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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. Although Gram Power followed nearly all of these recommendations, the company nevertheless faced significant challenges. First, demand for solar microgrids was very limited, largely due to the perception that grid power was imminent and preferred. The company installed only 10 microgrids after visiting 176 villages, so customer acquisition costs were high and economies of scale were lower than expected. 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 hampered the companys ability to deter theft. We conclude with a discussion of policy changes that could better support the integration of solar technologies into a coordinated rural electrification strategy. Keywords: Energy access, Microgrids, 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 24x7 power for all by providing electricity services to each household across the country [Ministry of Power, 2017].[1]

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.

As an alternative to grid extension, some policymakers have promoted the adoption of small-scale private 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 that, historically, entry-level private solar home systems have been unable to provide energy services beyond very basic end uses. In addition, the high upfront costs of these systems has been a barrier to adoption [Grimm et al., 2018, 2017, 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 relatively inexpensively and 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 between 2010 and 2015. In their initial years, Gram Power (GP) 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 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, due in part to government policies which have provided subsidized grid extension to many below-poverty-line (BPL) households. Households were unwilling to pay for a microgrid connection if a subsidized grid connection seemed imminent. Policy uncertainty with respect to future grid extension drove up customer acquisition costs and limited economies of scale in microgrid operations.

[1]This work is most recently conducted under the Saubhagya schemes in India, which indicate that all rural households and urban-poor households will receive electricity connections. However, this program excludes non-poor urban customers and does mention that households in remote or inaccessible villages will receive stand-alone solar photovoltaic systems if grid extension is deemed infeasible.

[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.

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 penalize theft in their own communities to increase revenue collection. Ultimately, these problems undermined the profitability of GP microgrid projects in India. The company has since suspended its microgrid business and pivoted their focus towards deploying their advanced metering infrastructure technology among grid-connected consumers.

The prior literature has documented several apparently successful microgrid installations that have improved energy access and other socioeconomic outcomes.[3] Other papers document mixed results.[4] Far less common, but no less important, is the documentation and analysis of microgrid projects that failed. Although researchers, governments, and aid organizations may be less inclined to shine light on initiatives that fall short of their goals, understanding the factors that lead projects down unsuccessful 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 remote communities in India between 2010 and 2015, 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 ambitious rural electrification targets. Over the time period of our study, microgrids seemed poised to play a critical role reaching difficult-to-access rural locations where grid extension was very costly or infeasible [Ministry of Power, 2013]. While the recent emphasis of rural electrification efforts has shifted more towards solar home systems, microgrid deployment is still part of long-term electrification plans in India.[5] In Bihar, for example, the state cabinefgrt has called for 100MW of solar microgrid capacity by 2022 [Pathanjali, 2017].

A growing literature reviews past experiences with microgrid deployment around the world in the

[3] 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.

[4] 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.

[5] Originally, the Deendayal Upadhyaya Gram Jyoti Yojanna (DDUGJY) rural electrification scheme created guidelines for rural electrification that excluded solar home systems as an acceptable form of electrification. In 2015, the DDUGJY guidelines were amended to allow for solar home systems to serve places where households were very scattered or in very small habitations. The Saubhagya scheme, introduced in 2017, promotes achieving universal electrification in rural geographies through solar home systems and includes no mention of microgrids.

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 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] However, achieving this goal by setting tariffs too low can be in direct odds with financial sustainability.
- **Financial Sustainability:** Pricing structures should ideally be designed to ensure that revenue collection meets cash flow requirements for the system [Schnitzer et al., 2014, Barnes

[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.

and Foley, 2004]. Inadequate tariff collection can result in under-investment in maintenance and operations. 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 parameters 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 Powers design and deployment strategy in Rajasthan, India.

2.2 Gram Power Overview

Gram Power was founded in 2010 by Yashraj Khaitan and Jacob Dickinson. The founders perceived an urgent need to expand 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. Gram Power found it needed to offer commissions as high as 50% to recruit village entrepreneurs. 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 daytime and nighttime 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 designed tiers of service to support small mills and other productive appliances. In spite of these efforts, Gram Power was unable to find sufficient demand for these productive or commercial loads.

- **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, which are outlined in the next bullet.

- **Affordability:** The GP pricing structure was designed to accommodate consumers' ability to pay. 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 price and the appliances that could be supported. A basic connection, priced at 1,000 INR supported cell phone charging and 2 LED lights. A connection charge of 2,500 INR would support a fan and TV in addition to lighting and cell phone charging. To support commercial applications, an additional 15,000 INR would support irrigation pumping and other commercial loads. Based on survey data collected by Gram Power, demand for the more expensive options was deemed to be too low. Ultimately, Gram Power offered only basic connections at a rate of 1,000 INR per connection. In addition to the connection costs, households paid 20 INR per kWh and 150 INR per month in fixed charges.

- **Financial Sustainability:** Gram Power's procurement cost per panel watt of solar plus storage was 300 INR at the time of our study. The initial capital subsidy rate provided by the MNRE was 150 INR per panel watt, although later in the installation process this figure dropped to 90 INR per panel watt. Thus, the capital cost after subsidy of a typical five-kilowatt system, which Gram Power installed to serve approximately 40 households, was approximately 750,000 INR under the 150 INR subsidy and 1,050,000 INR under the less generous 90 INR subsidy. At Gram Powers cost of capital, this amounts to between 7,500 INR and 10,500 INR in monthly interest costs on the original capital outlay.[8] For a five-kilowatt system with 40 connected households, Gram Power expected to receive 6,000 INR per month in fixed charges and 8,370 INR in volumetric charges after supplying 10% of these volumetric

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

[8] Gram Power faced a one-percent per month interest rate on capital loans at this time.

revenues to the village entrepreneur.[9] Thus, under perfect system performance and revenue collection efficiency, Gram Power could expect to recover all financial and capital costs in about six years under the original 150 INR subsidy and about 11 years under the less generous 90 INR subsidy. Gram Power expected their systems to last approximately 10 years, so under the more generous regime they may have been able to turn a profit if the system ran perfectly. However, given households' budget constraints, demand for electricity, and a realistic expectation that the system would not operate perfectly, one of the Gram Power's primary objectives with this initiative was to determine how much capital expenditure support (from governments, grants, etc.) was necessary to make microgrids privately feasible. As we explain below, due to significant operating challenges and high deployment costs, cost recovery proved to be much more difficult than expected.

- **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 over-arching 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 customer service representatives, 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 unlikely to receive grid access in the foreseeable future.[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.,

[9] At a capacity factor of 13%, Gram Power expected under favorable operating conditions that a 5- kW system could produce approximately 465 kWh of billable electricity per month. Furthermore, Gram Power initially aimed to pay the village entrepreneur 10% of total revenue from per-KWH charges but had to increase this number (sometimes to 50%) to entice individuals to accept this role.

[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.

[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.

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. Further, Gram Power conducted a number of household surveys in villages that met the technical criteria and showed sufficient interest in a microgrid.

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. In what follows, we highlight three factors that help rationalize the lower than expected demand for microgrid systems.

3.1 Policy Uncertainty and Lack of Coordination

One important barrier 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. Furthermore, during the time of our study the DDUGJY program implemented by the Indian government set a goal of complete electrification of all rural areas–aided by the promise of free electricity connections to BPL households. 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].

Another reason for low adoption was a failure of coordination within villages. In some instances, political or caste-level divisions within the village made it difficult to coordinate enough households to make a microgrid economical. In some of these cases, the two factions within the group demanded smaller independent systems that Gram Power did not wish to provide.

3.2 Cost Considerations

As part of our study, we surveyed 582 households in 16 villages that met technical criteria and showed significant interest in a microgrid.[12] Our survey is comprised of 346 households in the ten microgrid villages and 236 households in the six villages that did not ultimately adopt a microgrid. Table 1 summarizes differences between these two groups.

Since all 16 villages met the technical criteria and showed interest in a microgrid, the analysis in Table 1 provides a way to compare means between adopters and *almost*-adopters. Columns (1) and (2) in this table display the means for the two groups and column (3) displays the p-value associated with the difference-in-means t-tests across the two groups.

The results from this table show households in adopting villages are more likely to have a metal roof, have larger homes, are less likely to be BPL households, are less likely to be agricultural households, have more savings and access to credit and are more likely to use solar home systems and lamps than almost-adopting households. Further, we asked households how much of an additional hypothetical 100 INR they would spend on lighting versus savings or other consumption. Households in adopting villages allocated a larger share of this amount on average than almost-adopting households. We interpret this evidence as adopting households having higher willingness-to-pay for electricity services.

This evidence corroborates reports from Gram Power staff that upfront cost (i.e., the 1,000 INR connection charge) was prohibitive for most households. This is a large sum for relatively low-

[12] The baseline microdata were collected between September 2014 and May 2015 via a survey conducted on our behalf by JPAL South Asia after the village had agreed to pay for a microgrid but before the microgrid was installed.

income households. Moreover, households reportedly expressed concerns 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.

3.3 Unfamiliar Technology

We also use census data to compare adopting villages with other unelectrified villages (as defined by the census) within the same districts as our study area. These census data are reported at the village level, so we first collapse our household survey responses to village-level measures. Since the overlap between information collected via the Indian census and our baseline survey is limited, we can only compare these villages on a limited number of dimensions.[13] This analysis in Table 2 suggests that 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, one measure of wealth in developing-country contexts, suggesting that adopting villages have similar levels of wealth than other similarly located unelectrified villages in the Indian census. 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. Given the difference in time 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, it seems unlikely that this fully explains the large discrepancy between our communities and census. 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.

In sum, difficulties in customer recruitment increased deployment costs by a significant margin. Every unsuccessful attempt to sell a microgrid to a village drove the acquisition cost per system much higher. In Gram Power's experience, the expenditures intended to field 40 microgrid installations were instead spread across the 10 adopting villages. In this case, these costs were driven higher by overly optimistic expectations on the part of rural villagers that fully subsidized connection to the conventional grid was imminent. If households and communities had clear and realistic sense of the government's grid expansion plans, it is likely that demand for microgrids would have been higher and thus allowed Gram Power to spread their total customer acquisition cost (e.g., scoping visits, demand surveys, etc.) across more systems.

4 Challenge 2: Weak incentives undermine smart technology

In the ten communities where Gram Power deployed microgrid systems, it faced another set of challenges around system operations. The high-frequency consumption data collected by the company's metering infrastructure at multiple points on the microgrid network allows us to characterize these challenges in unprecedented detail.

Figure 1 summarizes the typical daily load and potential generation profile for the six villages with reliable smart meter data.[14] These data represent consumption across six master meters (one for each system) and 206 household meters based on the 1-minute interval data collected by Gram

[13] A larger suite of summary statistics for the microdata on households in the electrified sample are included in Table A2 in the appendix.

[14] We did not receive data for the other four sites from Gram Power.

Power's smart meters. The solid and dashed-black lines reflect average hourly load at the six centralized master meters and average metered household consumption at the 206 individual households, respectively. The gray line measures the power production *potential* based on weather and system characteristics using the NREL PVWatts India Solar Calculator. We base the potential generation profiles on the GPS coordinates of each system using the default parameters provided by NREL.[15] One exception to this rule is that we change the system losses from 14% to 34% to reflect more accurate projections based on the materials and inverters used in our setting. We then match the solar potential for each hour for each site to the hours that each system was operational to obtain the system-level potential production for each site. We create an average production potential for each site by hour and then sum these values to create the overall production potential by hour for the six sites used in this analysis.

Figure 1 highlights three important phenomena. First, note the different scales on the two vertical axes that highlight the disparity between default PVWatts parameters, which reflect nearly perfect operating conditions (in terms of panel soiling, maintenance and adequate storage) and actual 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. For example, Gram Power faced problems with the village entrepreneur failing to maintain the batteries (*e.g.*, not refilling them with water). The lost energy retention of the batteries implied that the system required less current to appear fully charged, which effectively capped the amount of power the solar panels could produce at a much lower level than if the batteries were healthy.[16] Another potential reason for this mismatch is that if consumption is not high enough, the system will only generate enough power to keep the battery bank full not the full potential output of the solar arrays.

Even if these production differences are driven by system or usage characteristics, Figure 1 also highlights how solar peak production during the middle of the day does not align well with the observed evening consumption peak. Average consumption peaks around 8PM, presumably due to lighting, which comprised the majority of household demand in these systems. In contrast, solar production occurs between 6AM and 7PM and peaks during the middle of the day. Gram Power designed the solar PV and battery storage systems with this mismatch in mind, but balancing mismatched production and consumption is costly.

Figure 2 plots the load data disaggregated by village. Two villages in our study—Khandpuriya and Kolipura—have system peaks in the late afternoon which are more closely aligned with solar production. This is reasonable given that households in these these two villages on average own nearly twice the wattage of appliances as households in other microgrid villages and are proportionally more likely to own high wattage fans, which are typically run for cooling during the daytime.[17] The greater appliance holdings in Khandpuriya and Kolipura are also why these locations received a 7.5 kW system while all other sites received a 5 kW system.[18]

Finally, Figures 1 and 2 illustrate the extent to which consumption recorded by the master meters (measuring total electricity use 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

[15] The default parameters included the azimuth degree (180), tilt degree (20), array type (fixed (open rack)), module type (Standard).

[16] Typical DC solar charge controllers monitor the voltage of the battery bank to determine the level of charge battery. If a battery is permanently damaged to 50% of its rated capacity, it will take half as much current to make the damaged battery appear "full" based on voltage.

[17] See Table A4 for documentation of these differences by way of difference-in-means tests between households in Kolipura and Khanpuriya and the other four systems.

[18] See Table A3 for an overview of the system capacities and number of households connected to each system.

negligible. 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 aggregate non-technical losses by system.[19]

4.1 Non-technical Losses

4.1.1 The Vicious Cycle

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 averaged across the six systems. This figure is constructed using the same data as Figures 1 and 2—the six master meters and the 206 household meters. The horizontal axis measures the *system week* or the week since a microgrid's installation. The left vertical axis measures both the availability of supply and losses in percentage terms. Since we do not observe production or battery capacity data for the systems directly, we infer power availability from the meter data. For each week of operation, we count the number of minutes that power is available based on the condition that at least one meter was registering positive consumption. We divide this by the total number of minutes in that week to obtain the proportion of minutes that power was available each week. We convert this proportion into a percent by multiplying by 100. To construct a weekly loss rate, we simply divide the amount of untraced electricity by the total throughput on the system and multiply by 100. We calculate the amount of untraced electricity for each system-week by subtracting the aggregate household load from the master meter load.[20] The vertical gray bars on the figure indicate the number of systems online in a given week. Figure 3 does not obviously support the vicious cycle hypothesis: there is no clear evidence that theft and bypassing activity increase following a decline in power supply.[21]

In Table 3, we report results from regressing the loss rate (measured at the system-week level) on various measures of power availability. The most flexible specification includes the contemporaneous availability rate, lagged availability, and an indicator variable for the period following a threshold outage event, which we define as the first time a system dipped below 25th percentile of electricity availability. Functionally, we estimate the following equation:

$$\begin{aligned}[\text{Losses }\%]_{it} =& \beta_0 \cdot [\text{Availability }\%]_{it} + \beta_1 \cdot [\text{Availability }\%]_{i,t-1} \\ &+ \beta_2 \cdot \mathbb{1}\left[t > t^i_{p25}\right]_{it} + \gamma_i + \eta_t + \epsilon_{it}\end{aligned} \tag{1}$$

where i indexes villages and t indexes system week; [Losses %] is our measure of losses measured as a percent and [Availability %] is the percent of hours electricity is available in a given system week; β_0 measures the relationship between concurrent energy availability and losses and β_1 measures the relationship between last period availability and losses. The indicator for the threshold

[19] In Appendix A1, we analyze these data at the individual level.

[20] Given the prepaid nature of these systems, the collection efficiency, or the proportion of billed electricity that is collected upon, is 100%. Thus, our measure of losses captures bypassing behavior as opposed to some combination of bypassing and non-payment.

[21] We also find no clear evidence that theft and bypassing activity increase following a decline in the power supply in the village-specific data (see Figure A1).

event, $\mathbb{1}\left[t > t^i_{p25}\right]$, is equal to one for all weeks after the first week the system recorded availability below the 25th percentile. As such, β_2 tests for structural shifts in losses after the system has poor availability for the first time. We include γ_i as a set of village fixed effects, to control for time-invariant, village-specific factors, and η_t is a set of system week fixed effects to control for aggregate time trends. ϵ_{it} is an error term. To account for serial correlation in the error term, we estimate Newey-West standard errors with a truncation parameter of five.[22]

The first column of Table 3 reports estimates of β_0 and β_1, measuring the change in losses associated with contemporaneous and one week lagged availability. The coefficient estimates are positive, suggesting that losses are higher when current system conditions are good. The second column, however, includes just the indicator variable and the positive coefficient suggests that losses are considerably higher after the first threshold availability event, consistent with the vicious cycle hypothesis. In other words, deviations from system and vintage average loss rates are positive after a poor availability week.[23] These results suggest that theft is over 16 percentage points higher in periods after the system recorded its first week below 25th percentile availability. The results in columns (3) and (4) include the indicator variable together with just contemporaneous and contemporaneous plus laggged availability and all coefficient estimates remain positive and statistically significant. The conditional correlations, particuarlly the coefficient on the threshold event indicator, provide some evidence that theft and availability are indeed related. It is important to note that variation in availability rates is not random, so we cannot easily test for a casual relationship between past system performance and the prevalence of theft. These results are consistent with a phenomenon in which episodes of poor system performance lead to a diffusion of theft behavior, although we cannot rule out other potential explanations.

4.1.2 Difficulties Curbing Theft

In our setting, non-technical losses and associated bypassing behavior can be detected either directly (meter tampering was 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.[24] The microgrid technology was designed to remotely shut off power supply to those areas or households where meter tampering or theft had been detected. This technological capability notwithstanding, enforcement proved difficult in practice.

One reason for these difficulties is the remote nature of the microgrids. It was prohibitively costly for Gram Power to establish a permanent local presence and monitor system operations directly. Instead, Gram Power (the principal) chose to rely on local village entrepreneurs (the agents) to implement penalties and 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. Agents' payment contracts were based on a 50% commission of electricity fees paid in an effort to incentivize theft detection and the enforcement of theft penalties and protocols. However, working against this incentive structure are strong social network effects. In practice, village entrepreneurs were very reluctant to report

[22]We tested a number of different truncation parameters and found that the standard error estimates were very stable.
[23]Results are similar using other low percentile thresholds.
[24]See Section 2.1 in the appendix for an individual-level analysis of bypassing activity using the high-frequency smart meter data.

theft and enforcement was rare.[25] 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, remote smart grid operating systems have not yet been completely automated, so the systems ineluctably 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 of revenue collection and penalty enforcement. This principal-agent problem constitutes an important vulnerability in smart microgrid systems located in remote areas (where smart microgrids are most cost competitive with conventional grid infrastructure).

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, more-immediate solution to rural electrification in many parts of the world. For example, Comello et al. [2017] estimate that, in remote parts of India where grid extension costs are prohibitive, energy service delivery costs can be substantially lower using a solar microgrid versus using diesel generators and kerosene lanterns to deliver the same services.

This paper assesses real world viability of this electrification alternative based on one companys experience installing microgrids in rural Rajasthan, India. We first document low levels of demand for microgrids. Suggestions by campaigning politicians that central grid extension could be imminent was one important factor that suppressed demand. High costs are another barrier to adoption. We speculate that a lack of familiarity with solar energy technologies could be another limiting factor.

Using data from operating microgrids, we show that once a system has been installed, cost recovery can be difficult or impossible once operating and revenue collection inefficiencies are accounted for. Theft was a debilitating 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. In our specific setting, the additional expenditure on smart metering technology did not pay off by reducing the dependence on human intervention for theft deterrence.

It is instructive to think about how policies could be designed to mitigate these issues and challenges. If governments publicized official schedules for grid expansion plans, villagers would be less likely to reject a microgrid out of concern 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. Relatedly, government programs that expand the conventional grid after a microgrid is present can undercut microgrid revenues. 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 any stranded costs [Comello et al., 2017]. The Ministry of New and Renewable Energy has issued

[25] 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.

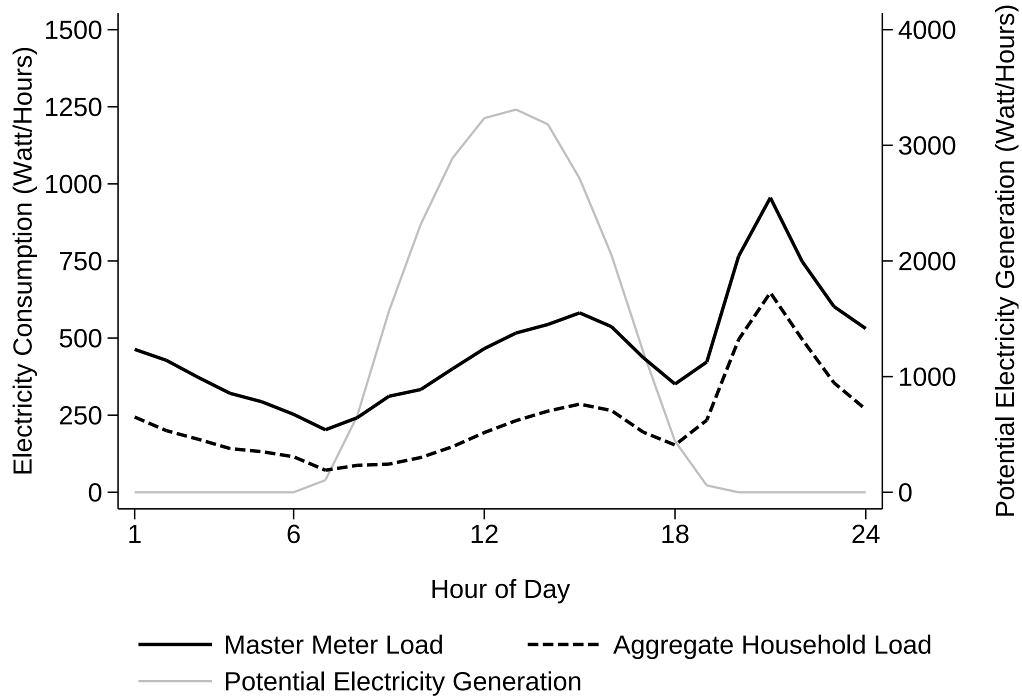
draft policy rules in 2016 that start to address these issues, but many of the details are still being worked out.[26]

Even if policy changes could provide a more stable operating environment for microgrid providers, formidable cost-recovery challenges remain. In particular, we have documented how microgrids can be susceptible to what amounts to an open access commons problem. Individuals connected to a common microgrid can find it privately beneficial to use the system without paying for it or contributing to its maintenance. Ultimately, in the case we consider, revenues collected could not cover the costs of continued operation. The principal-agent problems we have documented make it difficult to implement effective theft detection and deterrence protocols. Thus, in areas where theft is likely to be pernicious, even smart solar microgrid systems can fail.

In light of these challenges, private solar home solutions that fully internalize the costs of small-scale electricity generation may be more appealing. The costs of private PV systems coupled with efficient appliances have fallen significantly in recent years, making this option more cost competitive. India's recent shift towards deploying private systems, versus microgrids, in remote areas could offer a pragmatic solution to the economic challenges that complicate rural electrification. Moreover, policies need to be flexible and adaptive to new technologies, especially in an industry with such rapid technological advancement.

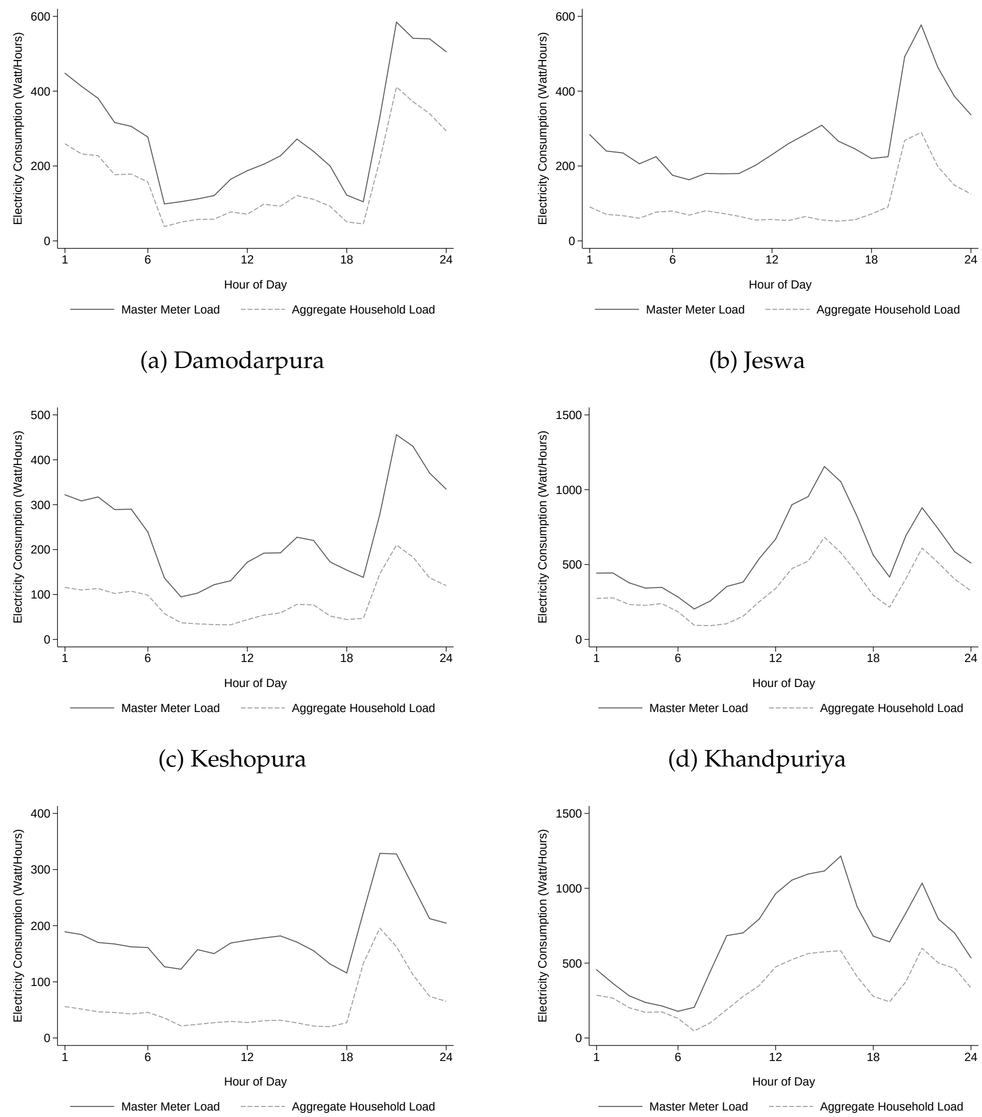
[26]See MNRE [2016] for details.

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 systems. We do not directly observe solar output from the systems, so we base this figure on production projections from the NREL PVWatts India Solar Calculator. We match these projected solar production figures for every hour of the year to each system based on whether that system was operational during that hour. The gray curve thus represents the average projected hourly production based on the actual hours of operation for each system.

Figure 2: Typical Daily Electricity Load Profile by Village



(a) Damodarpura

(b) Jeswa

(c) Keshopura

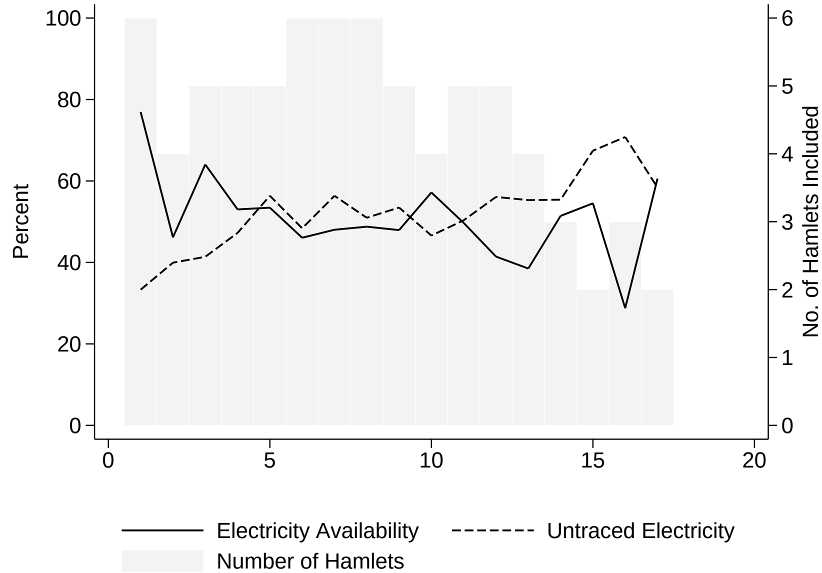
(d) Khandpuriya

(e) Khirkhiri

(f) Kolipura

Notes: Master meter load and aggregate household load are observed directly in the high-frequency meter data from the microgrid system. We drop periods of system downtime and collapse the remaining data at the hourly level (by meter type) to obtain the average hourly master meter load and average hourly aggregate household load.

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



Notes: This graph plots the simple average of the electricity availability percent and untraced electricity percent 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%. See Section 4.1 for a detailed account of how we impute power availability for each system.

Table 1: Difference-in-means Tests for Electrified vs. Non-Electrified Households

	Summary Statistics		Diff. p-Value
	(1) Microgrid	(2) No Microgrid	(3) (1) vs. (2)
Basic Characteristics			
Household Size	5.40	5.44	0.82
Household Members Age 18+	2.97	2.83	0.20
Household Members under Age 18	2.43	2.60	0.20
Metal Roof on Dwelling (=1)	0.12	0.00	0.00
Rooms in Dwelling	1.66	1.34	0.00
Main Water Source: Handpump (=1)	0.77	0.81	0.20
Main Cooking Source: Firewood (=1)	0.99	0.99	0.86
Socioeconomic Characteristics			
Non-BPL HH (=1)	0.52	0.41	0.01
Land Ownership (Acres)	0.85	1.01	0.28
Uses Land for Agriculture (=1)	0.66	0.91	0.00
HH Head is Farmer (=1)	0.47	0.70	0.00
Yearly Income (1000 INR)	66.58	54.47	0.05
Current Savings (1000 INR)	3.07	1.49	0.17
Current Outstanding Loans (1000 INR)	40.33	9.51	0.00
Energy Use			
Spending of 100 INR on Lighting	69.32	62.16	0.00
Uses Solar Home System (=1)	0.33	0.14	0.00
Uses Solar Lamp (=1)	0.02	0.00	0.02
Main Light Source: Kerosene (=1)	0.63	0.82	0.00
No. of Lights used Last Night	1.36	1.36	0.88
Subsidized Kerosene Exp. (INR/Month)	40.56	48.21	0.00
Unsubsidized Kerosene Exp. (INR/Month)	24.71	2.24	0.13
Observations	346	236	

Notes: Microgrid households are those who reside in one of the ten villages that received a microgrid installation from Gram Power. No microgrid households are households surveyed in other potential sites that did not adopt a microgrid. Columns (1) and (2) report the means for adopting and non-adopting households, respectively. Column (3) reports the p-values from a difference-in-means t-test across the two groups.

Table 2: 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
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	

Notes: 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. Columns (1) and (2) report the means for adopting and non-adopting households, respectively. Column (3) reports the p-values from a difference-in-means t-test across the two groups.

Table 3: Relating Aggregate Losses to Power Availability

	Dep. Variable: Percent AT&C Losses			
	(1)	(2)	(3)	(4)
Energy Availability (Percent)	0.166		0.344**	0.298**
	(0.117)		(0.131)	(0.131)
Lagged Energy Availability (Percent)	0.206**			0.233***
	(0.101)			(0.075)
Weeks After First Week Below...				
25th Percentile Availability		16.219**	24.091***	25.375***
		(8.010)	(7.111)	(6.824)
Hamlet FEs	Y	Y	Y	Y
System Vintage FEs	Y	Y	Y	Y
R-Sq	0.505	0.486	0.557	0.596
Observations	78	78	78	78

*Newey-West standard errors with a truncation parameter of 5 in parentheses. * $p < .10$, ** $p < .05$, *** $p < .01$.*

Notes: Energy availability is defined as the number of hours in a week that electricity is available divided by the total number of hours in that week represented as a percent. Losses are computed by differencing the total amount of metered household consumption from master meter consumption and then dividing by master meter consumption. System week is a running measure of the time since microgrid inception. The 25th Percentile Availability variable is an indicator equal to one for system weeks beyond the first occurrence of below 25th percentile power availability for each village.

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.

Michal 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/.

Michal 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.

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

Michael Grimm, Luciane Lenz, Jrg Peters, and Maximiliane Sievert. Demand for off-grid solar electricity: Experimental evidence from Rwanda. Ruhr Economic Papers 745, RWI - Leibniz-Institut fr Wirtschaftsforschung, Essen, 2018. URL http://hdl.handle.net/10419/175410.

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‘. Working Paper, July 2017.

M. Millinger, T. Mrlind, 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.

Ministry of Power. 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.

Ministry of Power. Guidelines for Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya). Technical Report F.No.44/2/2016-RE, October 2017. URL https://powermin.nic.in/sites/default/files/webform/notices/Guidelines_of_SAUBHAGYA.pdf.

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.

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 Bihars Electricity Woes, June 2017. URL http://ceedindia.org/mini-grids-a-practical-solution-to-bihars-electricity-woes/.

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.

A Appendix

A1 Determinants of Bypassing Behavior

Having documented enforcement problems, we present a more disaggregated analysis of non-technical losses in this Appendix. 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 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 A1 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.

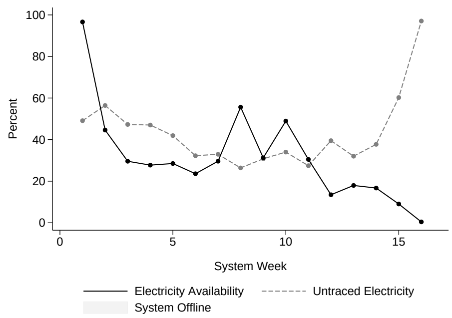
Table A1: Difference-in-Means for Baseline Variables by Bypasser Status

	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	

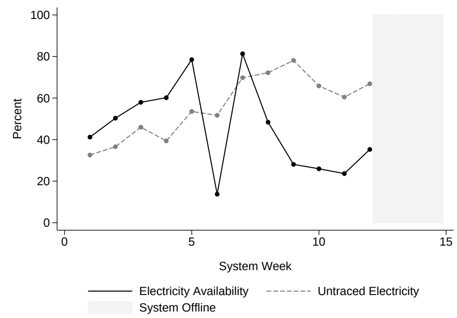
Notes: Bypasser status is determined by the algorithim outlined in Section A1. Columns (1) and (2) report the means for bypassing and non-bypassing households, respectively. Column (3) reports the p-values from a difference-in-means t-test across the two groups.

A2 Additional Figures & Tables

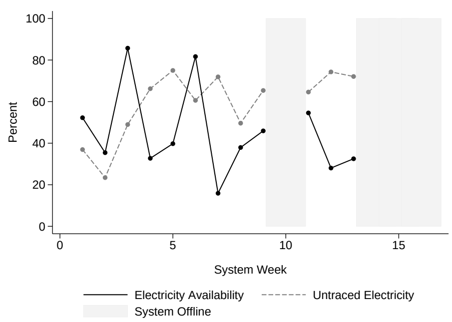
Figure A1: Availability and Losses by Village



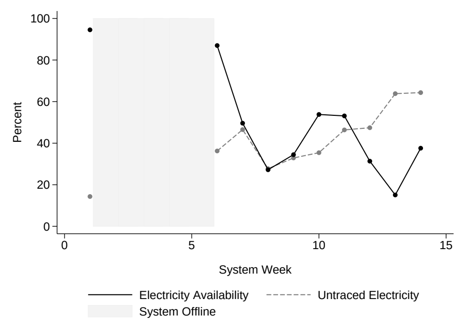
(a) Damodarpura



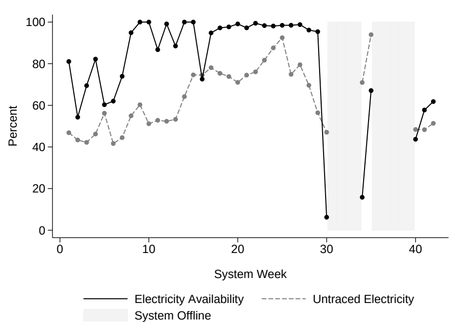
(b) Jeswa



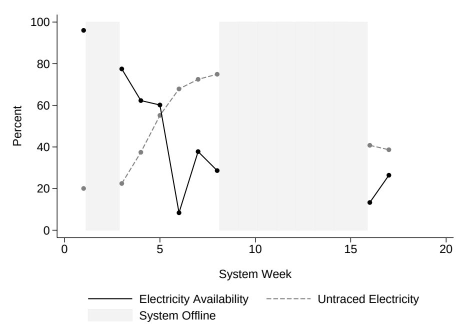
(c) Keshopura



(d) Khandpuriya



(e) Khirkhiri



(f) Kolipura

Notes: These graphs plot the percent of energy availability and untraced electricity by system week. Energy availability is defined as the number of hours in a week that electricity is available divided by the total number of hours in that week. Untraced electricity is computed by differencing the total amount of metered household consumption from master meter consumption. System week is a running measure of the time since microgrid inception.

Table A2: Summary Statistics at Baseline for Electrified Households

	N	Mean	Std. Dev.	Min	Max
Household Size	346	5.40	2.08	1	15
Household Members Age 18+	346	2.97	1.38	1	10
Household Members under Age 18	346	2.43	1.60	0	10
Metal Roof on Dwelling (=1)	346	0.12	0.33	0	1
Rooms in Dwelling	346	1.66	1.00	1	8
Main Water Source: Handpump (=1)	346	0.77	0.42	0	1
Main Cooking Source: Firewood (=1)	346	0.99	0.12	0	1
Non-BPL HH (=1)	341	0.52	0.50	0	1
Land Ownership (Acres)	346	0.85	1.73	0	9
Uses Land for Agriculture (=1)	346	0.66	0.48	0	1
HH Head is Farmer (=1)	346	0.47	0.50	0	1
Yearly Income (1000 INR)	346	66.58	77.65	0	730
Current Savings (1000 INR)	345	3.07	14.99	0	200
Current Outstanding Loans (1000 INR)	345	40.33	123.72	0	1800
Spending of 100 INR on Lighting	346	69.32	30.86	0	100
Uses Solar Home System (=1)	346	0.33	0.47	0	1
Uses Solar Lamp (=1)	346	0.02	0.15	0	1
Main Light Source: Kerosene (=1)	346	0.63	0.48	0	1
No. of Lights used Last Night	346	1.36	0.66	0	4
Subsidized Kerosene Exp. (INR/Month)	346	40.56	28.47	0	200
Unsubsidized Kerosene Exp. (INR/Month)	346	24.71	226.35	0	4000

Notes: Summary statistics computed for all households within the ten villages that received a microgrid installation from Gram Power.

Table A3: Microgrid System Characteristics

Village	PV Capacity	Battery	No. Household
Khirkhiri	5 KW	96 VDC	21
Khanpuriya	7.5 KW	120 VDC	47
Keshopura	5 KW	96 VDC	30
Kolipura	7.5 KW	120 VDC	48
Gajron	5 KW	96 VDC	39
Kasba Thana	5 KW	96 VDC	28
Kunda	5 KW	96 VDC	42
Jawaipura	5 KW	96 VDC	38
Jeswa	5 KW	96 VDC	36
Damodarpura	5 KW	96 VDC	32

Table A4: Appliance Ownership by System Size

	5KW System HHs		7.5KW System HHs		Diff. p-Value	
	(1) Ownership	(2) Watts	(3) Ownership	(4) Watts	(5) (1) vs. (3)	(6) (2) vs. (4)
All Appliances	1.00	67.67	1.00	163.56		0.06
Non-bulb Appliances	0.76	54.63	0.88	147.62	0.11	0.07
Mobile Phone	0.59	4.74	0.71	2.15	0.21	0.68
TV	0.07	4.55	0.26	1.29	0.00	0.53
DVD	0.03	4.23	0.09	0.00	0.14	0.42
Fan	0.41	16.67	0.62	29.82	0.03	0.25
Iron	0.01	2.88	0.06	35.29	0.03	0.02
Music System	0.10	21.54	0.18	13.24	0.22	0.77
Radio	0.01		0.00		0.64	
Computer	0.01		0.03		0.24	
Water Pump	0.01		0.00		0.64	
Fridge	0.00	0.00	0.06	63.53	0.00	0.03
Other	0.04	0.00	0.12	2.12	0.06	0.00
Observations	156	156	34	34		

Notes: There were eight 5KW systems installed (Khirkhiri, Keshopura, Gajron, Kasba Thana, Kunda, Jawaipura, Jeswa, Damodarpura) and two 7.5KW systems installed (Khanpuriya and Kolipura). Columns (1) and (3) report ownership rates for various appliances. Columns (2) and (4) report the average number of watts for that appliance, counting those who do not own that appliance as owning zero watts. Columns (5) and (6) report the p-values from a difference-in-means t-test across the two groups.

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