay for electricity blocks in advance each month during a monthly visit from an INENSUS recharge agent. Electricity blocks are added to a card that the customer then uses to activate the meter.

To facilitate change in customer demand and enable system operators to appropriately match generation to expected load, every six months, customers may decide how many electricity blocks they intend to purchase (INENSUS 2012b). As expected load increases or decreases, the system operator can add or remove additional generation (typically solar panels or wind turbines) and battery storage capacity to meet the demand. Because the electricity blocks are paid in advance without regard to actual consumption, are ordered over a relatively long time horizon (six months), and are priced with regard to the modular generation components, the system operator is able to make a more secure investment in both the initial design of the system and in added generation capacity. Though customers are responsible for purchasing the electricity blocks they order each six months, some flexibility is allowed in trading blocks between customers on the same mini-grid to accommodate changes in budget or need. Additional flexibility is provided by the inclusion of a diesel generator as part of the hybrid system. This generator can be used to meet energy or power demands that were not foreseen in the initial renewable energy system design (e.g. short term peak demands for productive uses or to bridge times when consumers run out of block energy before the end of the week). So called "extra energy" produced by the diesel generator is sold at higher rates than electricity blocks reflecting more expensive diesel fuel consumption.

In addition to the energy management offered by the electricity block system, the meters can provide additional demand-side management based on the status of the grid as indicated by the frequency. Individual meters can be programmed to disconnect during times of overload; decisions of how to prioritize meters are typically made as a community. Similarly, at times when excess power is available, non-essential loads, like water pumps, can automatically be turned on.

INENSUS conducted their first pilot in 2010 in Sine Moussa Abdou, a village of approximately 70 households in Senegal (INENSUS 2012a). In this first installation, customers and operators tested the electricity block tariff model and established a village committee to help make decisions regarding the power system. Additionally, with support from outside microfinance organizations and the availability of affordable electricity, several businesses were established in the community that included an electrical rice mill, an electrical peanut peeler, and electrical sewing machines. A second system was commissioned in 2011 and 30 more are planned for 2013.

CAT Project's Bushlight India

Bushlight India is a program run by the Australian company CAT Projects, which uses a comprehensive set of processes and technologies to provide isolated rural electrification, based on similar frameworks implemented in Australia over the past decade (CAT Projects 2011). This framework, referred to as the Village Energy Service Delivery Model (VESDM), emphasizes the importance of education and communication starting with village selection and initial system design. The central DSM technology in the VESDM is the Urja Bandhu, an energy management unit that meters the electricity. As an early step to inform system design, each user subscribes to a fixed daily energy budget (between 0-10 kWh/day) based on their desired appliance use and available funds. The solar generation and storage systems are typically sized according to this initial planning process, with a modest allowance (20% excess generation was purposely installed in each study) for consumers to increase their daily energy budgets in the future. The VESDM also provides DSM through the centralized "System Control Board" on which different load types are wired and monitored separately. This segregation allows for more careful monitoring of the system and enables load-shedding within the mini-grid on a prioritized basis.

In addition to being tested and implemented in over 120 aboriginal villages in Australia, to date, the Bushlight India model has been implemented in two villages in India: a village of 47 households in Orissa and a village of 48 households in West Bengal (CAT Projects 2011). Both systems were equipped with a 9.65 kWp solar array, a 10 kW inverter and 144 kWh capacity battery bank. The Village Energy Planning (VEP) process involved community level meetings, small group workshops, and planning sessions and household visits to establish the energy demand from connected households, businesses, and community buildings. As part of the VESDM, the VEP is a standardized process equipped with documentation and effective visual aids to facilitate these discussions. This process established household energy budgets and enabled the system designers to size the system for an average total consumption of 23 kWh per day in both villages. The Urja Bandhu energy management units continue to monitor electricity use in each of the households and regulate consumption at the previously agreed upon rate.

SharedSolar

SharedSolar, a project from the Modi Research Group at Columbia University, offers another take on prepaid metering coupled with centralized monitoring and control (SharedSolar 2012, Soto et al. 2012). A distinct innovation is the elimination of individual household meters in this system, relying instead on larger centrally-located meters that monitor and limit up to ten households individually and communicate with the central system. The system consists of four main components: the on-site generation (solar panels, batteries, and supporting electronics), the system meters, a central computer, and an external server.

To add energy credits to their account, users purchase scratch cards from local vendors and communicate with the system by sending an SMS message with the scratch card code from their mobile phone. The server receives the SMS message and communicates with the on-site computer, which adds credit to the household's account and controls the household's circuit through the collective meter accordingly. Users, the server, and the meters can communicate over the Internet or the mobile phone network. System operators can access the server to view information on customer accounts as well as generation and load profiles.

Users may purchase as much credit as they choose, but their energy use is restricted by a maximum power limit and maximum daily energy limit. A customer's electricity will be automatically disconnected by a relay in the centralized meter when their account runs out of credit, when they have exceeded their maximum daily energy use, or if they exceed the maximum power limit. SMS messaging is used as a tool to warn users at times when their credit is running low, and can be used by customers to check their balances and turn on or off power to their house. Though not yet incorporated in the system, project designers hope to additionally use SMS messaging as a form of DSM by telling customers when excess electricity is available at a reduced rate.

Starting in April of 2011, SharedSolar systems have been installed in several "Millennium Villages" in Mali and Uganda, and the team plans to install more throughout Africa. In addition to leading village discussions to assess demand and willingness to pay, the team conducted small-group trainings with all consumers on how to manage their account through the SMS system. These installations have been successful with initial data suggesting that most customers are using the equivalent of a 5 W LED light for 2-3 hours each night and maintaining a non-zero balance in their account over 90% of the time. The systems have also encouraged small businesses, enabled the installation of a local radio station, and improved hospital services in some of the pilot villages. Currently the SharedSolar installations have used off-the-shelf hardware and retail-priced SMS communications, but project designers hope to create custom hardware and negotiate more favorable communications pricing to increase functionality and reduce costs of the system.

Powerhive

Powerhive, based in Oakland, California, uses a similar system to that of SharedSolar with a centralized server controlling communal meters, relying on customers to communicate with the system through their mobile phone (Powerhive 2012). Distinct differences between the two systems include Powerhive's use of proprietary software and hardware in their system and the reliance on existing mobile money platforms instead of scratch cards for user payment. In their first installation near Kisii, Kenya in August of 2012, Powerhive has taken advantage of the prevalence and popularity of the existing mobile money platform, MPesa, to manage the payments for account credits (Kogan 2012, Juliobytes 2012).

Gram Power

Gram Power was founded by two recent graduates of University of California, Berkeley and is currently being piloted in a village in Rajasthan, India (Gram Power 2012, Pidd 2012, PowerNews11 2012). Gram

Power's Smart Microgrid involves the installation of a solar array, battery bank, inverters, a central monitoring system and proprietary, low-cost, pre-paid meters (Pidd 2012). A local entrepreneur purchases credit in bulk from Gram Power's Jaipur headquarters and then re-sells the credit to individual households. Credit is added to each household meter using Gram Power's small, wireless-capable, energy selling-device. In addition to the prepaid aspect of the system, Gram Power offers DSM in the form of a power limit. Each customer chooses a power limit, which can be programmed on their meter through the mini-grid's central computer. If one consumer is drawing more than their agreed upon power limit, the meter cuts off electricity to the house, indicates to the user that there is an overload, and then reconnects once the user reduces consumption. The pilot installation is reportedly successful with many local consumers upgrading their initial power allotment to enable the use of coolers, fans, buttermilk machines, TVs, and DVD players.

Lumeter

Lumeter's model also uses small prepaid meters installed in each house to manage consumption (Lumeter 2012). Users can purchase credit in the form of a code from a local vendor to add energy to their meter. Though not particularly relevant to DSM, the innovation in the Lumeter system is in the accounting end of their business model; local vendors purchase codes by SMS from the Lumeter server, which then communicates this purchase to project funders and manages back-end accounting. By use of this back-end accounting, project developers or community members can purchase Lumeter meters at a substantially reduced initial cost (manufacturing cost) and gradually pay for the full cost of the meters through a commission on transactions over time. As for DSM capability, in addition to the prepaid aspect, their meters also have programmable current limits and enable load-shedding to prioritize specific loads when the system is overloaded. Lumeter has recently produced their first prototypes and plans to start field trials in Peru this year.

CONCLUSION

This report provides an assessment of current methods of managing loads in the context of the isolated, village-scale mini-grid, which is typically limited in both generation capacity and finances. With limited generation capacity, some form of DSM strategy or technology is required to maintain reliable electricity service and ensure equitable sharing of the resource among users. However, due to limited financial resources, any DSM measures applied must be cost-effective and appropriate to the particular mini-grid.

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 current limiter should be included in the system design to ensure equitable power use. For systems that typically produce excess generation throughout the day and have very low costs of marginal generation, such as micro-hydro mini-grids with no storage, “smart” current 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, or electronic circuit breaker, but the enhanced ability to use high-power appliances when ample electricity is available would 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 ambulatory 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.

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