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Solar microgrids and remote energy access

How weak incentives can undermine smart technology

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Solar Microgrids and Remote Energy Access: How Weak Incentives Can Undermine Smart Technology

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ABSTRACT

This paper documents the challenges faced by one company, Gram Power, installing and operating solar microgrids in rural India. We begin by summarizing the existing literature on best practices for microgrid deployment and show that Gram Power followed nearly all of the recommendations. Nonetheless, Gram Power faced significant challenges in convincing communities to take up a microgrid, largely due to the perception that grid power was imminent and preferred. The company installed only 10 microgrids after visiting 176 villages, so its customer acquisition costs were higher than expected and economies of scale were lower than expected. Also, in villages where microgrids were eventually deployed, Gram Power faced challenges collecting revenues, mainly due to theft. Even though Gram Power installed sophisticated meters that could detect theft remotely, principal-agent problems, combined with the remote location of the microgrids, hampered the company's ability to stop theft. We conclude by discussing how policy may or may not be able to address some of these challenges going forward.

Keywords: Energy innovation, Energy transition, Microgrid, India

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1. INTRODUCTION

Over 1 billion people currently live without electricity in their homes, and nearly one third of these people live in India (OECD/IEA, 2017). In recent years, expanding access to a modern energy supply has become an important goal for policymakers, non-governmental organizations, and international donors. The United Nations includes "access to affordable, reliable, sustainable and modern energy for all" among its Sustainable Development Goals (United Nations, 2015). In India, the government has a set goal of achieving universal electrification for urban and rural households by 2020 (Press Trust of India, 2017).

Although there is widespread support for expanding access to electricity, experts disagree about how to meet these objectives. The costs of extending and maintaining large-scale grid infrastructure to remote areas can be very high. Moreover, once connections to the grid have been established, utilities and distribution companies often face weak incentives to provide reliable service to poor and remote communities.

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As an alternative to grid extension, some policymakers have promoted the adoption of small-scale solar systems that allow households to generate their own electricity. An advantage of this self-generation solution is that it does not require costly grid extension. A limitation is, historically, entry-level private solar home systems have been unable to provide energy services beyond very basic end uses. In addition, these systems have generally been too expensive for meaningful adoption by first-time users without subsidization (Grimm et al., 2017a,b; Lee et al., 2016; Aklin et al., 2016; UNDP, 2011; Mondal, 2010; Wamukonya, 2007; Nieuwenhout et al., 2001).

In many ways, microgrids appear to offer the best of both worlds. Innovative private companies have developed scalable microgrid systems that provide small-scale grid access to remote areas in a relatively inexpensive way, often more quickly than utilities or governments can extend the centralized grid (IEG, 2008). Microgrids can be powered with clean, alternative energy sources, such as solar, hydro and wind. Moreover, it is possible to integrate microgrid infrastructure with the national grid if and when it arrives (Urpelainen, 2014).

This paper describes the experience of one company working at the frontier of smart grid deployment in India. In their initial years of work, Gram Power pioneered smart microgrids by combining proprietary smart meter technology with off-the-shelf solar panels, batteries, and inverters to provide an integrated "smart microgrid" for villages and communities. The company has been internationally recognized and received several patents for its technology innovations that address the basic power needs of rural villages in India.[2]

Mindful of lessons learned from past microgrid initiatives, Gram Power (GP) developed technologies and deployment strategies that incorporated many of the best practices identified in the literature (see, for example, Schnitzer et al. (2014), Sovacool (2012), Brass et al. (2012), UNDP (2011) and ESMAP (2000)). This approach notwithstanding, the company encountered several formidable challenges. One limiting factor was low demand for solar microgrids in remote areas. This drove up customer acquisition costs and limited economies of scale in operations. A second complication involved consumers bypassing meters (and other forms of theft). Although the GP smart metering technology could detect and, in principle, redress these issues, local operators were unwilling to crack down on theft in their communities to increase revenue collection. Moreover, the Indian Government has several electrification schemes through which grid extension is free for below-poverty-line (BPL) populations and power is supplied to these communities at extremely subsidized rates.[3] Such policies, along with India's unstable subsidy policies for microgrids, made it financially unviable for microgrids to operate in such remote settings. Ultimately, these problems undermined the profitability of GP microgrid projects in India. The company subsequently suspended its microgrid business and renewed their focus on deploying their advanced metering infrastructure technology for grid-connected consumers.

The prior literature has documented several apparently successful microgrid installations that have improved energy access and other socioeconomic outcomes.[4] Some papers document mixed results.[5] Far less common, but no less important, is the documentation and analysis of microgrid projects that did not achieve their objectives. Although researchers, governments, and aid organizations may be less inclined to shine a light on initiatives that fall short of their goals, understanding the factors that lead projects down unexpected paths is critical for informing policy design and targeting future infrastructure investments.

This paper provides a comprehensive review of one initiative to deploy microgrid systems in

[2]Gram Power has received awards and recognition from the NASA LAUNCH Energy Challenge, World Wildlife Foundation, Indian Government, Indian Prime Minister Narendra Modi, New York Times and several other organizations.

[3]Need cite.

[4]Kirubi et al. (2009) documents increases in both productivity and income from a diesel-based microgrid in Kenya. Meeks and Thompson (2017) present evidence suggesting wage employment opportunities increase in Nepal due to micro-hydro systems. Rao et al. (2015) find that women spend more time in leisure and enterprise after the installation of various types of microgrids.

[5]Millinger et al. (2012) and Aklin et al. (2017) document increased access to electricity and decreased spending on kerosene, but find no measurable impacts on employment or education-related outcomes.

remote communities in India, paying particular attention to the challenges that ultimately undermined the commercial viability of privately funded rural microgrid projects. Section II provides background and an overview of the services Gram Power set out to provide in rural villages. We describe the program design, cost structure, and value proposition *vis-a-vis* best practices recommended in previous literature. Section III describes the customer recruitment process and highlights some of the unexpected difficulties. Section IV describes the process of microgrid installation. Section V describes operations and challenges associated with theft and revenue collection. Because the project included a rigorous evaluation component, we are able to analyze these outcomes in unprecedented detail. Section VI concludes with a summary of lessons learned and associated policy implications.

2. BACKGROUND

A "microgrid" generally refers to a small group of interconnected loads and distributed energy resources that can be operated in a coordinated and self-contained way. While the number of microgrids in operation remains relatively small, policymakers and project developers are increasingly enthusiastic about the potential role these systems could play in serving remote regions in particular. In India, policymakers have set generous targets for electrification, and microgrids play a critical role for reaching difficult-to-access rural locations where grid extension is infeasible (MOP, 2013). In Bihar, for example, the state cabinet has recently called for 100MW of solar microgrid capacity by 2022, which is not inconsequential given Bihar had just over 4GW of total electric generating capacity as of January 2018 (Central Electricity Authority, 2018; Pathanjali, 2017).

A growing literature reviews past experiences with microgrid deployment around the world in the interest of identifying best practices and protocols (see, for example, Schnitzer et al. (2014), Sovacool (2012), Brass et al. (2012), Palit and Chaurey (2011) and ESMAP (2000)). In this section, we briefly summarize these principles and assess the extent to which Gram Power was able to adhere to them.

2.1 Microgrid Best Practices

First and foremost, the prior literature underscores the importance of meaningful engagement of key stakeholders:

- **Community engagement:** Numerous studies underscore the importance of engaging the local community (including households, local politicians, village organizations, etc.) at all stages of the project design and deployment (see, for example, ARE (2014) Sovacool (2012); Brass et al. (2012) and Palit and Chaurey (2011)). ESMAP (2000) warn that microgrid projects will be destined to fail unless they are promoted from within.

- **Political context:** Microgrids are often deployed in dynamic environments where changing regulatory incentives and evolving policy priorities can conflict with microgrid operations (Bhattacharyya and Palit, 2016; Palit and Bandyopadhyay, 2015; Bhattacharyya, 2013; Brass et al., 2012; UNDP, 2011; Palit and Chaurey, 2011; Painuly, 2001). Schnitzer et al. (2014) recommend coordinating with government agencies early in the project development stage, and formulating contingency plans that can accommodate changes in economic incentives and policy direction.

Another set of best practices pertain to sizing the microgrid system and load management:

- **System capacity:** Ideally, a microgrid should be sized to match local energy demand (Brass et al., 2012; UNDP, 2011; Chaurey and Kandpal, 2010). However, it can be very difficult to forecast future electricity demand ex ante (see, for example, Blodgett et al. (2017) and Boait et al. (2015)). In light of these difficulties, some recommend investing in more modular systems that can be readily expanded or contracted to match consumer demand (Cronje et al., 2012).

- **Commercial loads:** Several studies have highlighted the importance of promoting and supporting commercial loads and associated income-generating activities (see, for example, Sovacool (2012) and ESMAP (2000)).

- **Load management:** Microgrid systems are likely to be capacity constrained during hours of peak consumption. The literature recommends several approaches to ensuring system reliability at peak times. These include the use of load limiters or distributed intelligent load control, investments in more efficient appliances, restrictions on what types of appliances consumers can use, and efforts to ensure that consumers understand the design limits of the system (Alstone et al., 2015; Harper, 2014; Brass et al., 2012; ESMAP, 2000).

The literature has also identified principles to guide the design of price schedules:

- **Affordability:** Much of the literature emphasizes the importance of designing price schedules that are acceptable and affordable for a wide range of users (ARE, 2014; Sovacool, 2012; ESMAP, 2000).[6]

- **Sustainability:** Pricing structures should be designed to ensure that revenue collection matches cash flow requirements for the system (Schnitzer et al., 2014; Barnes and Foley, 2004). Inadequate tariff collection can lead to poor operation and maintenance, which can undermine long-term success. Somewhat counter-intuitively, donor support in the early stages of a project can hurt long-term prospects if it weakens the incentive to establish a sustainable tariff structure (Schnitzer et al., 2014; Tenenbaum et al., 2014).

Once the system and service operation designs have been established, service providers have a host of important decisions to make regarding deployment and operations. Schnitzer et al. (2014) make the distinction between a "virtuous cycle", in which the microgrid owner provides high quality service such that customers are willing to pay according to the agreed price schedules, and a "vicious cycle", in which poor contractor performance and poor service quality leads to non-payment, theft, and revenues that do not cover costs. To avoid the latter situation, recommended best practices include:

- **Timely and quality construction** of the microgrid infrastructure to shape communities' initial impressions about quality and the level of commitment.

- **Customer support and proper maintenance** in order to maintain a good relationship with customers (Ahlborg and Hammar, 2014; Sovacool, 2012; Millinger et al., 2012). Schnitzer et al. (2014) endorse involving the community in the operations, management and maintenance of the system. However, they warn that without adequate training, local operators will be unable to undertake the various maintenance and operations tasks effectively (Schnitzer et al., 2014; Palit et al., 2013).

- **Accurate billing** as well as simple bill payment processes to increase consumers willingness and ability to pay in a timely manner (Brass et al., 2012).

Finally, past studies have offered recommendations on how to manage and/or deter non-technical losses (including theft):

- **Zero-tolerance** for theft and continued non-payment. Clearly articulated penalties with strong enforcement can increase the financial viability of the system (ARE, 2014; Schnitzer et al., 2014; ESMAP, 2000). Schnitzer et al. (2014) note that employing a bill collector from outside the community can help increase bill payment as it may be uncomfortable for a local bill collector to confront friends and relatives about theft or non-payment.

In the following subsection, we will outline how these best practices informed Gram Power's design and deployment strategy in Rajasthan, India.

[6]For example, ESMAP (2000) endorses the provision of a “lifeline” tariff sufficient for simple lighting so that even the poorest members of a community can have access to electricity.

2.2 Gram Power Overview

Gram Power was founded in 2010 by Yashraj Khaitan and Jacob Dickinson. The founders perceived an urgent need for expanded access to electricity, particularly in remote parts of India. Recognizing that conventional grid extension to remote villages would be prohibitively expensive, Khaitan and Dickinson worked to develop an alternative. The microgrid system, coupled with a prepaid service model, reflected many of the best-practice criteria summarized above.

- **Community engagement:** Gram Power invested heavily in consumer engagement and education. They hired NGOs that had previous experience in targeted areas to facilitate initial interactions with the local village leaders. In each community, Gram Power identified and hired a "village entrepreneur" to act as a local agent. This entrepreneur was tasked with facilitating community involvement, consumer education, and local management of system operations. The entrepreneur was employed on a commission basis and the company started with relatively low 5% commission rates. Given the lack of success at this level, the company increased these rates (up to 50%) to try to properly incentivize the village entrepreneur. In addition, Gram Power contemplated hiring an outside bill collector as recommended by Schnitzer et al. (2014), but found that there was insufficient commission available to the bill collector since total revenue collected was small and the sites were remote.

- **Political context:** Recognizing that microgrids are widely viewed as an inferior alternative to a conventional grid connection, GP targeted areas that were unlikely to receive a grid connection in the foreseeable future.[7] These included extremely remote villages and protected areas where regulations prohibited grid extension for ecological reasons.

- **System capacity:** During the initial site identification, Gram Power analyzed what day-time and night-time loads were currently used in the village (through solar home systems, diesel generators, etc.). Secondly, they asked villagers what monthly payment plan they would consider for service (see the affordability bullet below for a description of the various proposed rate plans). Third, they gathered detailed income information from potential customers to gauge their ability to pay for services. In addition to the income data, they assessed the willingness of local politicians (Panchayats) to donate part of the connection fees to cover households who were unable or unwilling to pay the fees. With this information in hand, Gram Power sized panels, inverters, distribution lines and batteries. They designed the systems to allow for modular expansion or contraction over time.

- **Commercial loads:** Gram Power worked with the village entrepreneur to identify potential commercial loads that could be supported by a microgrid. Further, they offered various tiers of service. The highest tier could support small mills and other productive appliances.

- **Load management:** Technologically, a key benefit of the Gram Power systems lies in the proprietary smart metering technology that can remotely limit loads and differentially monitor consumption levels based on the different tariff rates they originally proposed (see next bullet for details).

- **Affordability:** As mentioned in the system capacity bullet, the GP pricing structure was based on consumers ability to pay tariffs. The pricing structure included an initial connection charge, a monthly fee, and a volumetric (per kWh) charge. Initially, three rate plans were proposed, differentiated in terms of the appliances that could be supported. A basic connection, priced at 1000 INR supported cell phone charging and 2 LED lights. A connection charge of 2500 INR would support a fan and TV in addition to lighting and cell phone charging. To support commercial applications, an additional 15000 INR would support irrigation pumping.

[7] Pueyo (2013) suggests this is a common criteria for many microgrid installations.

Ultimately, the second and third options were deemed to violate the affordability criteria, so Gram Power elected to offer only basic connections at a rate of 1000 INR per connection. In addition to the connection costs, households paid 20 INR per kWh and 150 INR per month.

- **Sustainability:** Gram Power set the connection fees, fixed charges and per-kWh fees given the affordability constraints discussed above. Full recovery of all capital and operating expenditure would have required per kWh fees upwards of 50 INR, which was deemed by Gram Power to violate the affordability criteria. For example, MNRE suggests that the capital cost of a typical 5 kilowatt system, which Gram Power installed to serve approximately 40 households, is about 150,000 INR.[8] At Gram Power's cost of capital, this amounts to 15,000 INR of monthly capital costs. Gram Power deemed that a monthly fixed charge of 150 INR per customer met the affordability criteria, amounting to 6,000 INR per month at 100% collection. At a capacity factor of 13%, the 5 kW system will produce approximately 475 kWh per month. So, if all households were paying 20 INR per kWh, yielding 9,500 INR per month in variable charges, and collection rates were 100%, the system would barely cover its capital costs and no operating or customer acquisition costs.[9]

- **Timely and quality construction:** With regards to technology deployment, the quality of the work done by the contractors initially hired by Gram Power was disappointing. Recognizing the importance of high quality and timely deployment, Gram Power took over construction and installation responsibilities and was able to complete system installation within a month at each site.

- **Customer support and proper maintenance:** One overarching challenge with both deployment and operations was the remote nature of these systems. Gram Power's choice to enlist local community members to implement on-the-ground operations (from customer service to system maintenance) was as much a choice of necessity as an effort to engage the local community. The village entrepreneurs were trained to act as a customer service representative, collect tariffs, conduct routine maintenance, monitor system losses, enforce penalties for nonpayment, etc.

- **Billing:** GP smart meters allowed for easy recharging of electricity fees through vouchers sold by the village entrepreneur. The local village entrepreneur also collected fixed fees, which provided easy, local payment given the size of the study areas.

- **Theft detection and deterrence:** One distinguishing feature of the GP smart metering technology is the ability to detect theft or meter tampering at a very granular level. Sensors on the network can quickly identify discrepancies between power flows and metered consumption.[10] GP smart meters can also sense and signal tampering. In response to either theft or tampering, power supply can be remotely disabled. In addition, village entrepreneurs were trained to detect theft and enforce penalties.

3. CHALLENGE 1: SOLAR MICROGRIDS ARE A TOUGH SELL

The project was initially designed to install up to 40 microgrids in rural Rajasthan. In the planning stages, Gram Power compiled a list of communities that were not targeted for grid extensions over the

[8] This figure is derived based on the 30% benchmark MNRE subsidy rate set at 100 INR per panel watt. This implies an allowed cost of capital around 300 INR per panel watt (with battery storage). See MNRE (2014) for details on the subsidization plan.

[9] In terms of cost recovery, part of Gram Power's objective in this roll-out was to determine what amount of capital expenditure support (from governments, grants, etc.) was necessary to make microgrids privately feasible. As such, this first stage of Gram Power's operations was supported generously via outside, non-governmental grant funding.

[10] Theft detection algorithms embedded in the data concentrator unit analyze power flows via line-specific master meters. If the cumulative metered energy consumption on a line is less than 90% of the total metered supply, the master meters are programmed to shut off supply to that line.

next 2 years.[11] Gram Power visited 176 villages to assess technical potential (e.g., land availability, cellular network availability, distance between households) and economic viability (e.g., willingness and ability to pay for a connection, demand for energy services). Information sessions were held to introduce the technology, explain the value proposition, and answer questions.

Gram Power found it far more difficult than expected to find villages with sufficient demand for a microgrid. Although many sites met the technical criteria for installation, only 10 microgrids were ultimately deployed. One important barrier to acceptance was the lack of clear mandate from the Indian government with respect to which regions would receive a heavily subsidized connection to the national grid. In many villages, grid connections had been promised by politicians during their election campaigns. The fallibility of these promises notwithstanding, this dramatically reduced rural consumers willingness to pay for a microgrid connection, which is consistent with the survey-based analysis in Comello et al. (2017).

Table 1 compares baseline summary statistics for villages that adopted microgrids to statistics on other unelectrified villages (as defined by the Indian census) within the same districts as our study area.[12] Since the data from the Indian census are much more limited than our baseline information, we can only compare these villages on a limited number of dimensions.[13] The villages where Gram Power installed microgrids are similar in terms of average household size to other unelectrified villages. Households in adopting villages are just as likely to have a metal roof as other households but are much less likely to own a toilet—suggesting that adopting villages may be less wealthy, on average, than other unelectrified villages. Most importantly, however, households in the adopting sample are much more likely to use solar lighting and are less likely to use kerosene as their main lighting source.[14] Given that these villages eventually adopted a microgrid, a positive prior experience with solar technology could explain a higher willingness to adopt another solar-based technology. Alternatively, these households could be generally more receptive to any technology that affords increased electricity access.

Even in villages where demand was sufficient for a microgrid to be installed, the rural villagers were very skeptical about giving money to Gram Power, a private company, on the promise of receiving a system at a later date. This lack of trust between Gram Power and their potential customers led to further costly delays with respect to mobilization.

In sum, difficulties in customer recruitment increased deployment costs by a significant margin. For any new technology, customer acquisition costs can significantly increase the cost of doing business. In this case, acquisition costs were driven much higher by overly optimistic expectations, on the part of rural villages, that fully subsidized connection to the conventional grid was imminent. These costs could have been reduced if households and communities had clear and realistic sense of the government's grid expansion plans.

4. CHALLENGE 2: WEAK INCENTIVES UNDERMINE SMART TECHNOLOGY

In the communities where Gram Power eventually deployed microgrid systems, it faced another set of challenges around system operations. The high-frequency production and consumption data collected by the company's metering infrastructure at multiple points on the microgrid network allows us to analyze these challenges by depicting system operations and household consumption patterns in

[11] Since the Government of India has no clear mandate regarding the regions that will get grid extension, a wide variety of sources were used to prepare this list.

[12] Our baseline data were collected between September 2014 and May 2015. For adopters, these data were collected after the village had agreed to pay for a microgrid but before the microgrid was installed. The census data are from the 2011 Indian census.

[13] A larger suite of summary statistics for the electrified sample are included in Table A1 in the Appendix.

[14] Given the difference in dates between our baseline survey (2014-2015) and the Indian Census (2011), we acknowledge that the differences could reflect increased penetration of solar home systems over time. However, we believe it is unlikely that this fully explains the large discrepancy between our communities and census.

unprecedented detail.

Figure 1 summarizes the typical daily load using data from our entire study sample and potential generation profile using projected data.[15] On the left-hand vertical axis, we measure energy consumption, which is derived directly from the meter data. The solid and dashed black lines reflect average system-level hourly load at centralized master meters and average metered consumption (i.e. the system-level sum of individual households), respectively. Since we do not observe data on solar production directly, the right-hand vertical axis depicts the average power potential (the gray line) based on weather and system characteristics using the NREL PVWatts Solar Calculator for India.[16] The different scales on the two vertical axes highlight the disparity between default PVWatts parameters, which reflect nearly perfect operating conditions in terms of panel soiling and maintenance, and production at the Gram Power systems. It is unlikely that the Gram Power systems were operating at peak capacity throughout the study, which may be one reason for the relative mismatch of the scales on the left and right vertical axes.

Figure 1 also highlights how solar peak production during the middle of the day does not align with the evening consumption peak in this setting. Average consumption peaks around 8PM, presumably due to lighting, which comprised the majority of household demand in these systems. Solar production, however, occurs between 6AM and 7PM and peaks during the middle of the day.

While Gram Power designed these solar plus battery storage systems with this mismatch in mind, the point remains that reconciling production and consumption is costly. The disaggregated data in Figure 2 show that two of the villages in our study—Khandpuriya and Kolipura—have system peaks in the late afternoon which are more closely aligned with solar production.

Figures 1 and 2 also illustrate the extent to which consumption recorded by the master meters (measuring total electricity load on the system) exceeds the consumption recorded by household meters. Absent theft, we would expect to see the solid black line very close to the dashed black line. Given the size and proximity of these systems to the consumers, technical losses (e.g., energy dissipated in the conductors and distribution line and magnetic losses in transformers) should be negligible. Although the aggregate household load does not include, for example, system power or electricity for community buildings (which was a feature of some of the systems), community building consumption was very limited on these systems. We thus interpret the vertical difference between the solid black and dashed gray line as a measure of commercial or 'non-technical' losses. These non-technical losses (and associated revenue losses) ultimately reached unsustainable levels. In what follows, we analyze non-technical losses at both the aggregate and household level.

4.1 Non-technical losses

As noted above, the prior literature warns of a "vicious cycle" in which poor contractor performance and poor service quality lead to customer dissatisfaction, theft, and low cost recovery for the operator. In this setting, we can analyze the temporal patterns of power availability and theft to assess whether non-technical losses manifest after (and possibly in response to) supply interruptions and poor service.

Figure 3 summarizes temporal patterns in power supply and our measure of non-technical losses. The horizontal axis measures the week of microgrid operations.[17] The left vertical axis measures both the availability of supply (power supply as a share of system capacity) and non-technical losses (i.e., the share of master meter throughput that is unmetered at the household level). These measures are averaged across all operating systems.[18] The right-hand vertical axis indicates the number of villages

[15] Of the ten systems installed, six have reliable smart meter data and this analysis is restricted to data from those sites.

[16] We base the potential generation profiles on the GPS coordinates of each system using the default parameters for the NREL PVWatts India Solar Calculator. One exception to this rule is changing the system losses from 14% to 34% to reflect more accurate projections based on the materials and inverters used in our setting. The NREL output is a solar potential for each hour of the year that we then match with the actual hours that each system was operational. This exercise gives us a projected solar output based on the actual hours of operation of each system.

[17] We use this measure as opposed to the calendar week to ensure we are aggregating over systems of the same vintage.

[18] For example, if one village had 80% power availability, two villages had 20% power availability and three were offline on

that are operational in a given system week.[19]

In Figure 3, there is no clear evidence that theft and bypassing activity increase following a decline in power supply. Particularly in the early weeks of system operations, average electricity availability is relatively flat as non-technical losses increase over time.

Non-technical losses and associated bypassing behavior are easy to detect either directly (meter tampering was patently obvious on field visits) or remotely via distributed smart meters, As mentioned in Section 2.2, Gram Power's smart metering technology could instantly identify areas where non-technical losses exceeded threshold values. The microgrid technology remotely shut off power supply to those areas or households where meter tampering or theft were detected. This technological capability notwithstanding, enforcement proved difficult in practice.

One reason for these difficulties is the remote nature of these microgrids. Costs to Gram Power of monitoring system operations directly were prohibitive. Thus, Gram Power (the principal) chose to rely on local village entrepreneurs (the agents) to implement theft deterrence protocols once theft was detected. As part of their training, Gram Power instructed each village entrepreneur to report bypassing behavior and enforce prescribed penalties.

In practice, this principal-agent relationship did not work well because the local entrepreneur's incentives were not well aligned with Gram Power's objectives, even though their payment contract was based on commission of electricity fees. In practice, village entrepreneurs did not report theft and enforcement was rare.[20] One commonly cited reason is that interpersonal relations and inter-caste dynamics made it difficult for system operators to do their job. In one field visit, for example, the village entrepreneur reported that he could take responsibility for payments, but only for those in his caste and not for the other members of the community. In another, the entrepreneur acknowledged that people in his village were stealing, but refused to provide names or document this behavior formally.

In sum, this principal-agent problem exposes an important vulnerability in smart microgrid systems located in remote areas (where smart microgrids are most cost competitive with conventional grid infrastructure). Remote smart grid operating systems cannot be completely automated; these systems inevitably require a human component. The delegation of monitoring and enforcement responsibilities to local agents can be greatly complicated by the interpersonal relationships that limit the effectiveness with which revenues are collected and penalties are enforced.

4.2 Determinants of Bypassing Behavior

Having documented enforcement problems, we now turn to a more disaggregated analysis of non-technical losses. More precisely, we assess whether households who choose to bypass their meters are systematically different along observable dimensions (e.g., income, appliance ownership) as compared to households who do not consume unmetered electricity.

While we cannot directly observe bypassing behavior at the household level, we can infer this behavior using highly disaggregated metered consumption data. The intuition behind our approach is as follows: if a household's metered energy consumption is uncharacteristically low when untraced electricity on the entire system is high, then it is likely that this consumer is bypassing their meter.

However, comparing simple averages of household consumption during periods of high theft and low theft will be misleading if, for example, days with high theft also happen to be days with low power availability (e.g., due to weather or battery availability). With this consideration in mind, we propose the following algorithm for identifying likely bypassers:

Step #1: For each household, we take observed daily metered consumption and subtract the average production for their village on that day. This difference generates a measure ofeach household's

a given week, the aggregate electricity variable would equal 40% (or $\frac{80+20+20}{3}$%).

[19]The figure is truncated at week 17, as only one system remained operational after 17 weeks.

[20]The only instance of enforcement we are aware of happened when one village entrepreneur shut down the entire system due to rampant theft which was causing system instability.

deviation from village-day averages. This helps us control for village-day specific factors, such as weather or system health, that affect all consumers equally.

Step #2: We normalize these deviations for each household by applying a standard normal transformation at the household level to the demeaned data from Step 1. This transformation turns each consumption observation into a z-score based on a household-specific mean and standard deviation. This allows us to accurately compare households with different usage patterns.

Step #3: We calculate each household's average consumption z-score during periods of low theft and subtract the household's average consumption z-score during periods of high theft. Households with high values of this difference are likely to consume more metered electricity during periods of low theft and/or less during periods of high theft.

Step #4: Finally, we define households with differences in the top-10th percentile of this distribution by village as likely bypassers.

Having identified likely bypassers with this approach, we can test if there are any baseline difference between bypassing and non-bypassing households. Table 2 presents difference-in-means tests for a number of covariates, showing that bypassing households are different on a number of dimensions. Bypassers appear to be better-off financially, as they are less likely to have BPL status and they have higher annual income. Bypassers also appear to demand a higher quantity of energy services. Bypassers use more lights at night and are more likely to own and use solar lamps. The proportion of households with solar home systems is statistically similar across the two groups, however, bypassers own more of these devices than non-bypassing households, on average. Similarly, while bypassers and non-bypassers own the same number of appliances on average, the total wattage of appliances for bypassers is approximately three times larger. Notably, this difference is driven by non-bulb appliances, suggesting that this difference is driven by demand for electricity uses other than lighting.

5. DISCUSSION & CONCLUSION

Microgrid proponents point to the high costs and long delays associated with grid extension and promote microgrids as a relatively low-cost, immediate solution to rural electrification in many parts of the world. For example, Comello et al. (2017) demonstrate an economic rationale for microgrids in rural India. They calculate that the unit costs for electricity can be substantially lower with a microgrid than if a household were to obtain similar services with a diesel generator or kerosene lantern.

This paper assesses real world viability of this electrification alternative based on one company's experience installing microgrids in rural Rajasthan, India. We first document very low levels of demand for microgrids. Presumably, this is partly due to low household incomes. Suggestions by campaigning politicians that central grid extension could be imminent was another factor that suppressed demand.

Using data from microgrids that were installed in this region, we further show that cost recovery can be difficult or impossible if theft is prevalent. Theft was a prevalent problem in our setting, even though the smart meters deployed could detect theft remotely. While best practices underscore the importance of engaging the community to help implement maintenance and enforce penalties to deter theft, principal-agent problems can make this difficult to implement in practice. Even the smartest technology can be ineffective if it requires human intervention and the incentives of the agents are not perfectly aligned with system success.

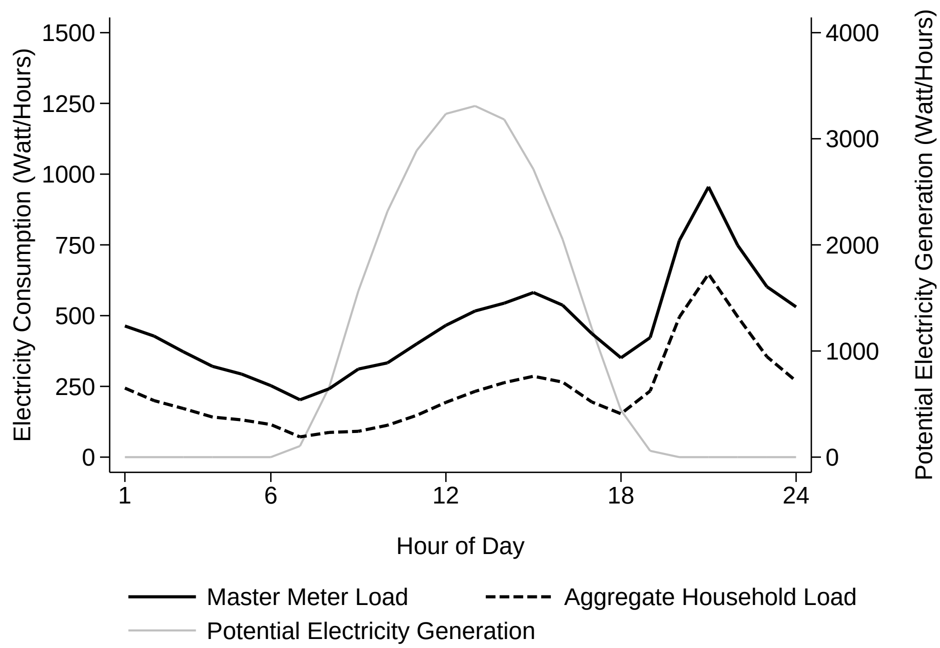
It is instructive to think about how policies can be designed to mitigate these issues and create a more favorable environment for rural microgrid providers. For example, if the federal or state governments publicized detailed schedules indicating grid expansion plans, villagers would be less likely to reject a microgrid fearing that it would preclude a grid connection in the future. On the other hand, such prescriptive lists preclude adaptation to new information or evolving policy priorities.

Even if policymakers were to clearly identify the set of villages to be served by microgrids, they would need to address the formidable financial challenges faced by microgrid providers. If microgrids are to be deployed and operated by private companies, and if these companies are expected to scale to a point where they do not require donor funding, there has to be a way for companies to cover installation and operating costs. In an environment where the government is implicitly and explicitly subsidizing grid electricity access for low income residential customers, charging microgrid customers tariffs sufficient to cover costs would lead to inequities across villages served by microgrids and those served by the grid. These inequities will only exacerbate villagers' preferences for grid connections.

Finally, private microgrid providers would face lower financing costs if there were policies in place to insure against regulatory risk and address the dynamic relationship between microgrids and the grid. If the government extends the grid to connect a village with an operating microgrid, explicit provisions should be made to determine how the microgrid will technologically interconnect with the grid and how the private microgrid provider will recover costs (Comello et al., 2017). The Ministry of New and Renewable Energy has issued draft policy rules in 2016 that start to address these issues, but many of the details are still being worked out.[21] As these policies are developed and implemented, it will be important to rigorously and objectively evaluate the extent to which they mitigate the challenges we've identified so as to translate the potential of smart microgrids into real-world success.

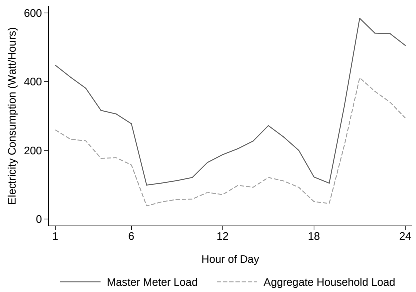
[21] See MNRE (2016) for details.

Figure 1: Typical Daily Load & Projected Generation Profile – All villages

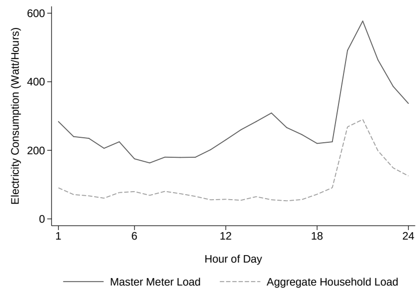


Notes: Master meter load and aggregate household load are observed directly in the high-frequency meter data from the microgrid system. However, We do not observe solar output from the systems, so we base this figure on production projections from the NREL PVWatts India Solar Calculator. We do however know if a system was online, which allows us to match these projected solar production for every hour of the year to each system based on whether that system was operational during that hour. The above curve thus represents the average projected hourly production based on the actual hours of operation of each system.

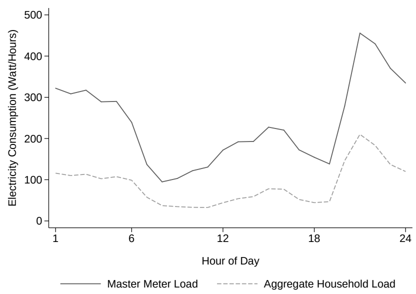
Figure 2: Typical Daily Electricity Load Profile by Village



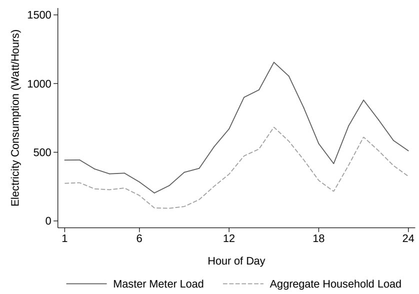
(a) Damodarpura



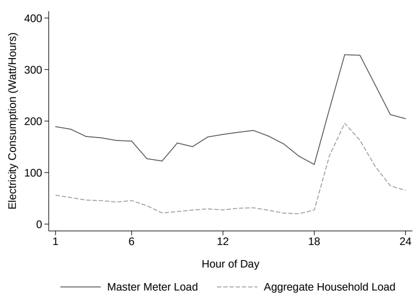
(b) Jeswa



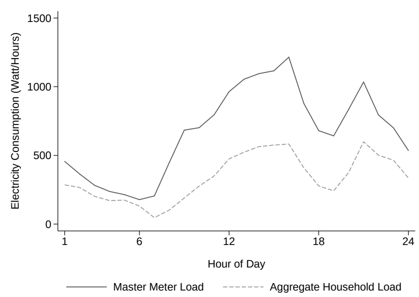
(c) Keshopura



(d) Khandpuriya

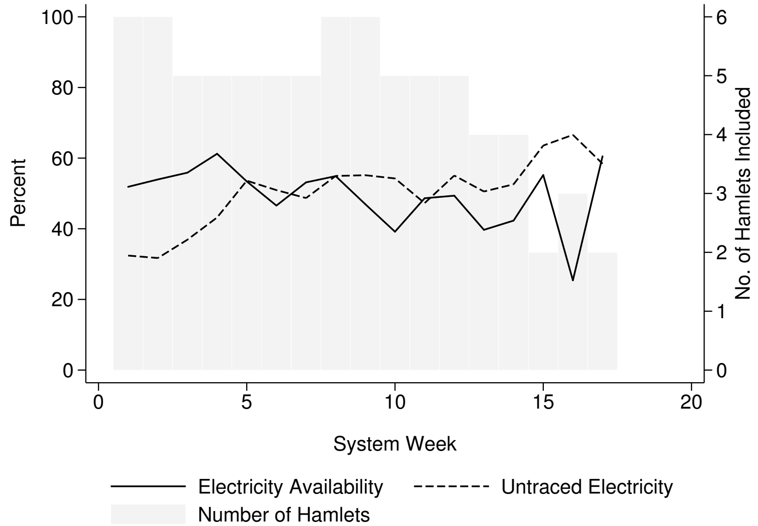


(e) Khirkhiri



(f) Kolipura

Figure 3: Aggregated Electricity Availability and Aggregate Technical and Commercial Losses



Notes: This graph plots the simple average of electricity availability and untraced electricity for all villages with operational systems on a given week. For example, if one village had 80% power availability, two villages had 20% power availability, and three were offline on a given week, the aggregate electricity variable would equal 40%.

TABLE 1
Village-level Comparisons with Indian Census Statistics in Sample Districts

	Summary Statistics		
	(1) Baseline: Microgrid Only	(2) Indian Census	(3) (1) vs. (2)
Basic Characteristics			
Average HH Size	5.36	5.27	0.72
Metal Roof	0.12	0.12	0.97
Toilet Ownership	0.04	0.37	0.01
Main Light Source: Kerosene	0.64	0.87	0.00
Main Light Source: Solar	0.23	0.08	0.00
Main Water Source: Handpump	0.76	0.40	0.01
Main Cooking Source: Firewood	0.99	0.92	0.30
Observations	10	556	

Note: These comparisons use baseline data collapsed at the village level to obtain comparable statistics to those found in the 2011 Indian Census. The census villages are the entire set of villages without electricity for domestic use as defined by the Indian Census in 2011 in the districts we initially surveyed. These districts are: Banswara, Baran, Barmer, Bundi, Chittaurgarh, Kota, Pratapgarh and Pali.

Table 2
Summary Statistics at Baseline by Bypasser Status

	Summary Statistics		Diff. p-Value
	(1) Bypassers	(2) Non-Bypassers	(3) (1) vs. (2)
Household Characteristics			
Household Size	4.87	5.16	0.57
Household Members Age 18+	3.13	2.90	0.52
Household Members under Age 18	1.73	2.27	0.15
Rooms in Dwelling	2.13	1.74	0.21
Metal Roof on Dwelling (=1)	0.20	0.13	0.43
Non-BPL HH (=1)	0.80	0.55	0.06
Belong to Dominant Caste (=1)	0.67	0.49	0.19
Land Ownership (Acres)	0.56	0.96	0.42
HH Head is Farmer (=1)	0.53	0.45	0.53
Uses Land for Agriculture (=1)	0.67	0.71	0.73
Yearly Income (1000 INR)	106.20	68.80	0.11
Current Savings (1000 INR)	8.27	3.58	0.20
Current Outstanding Loans (1000 INR)	22.00	31.02	0.63
Energy Use			
No. of Lights used Last Night	1.87	1.45	0.03
Owns Solar Lamp (=1)	0.13	0.01	0.00
Uses Solar Lamp (=1)	0.13	0.00	0.00
No. of Solar Lamps Used	0.20	0.00	0.00
Owns Solar Home System (=1)	0.60	0.42	0.19
Uses Solar Home System (=1)	0.60	0.42	0.18
No. of Solar Home Systems Used	1.00	0.48	0.00
No. of Kerosene Lamps Owned	1.20	1.31	0.58
Subsidized Kerosene Exp. (INR/Month)	33.73	42.65	0.28
Unsubsidized Kerosene Exp. (INR/Month)	3.33	42.44	0.64
Appliance Ownership			
Any Appliance (Count)	5.67	4.30	0.47
Any Appliance (Total Watts)	237.67	72.76	0.02
Any Bulb (Count)	2.27	2.17	0.55
Any Bulb (Total Watts)	13.40	13.63	0.92
Non-Bulb Appliances (Count)	3.40	2.13	0.50
Non-Bulb Appliances (Total Watts)	224.27	59.13	0.02
Observations	15	176	

Notes: Bypasser status is determined by the algorithim outlined in Section 4.2. The p-values in column (3) are calculated from difference-in-means t-tests using robust standard errors.

References

Helene Ahlborg and Linus Hammar. Drivers and barriers to rural electrification in Tanzania and Mozambique – Grid-extension, off-grid, and renewable energy technologies. *Renewable Energy*, 61:117–124, January 2014. ISSN 0960-1481. doi: 10.1016/j.renene.2012.09.057. URL http://www.sciencedirect.com/science/article/pii/S096014811200657X.

Michaël Aklin, Chao-yo Cheng, Johannes Urpelainen, Karthik Ganesan, and Abhishek Jain. Factors affecting household satisfaction with electricity supply in rural India. *Nature Energy*, 1(11):nenergy2016170, October 2016. ISSN 2058-7546. doi: 10.1038/nenergy.2016.170. URL https://www.nature.com/articles/nenergy2016170/.

Michaël Aklin, Patrick Bayer, S. P. Harish, and Johannes Urpelainen. Does basic energy access generate socioeconomic benefits? A field experiment with off-grid solar power in India. *Science Advances*, 3 (5):e1602153, May 2017. ISSN 2375-2548. doi: 10.1126/sciadv.1602153. URL http://advances.sciencemag.org/content/3/5/e1602153.

Peter Alstone, Dimitry Gershenson, and Daniel M. Kammen. Decentralized energy systems for clean electricity access. *Nature Climate Change*, 5(4):nclimate2512, March 2015. ISSN 1758-6798. doi: 10.1038/nclimate2512. URL https://www.nature.com/articles/nclimate2512.

ARE. Hybrid Mini-Grids for Rural Electrification - Lessons Learned. Text, Alliance for Rural Electrification, Brussels, Belgium, 2014. URL https://ruralelec.org/publications/hybrid-mini-grids-rural-electrification-lessons-learned.

Douglas Barnes and Gerald Foley. Rural electrification in the developing world: a summary of lessons from successful programs. *Joint UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP), World Bank, Washington, DC*, 2004.

Subhes C. Bhattacharyya. To regulate or not to regulate off-grid electricity access in developing countries. *Energy Policy*, 63:494–503, December 2013. ISSN 0301-4215. doi: 10.1016/j.enpol.2013.08.028. URL http://www.sciencedirect.com/science/article/pii/S0301421513008215.

Subhes C. Bhattacharyya and Debajit Palit. Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required? *Energy Policy*, 94:166–178, July 2016. ISSN 0301-4215. doi: 10.1016/j.enpol.2016.04.010. URL http://www.sciencedirect.com/science/article/pii/S0301421516301781.

Courtney Blodgett, Peter Dauenhauer, Henry Louie, and Lauren Kickham. Accuracy of energy-use surveys in predicting rural mini-grid user consumption. *Energy for Sustainable Development*, 41:88–105, December 2017. ISSN 09730826. doi: 10.1016/j.esd.2017.08.002. URL http://linkinghub.elsevier.com/retrieve/pii/S0973082617304350.

P. Boait, V. Advani, and R. Gammon. Estimation of demand diversity and daily demand profile for off-grid electrification in developing countries. *Energy for Sustainable Development*, 29:135–141, December 2015. ISSN 09730826. doi: 10.1016/j.esd.2015.10.009. URL http://linkinghub.elsevier.com/retrieve/pii/S0973082615001040.

Jennifer N. Brass, Sanya Carley, Lauren M. MacLean, and Elizabeth Baldwin. Power for Development: A Review of Distributed Generation Projects in the Developing World. *Annual Review of Environment and Resources*, 37(1):107–136, 2012. doi: 10.1146/annurev-environ-051112-111930. URL https://doi.org/10.1146/annurev-environ-051112-111930.

Central Electricity Authority. Central Electricity Authority Monthly Reports of Installed Capacity – January 2018. Technical report, January 2018. URL http://www.cea.nic.in/reports/monthly/installedcapacity/2018/installed_capacity-01.pdf.

Akanksha Chaurey and Tara Chandra Kandpal. Assessment and evaluation of PV based decentralized rural electrification: An overview. *Renewable and Sustainable Energy Reviews*, 14(8):2266–2278, 2010.

Stephen D. Comello, Stefan J. Reichelstein, Anshuman Sahoo, and Tobias S. Schmidt. Enabling Mini-Grid Development in Rural India. *World Development*, 93:94–107, May 2017. ISSN 0305-750X. doi: 10.1016/j.worlddev.2016.12.029. URL http://www.sciencedirect.com/science/article/pii/S0305750X15312316.

W. A. Cronje, I. W. Hofsajer, M. Shuma-Iwisi, and J. I. Braid. Design considerations for rural modular microgrids. In *2012 IEEE International Energy Conference and Exhibition (ENERGYCON)*, pages 743–748, September 2012. doi: 10.1109/EnergyCon.2012.6348249.

ESMAP. Mini-Grid Design Manual. Technical report, Joint UNDP/World Bank Energy Sector Management

Assistance Program (ESMAP), Washingtion, D.C., 2000. URL http://documents.worldbank.org/curated/en/730361468739284428/pdf/multi-page.pdf.

Michael Grimm, Luciane Lenz, Jörg Peters, and Maximiliane Sievert. Demand for Off-Grid Solar Electricity – Experimental Evidence from Rwanda. SSRN Scholarly Paper ID 2922433, Social Science Research Network, Rochester, NY, February 2017a. URL https://papers.ssrn.com/abstract=2922433.

Michael Grimm, Anicet Munyehirwe, Jörg Peters, and Maximiliane Sievert. A First Step up the Energy Ladder? Low Cost Solar Kits and Household's Welfare in Rural Rwanda. *The World Bank Economic Review*, 31(3): 631–649, 2017b. doi: 10.1093/wber/lhw052. URL +http://dx.doi.org/10.1093/wber/lhw052.

Meg Harper. Review of Strategies and Technologies for Demand-Side Management on Isolated Mini-Grids. April 2014. URL https://escholarship.org/uc/item/0wc020br.

IEG. The Welfare Impacts of Rural Electrification: A Reassessment of the Costs and Benefits. Technical report, The World Bank: Washington, D. C., 2008. URL http://siteresources.worldbank.org/EXTRURELECT/Resources/full_doc.pdf.

Charles Kirubi, Arne Jacobson, Daniel M. Kammen, and Andrew Mills. Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya. *World Development*, 37(7):1208–1221, July 2009. ISSN 0305-750X. doi: 10.1016/j.worlddev.2008.11.005. URL http://www.sciencedirect.com/science/article/pii/S0305750X08003288.

Kenneth Lee, Edward Miguel, and Catherine Wolfram. Appliance Ownership and Aspirations among Electric Grid and Home Solar Households in Rural Kenya. *American Economic Review*, 106(5):89–94, May 2016. ISSN 0002-8282. doi: 10.1257/aer.p20161097. URL https://www.aeaweb.org/articles?id=10.1257/aer.p20161097.

Robyn Meeks and Hope Thompson. Grid versus Off-grid in Nepal: Heterogeneity in Electricity Services and Enterprise Development‘. Technical report, July 2017.

M. Millinger, T. Mårlind, and E. O. Ahlgren. Evaluation of Indian rural solar electrification: A case study in Chhattisgarh. *Energy for Sustainable Development*, 16(4):486–492, December 2012. ISSN 0973-0826. doi: 10.1016/j.esd.2012.08.005. URL http://www.sciencedirect.com/science/article/pii/S0973082612000622.

MNRE. Central Financial Assistance (CFA) for "Off-grid and Decentralized Solar Applications Programme" for the year 2014-15. Technical report, November 2014.

MNRE. Draft National Policy on RE based Mini/Micro grids. Technical report, January 2016. URL http://mnre.gov.in/file-manager/UserFiles/draft-national-Mini_Micro-Grid-Policy.pdf.

Md. Alam Hossain Mondal. Economic viability of solar home systems: Case study of Bangladesh. *Renewable Energy*, 35(6):1125–1129, June 2010. ISSN 0960-1481. doi: 10.1016/j.renene.2009.10.038. URL http://www.sciencedirect.com/science/article/pii/S096014810900531X.

MOP. Continuation of Rajiv Gandhi Grammen Vidyutikaran Yojana (RGGVY) in 12th & 13th plan - Scheme of Rural Electricity Infrastructure and Household Electrification. Technical report, Ministry of Power, Government of India, September 2013. URL http://www.ddugjy.gov.in/mis/portal/memo/OFFICE-MEMORANDUM-12th-plan-rggvy.pdf.

F. D. J. Nieuwenhout, A. Van Dijk, P. E. Lasschuit, G. Van Roekel, V. A. P. Van Dijk, D. Hirsch, H. Arriaza, M. Hankins, B. D. Sharma, and H. Wade. Experience with solar home systems in developing countries: a review. *Progress in Photovoltaics: Research and Applications*, 9(6):455–474, 2001.

OECD/IEA. Energy Access Outlook 2017: From Poverty to Prosperity. Technical report, 2017.

J. P Painuly. Barriers to renewable energy penetration; a framework for analysis. *Renewable Energy*, 24 (1):73–89, September 2001. ISSN 0960-1481. doi: 10.1016/S0960-1481(00)00186-5. URL http://www.sciencedirect.com/science/article/pii/S0960148100001865.

Debajit Palit and Kaushik Ranjan Bandyopadhyay. Regulating off-grid electricity delivery. *Economic & Political Weekly*, 50(10):47, 2015.

Debajit Palit and Akanksha Chaurey. Off-grid rural electrification experiences from South Asia: Status and best practices. *Energy for Sustainable Development*, 15(3):266–276, September 2011. ISSN 0973-0826. doi: 10.1016/j.esd.2011.07.004. URL http://www.sciencedirect.com/science/article/pii/S0973082611000500.

Debajit Palit, Benjamin K. Sovacool, Christopher Cooper, David Zoppo, Jay Eidsness, Meredith Crafton, Katie Johnson, and Shannon Clarke. The trials and tribulations of the Village Energy Security Programme (VESP) in India. *Energy Policy*, 57:407–417, June 2013. ISSN 0301-4215. doi: 10.1016/j.enpol.2013.02.006. URL http://www.sciencedirect.com/science/article/pii/S0301421513000918.

Anand P. Pathanjali. Mini-Grids: A Practical Solution To Bihar's Electricity Woes, June 2017. URL http://ceedindia.org/mini-grids-a-practical-solution-to-bihars-electricity-woes/.

Press Trust of India. PM Narendra Modi to launch 'power for all' scheme on September 25. *The Economic Times*, September 2017. URL https://economictimes.indiatimes.com/industry/energy/power/pm-narendra-modi-to-launch-power-for-all-scheme-on-september-25-power-minister-r-k-singh/articleshow/60805044.cms.

Ana Pueyo. The Evidence of Benefits for Poor People of Increased Renewable Electricity Capacity: Literature Review. 2013.

Narasimha D. Rao, Anjana Agarwal, and Davida Wood. Impacts of Small-Scale Electricity Systems. Technical report, World Resources Institute, 2015. URL https://www.wri.org/sites/default/files/Impacts_of_Small-Scale_Electricity_Systems.pdf.

Daniel Schnitzer, Deepa Shinde Lounsbury, Juan Pablo Carvallo, Ranjit Deshmukh, Jay Apt, and Daniel M. Kammen. Microgrids for Rural Electrification: A critical review of best practices based on seven case studies. *United Nations Foundation*, 2014.

Benjamin K. Sovacool. Deploying Off-Grid Technology to Eradicate Energy Poverty. *Science*, 338(6103): 47–48, October 2012. ISSN 0036-8075, 1095-9203. doi: 10.1126/science.1222307. URL http://science.sciencemag.org/content/338/6103/47.

Bernard Tenenbaum, Chris Greacen, Tilak Siyambalapitiya, and James Knuckles. *From the bottom up: how small power producers and mini-grids can deliver electrification and renewable energy in Africa*. World Bank Publications, 2014.

UNDP. Towards an "Energy Plus" Approach for the Poor: A review of good practices and lessons learned from Asian and the Pacific. Technical report, Bangkok Thailand, 2011.

United Nations. RES/70/1. Transforming our world: the 2030 agenda for sustainable development. *Seventieth United Nations General Assembly, New York*, 25, 2015.

Johannes Urpelainen. Grid and off-grid electrification: An integrated model with applications to India. *Energy for Sustainable Development*, 19(Supplement C):66–71, April 2014. ISSN 0973-0826. doi: 10.1016/j.esd.2013.12.008. URL http://www.sciencedirect.com/science/article/pii/S0973082613001142.

Njeri Wamukonya. Solar home system electrification as a viable technology option for Africa's development. *Energy Policy*, 35(1):6–14, 2007.

APPENDIX

TABLE A1
Summary Statistics at Baseline for Electrified Households

	N	Mean	Std. Dev.	Min	Max
Household Size	188	5.14	1.90	1	15
Household Members Age 18+	188	2.91	1.35	1	10
Household Members under Age 18	188	2.23	1.39	0	8
Metal Roof on Dwelling (=1)	188	0.13	0.34	0	1
Toilet Access (=1)	188	0.00	0.00	0	0
Rooms in Dwelling	188	1.77	1.17	1	8
Main Water Source: Handpump (=1)	188	0.72	0.45	0	1
Main Cooking Source: Firewood (=1)	188	0.99	0.10	0	1
Non-BPL HH (=1)	187	0.57	0.50	0	1
Land Ownership (Acres)	188	0.94	1.81	0	8
Uses Land for Agriculture (=1)	188	0.71	0.46	0	1
HH Head is Farmer (=1)	188	0.46	0.50	0	1
Yearly Income (1000 INR)	188	72.22	87.84	0	730
Current Savings (1000 INR)	187	3.94	13.53	0	100
Current Outstanding Loans (1000 INR)	187	30.53	69.10	0	500
Owns Solar Lamp (=1)	188	0.02	0.14	0	1
Owns Solar Home System (=1)	188	0.44	0.50	0	1
Owns Kerosene Lamp (=1)	188	0.89	0.32	0	1
Uses Solar Home System (=1)	188	0.44	0.50	0	1
No. of Solar Home Systems Used	188	0.52	0.66	0	3
Uses Solar Lamp (=1)	188	0.01	0.10	0	1
No. of Solar Lamps Used	188	0.02	0.16	0	2
Main Light Source: Kerosene (=1)	188	0.53	0.50	0	1
Main Light Source: Solar (=1)	188	0.37	0.48	0	1
No. of Lights used Last Night	188	1.48	0.72	0	4
Subsidized Kerosene Exp. (INR/Month)	188	41.99	30.82	0	200
Unsubsidized Kerosene Exp. (INR/Month)	188	39.10	305.64	0	4000

Notes: Summary statistics computed only for households matched to a smart meter in the six of the ten microgrid villages.

TABLE A2
Microgrid-related Costs

Tariff Component	Expenditure (USD)	Percent of Total Expenditure
Installation Cost	108,476	47.34
Customer Acquisition	45,399	19.82
Overhead & Operation/Maintenance	75,254	32.84
Total	229,130	100
Total per System	22,913	$N = 10$
Total per Connection	664	$N = 345$

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