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RESEARCH PAPER

Solar Microgrids in Rural India: A Case Study of Household Benefits

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Abstract: This study evaluates the benefits that rural households in India derive from dedicated solar microgrid service systems. A case study was conducted in Lakshmipura-Jharla, Rajasthan, a village in western India with significant potential for producing solar energy. In 2013, a private investor set up a solar microgrid in the village and distributed energy-efficient appliances. Its goal was to give poor households access to modern energy services. The study data were collected through a survey conducted among randomly selected households in the village. The survey found that such an electricity provision service had multidimensional benefits: flexible use of the energy service, more effective time allocation among women, more study time for students, improved indoor air quality, and safer public places. Given the initial unmet demand for modern energy in the village, technological interventions supported by policy has helped to expand consumption possibilities and new demand for services has emerged. The household-level frontier rebound effect is estimated to be more than 100%, reflecting a one-and-a-half times increase in the demand for illumination services among rural households. Frontier rebound effect estimates help quantify the benefits of solar microgrids and energy-efficient appliances for households in rural areas. The results of this study are consistent with existing literature that suggests that efficient appliances and

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access to electricity will increase the energy demand manifold and satisfy the growing and largely unmet demand for energy.

Keywords: Modern Energy Services; Energy-efficient Appliances; Frontier Rebound Effect; Rural Household; Solar Microgrid.

1. INTRODUCTION

The Indian government has implemented several initiatives to promote and accelerate the scaling up of rural electrification and efficient appliances use through new institutional arrangements and policy support. Solar microgrids are considered an alternative service delivery model to grid electricity in remote villages that either do not have grid connectivity (Thirumurthy *et al.* 2012; World Bank 2008) or where it is neither feasible nor cost-effective. While on an average grid electricity is less expensive than off-grid options, the levelised cost per kWh of grid extension rises steeply beyond a certain distance from the central facility (World Bank 2010; Bruckner *et al.* 2014). Therefore, microgrids are seen as a cost-effective solution for rural electrification in India (Venkataraman and Marnay 2008). It is important to scrutinize past experiments for lessons that may help us better understand which policy interventions will aid the speedy advancement of such initiatives and boost the demand for such electricity among rural households. This can help us assess the microgrid capacity required and how quickly supporting infrastructure needs to be built. The first mention of solar microgrids at the policy level in India can be found in the Decentralised Distributed Generation (DDG) scheme proposed by the Ministry of Power as part of the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), 2005. This programme's goal was to electrify villages where grid connectivity is neither feasible nor cost-effective and to supplement power provision in areas where the grid supply is available for less than six hours a day. In 2014, rural electrification gained momentum with Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) and the Integrated Power Development Scheme (IPDS), which emphasized solar energy and introduced a smart metering system to enhance end-user access. In addition, the Indian government also designed a policy instrument for subsidy allocations to encourage private investors to enter the electric services market through private microgrid systems in rural areas. A microgrid is an integrated, local system that generates electricity and transmits it to end-users (residential and commercial users) within a limited geographical region. A microgrid operating on renewables like biomass, wind, and solar photovoltaic (PV) technology can help increase power quality, reliability, efficiency, and sustainability (Kaundinya *et al.* 2009). The argument in favour of renewable energy-based microgrids and energy-efficient appliances is mostly driven by the scarcity of non-renewable fossil fuel–based energy and its impact on human health and climate change. Microgrid systems also provide more reliable electricity, as outages or interruptions in supply can be quickly identified and corrected. Additionally, transmission and distribution costs are low with microgrids and very little electricity is lost during transmission (Hirsch *et al.* 2018).

In India, a large number of rural households without access to grid electricity or any other reliable energy source depend on firewood or fossil fuels to meet basic energy needs like cooking and illumination. The detrimental health and environmental impacts of these fuels are well known (Johnson and Chiang 2015; Parikh 2011). Therefore, reliable access to cleaner energy sources is crucial in terms of the environment and climate change mitigation (Millward-Hopkins *et al.* 2020; World Bank 2008; GEA 2012; Alliance for Rural Electrification 2011); in addition, it stands to contribute towards meeting multiple Sustainable Development Goals (SDGs) by improving households' health and quality of life (UNEP 2017). However, it is difficult to estimate the level, pattern, and growth of total energy demand at the community scale. This makes it difficult for private companies to invest in microgrids (Williams *et al.* 2015; Wang and Huang 2014). Therefore, to plan and design better solar microgrids, it is essential to understand the demand for such grids and how they benefit users and the community.

Contemporary literature on energy demand indicates that when a certain energy service becomes more technically efficient, energy demand in total increases and not just for that particular energy service. This is called the "rebound effect" (Chakravarty *et al.* 2013; Sorrell and Dimitropoulos 2008; Vikstrom 2008; Greening *et al.* 2000; Saunders 2000; Roy 2000). This happens because users interpret energy efficiency increases as the increased availability of energy services at the same price; in other words, as the effective prices of energy services reduce, consumers respond by demanding more of that energy service. The literature suggests that the rebound effect can be partial or full or may backfire (Roy 2000; Roy *et al.* 2013; Lin and Liu 2013a; Lin and Liu 2013b; Lin and Liu 2015; Druckman 2011; Saunders 2000; Sorrell 2009). But these outcomes are dependent on whether the demand increase is relatively lesser, equal to, or greater than the magnitude of energy efficiency improvement.

The frontier rebound effect is a special case that the literature describes as an increase in the total energy demand due to improved efficiency as a result of a technological innovation within a particular energy service—such as in the case of fuel-efficient cars in mobility services or LED bulbs in illumination services (Jenkins *et al.* 2011; Saunders 2013). The literature also shows, through empirical studies, that when one energy service becomes cheaper and more easily available, consumers devise new and innovative ways to use that energy (Saunders and Tsao 2012), which leads to an increase in the total energy demand. This is an extreme case of the rebound effect caused by the increased availability of opportunities for energy consumption and discovery of unforeseen opportunities for substitution. This increased consumption can have a significant impact on economic activities. This phenomenon is often seen in developing countries with constrained energy access and a lot of unmet demand (Roy 2000; Chakravarty *et al.* 2013). The presence of such an effect indicates that unmet demand falls faster with an increase in the social well-being of the beneficiary (Saunders 2013; Freeman 2018).

This case study explores solar microgrids as an alternative electricity service provision system in human settlements with high unmet demand. The study also examines the role of energy-efficient appliances in such environments. The case study was based on the village Lakshmipura-Jharla in India, where a single solar microgrid system was set up by a private investor. The details of the study are covered in Section 2. Section 3 discusses the estimated frontier rebound effect based on the available data. Section 4 presents a discussion of the results, and Section 5 provides concluding remarks.

2. THE CASE STUDY SITE

The first commercial-scale solar microgrid (and energy-efficient appliances programme) was set up in 2012–2013 as a private–public partnership (PPP). Gram Power (a private solar microgrid company based in India) set up its pilot project in the village Lakshmipura-Jharla in the Tonk district of Rajasthan, which was unconnected to the grid. High levels of solar irradiance[3] made it an apt location for the project, and in March 2012, a microgrid with a capacity of 2kW was set up. One of the authors visited the village in July 2013. The study site is located 1 km from the relatively well-connected village of Khareda, which, in turn, is located 150 km from Rajasthan's capital city, Jaipur.

In 2003–2004, a start-up introduced the '*jugnu*' system, wherein individual solar lanterns were distributed to village households at the subsidized price of ₹7,000 ($111)[4] per unit. However, these lanterns could only provide four

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[3]Solar irradiance is a measure of the solar radiation (power per unit area on the earth's surface) produced by the sun in the form of electromagnetic radiation (IPCC 2007).

[4]All conversion in this study is calculated using the exchange rate: USD 1 = INR 63 (average exchange rate for the year 2013).

hours of light a day, leading to high unmet demand. Then, in 2012, a private company set up a solar microgrid in the village and provided households with smart meters that allowed them to access 24x7 uninterrupted electricity supply. They also provided households with two energy-efficient 14 W or 16 W compact fluorescent lamp (CFL) bulbs. At the time, the cost of a bulb was around ₹70 when bought in bulk. The bulbs were distributed at a subsidized price of ₹15 per bulb as per the Bachat Lamp Yojana (2012) to microgrid-connected households. The private company installed and operated the microgrid in collaboration with the state renewable energy board under the Ministry of Power and the Development Impact Lab (DIL), University of California, Berkeley, USA, provided scientific knowledge. Private investors provided 80% of the total cost of installation in return for import duty exemption for certain components in the system. The remaining 20% was contributed by the Indian government under the Jawaharlal National Solar Mission (2010). The objective of the PPP model was to leverage private investment to expand the supply capacity and meet new energy demand through renewable sources such as solar (World Bank 2008; GEA 2012; Alliance for Rural Electrification 2011; UNEP 2017) (Table 1).

Unlike solar lantern systems that are meant for use within the home, microgrids provide uninterrupted power service 24x7 at a community level. The latter provides flexibility to end-users in their choice of appliances and has better social, environmental, and economic benefits compared to lanterns while reducing costs by utilizing economies of scale (Table 1). Despite these well-established benefits, there exist some practical barriers to solar microgrids—for example, the poor availability of skilled technicians, lack of timely maintenance and monitoring, etc. (Fowlie *et al.* 2018). In our case study, we found that the private partner was committed to overcoming these known barriers.

Table 1: Solar Microgrid Systems: Benefits and Barriers

	Benefits and barriers				**References**
Actors		**Producer & distributor**	**End-user**	**Other**	
Benefits	**Economic**	Low cost of raw energy, reduces transmission loss	Planned electricity consumption	Local employment generation, economic development	Dieckmann 2013; Chen *et al.* 2011
	Social		Improvements in health, study time, cooking time, communal activities, etc.		Fowlie *et al.* 2018; World Bank 2008
	Environmental	Less greenhouse gas (GHG) emissions, less local pollution, less non-renewable energy use			Dieckmann 2013; Kamel *et al.* 2015; Molina and Mercado 2010; Vachirasricirikul and Ngamroo 2011
Barriers		Lack of improved technologies, efficient monitoring systems, and expertise	Higher electricity tariffs	Regulatory barriers	CEA 2012; Chakravarty 2016

Source: Compiled by authors from various sources

3. END-USER BENEFITS OF THE SOLAR MICRO-GRID: ESTIMATION OF THE FRONTIER REBOUND EFFECT

Estimating the frontier rebound effect can show how an increase in the efficiency of any appliance changes end-user behaviour and affects their total energy consumption (Chakravarty *et al.* 2013; Sorrell and Dimitropoulos 2008; Vikstrom 2008; Herring 1998, 2006; Greening *et al.* 2000). Khazzoom first mentioned this effect in the early 1980s when discussing household energy consumption (Wei 2010; Sorrell 2007; Allan *et al.* 2008; Allan *et al.* 2006; Herring 2006; Saunders 2000a; Khazzoom 1980). The literature shows that end-users respond in the same way to energy efficiency as they do to a decrease in energy prices (Sorrell and Dimitropoulos 2008). Therefore, the rebound effect is equivalent to the percentage change in the demand for energy services, i.e., the perceived reduction in price due to efficiency improvements in energy-using appliances (Berkhout *et al.* 2000; Sorrell 2007; Saunders 2005; Sorrell and Dimitropoulos 2008; Frondel *et al.* 2008; Binswanger 2001). The change in energy service demand due to a change in perceived price can be greater than 100% in magnitude, which is identified as the frontier rebound effect. Energy efficiency gains create opportunities for undertaking new economic activities using the same supply of appliances. In parallel, the demand goes up for new energy-embedded products (Jenkins *et al.* 2011; Saunders 2013). For example, Tsao *et al.* (2010) analysed 300 years' worth of historical data about lighting appliances and fuel-use from three continents and discovered that despite advances in appliances and fuel-use efficiency, energy consumption has been increasing.

Evidence from past studies in India shows a widely varying rebound effect (Roy 2000; Roy *et al.* 2013; Chakravarty and Roy 2017). There was super-conservation or a negative rebound among sufficiently conscious urban consumers (Chakravarty and Roy 2017); however, "backfire" (Roy 2000; Roy *et al.* 2013) was more likely in households with unmet energy demand. Sorrell (2007; 2009) observed that backfire due to the frontier rebound effect is most likely to occur with general-purpose technologies as they usually have a wide scope for improvement and elaboration. These general-purpose technologies complement existing and potential new technologies, particularly when energy efficiency gains can be made at an early stage in the development and diffusion of the technology. The opportunities created by these technologies can have significant, long-term effects on innovation, productivity, and economic growth; the subsequent increase in economy-wide energy consumption further increases these effects.

To understand the frontier rebound effect of the microgrid system, we compared the benefits accrued to households from solar microgrids against a benchmark situation, i.e., households' illumination consumption via domestic solar lantern systems. To estimate the frontier rebound, we used the following equation (1) (Roy 2000; Saunders 2012, 2013; Freeman 2018):

$$Frontier\ Rebound = \frac{\%\ change\ in\ energy\ service\ consumption}{\%\ change\ in\ energy\ service\ price} = \frac{\Delta q}{\Delta p} \times \frac{p_t}{q_t} = \frac{q_n - q_0}{p_n - p_0} \times \frac{p_0}{q_0} \ldots \ldots eq(1)$$

Where, *q* represents energy service consumption and *p* represents the price (implicit) of the energy service.

Specifically, $\Delta q = q_n - q_0$

Where, q_n is the energy service consumption at the current time point and q_0 is the energy service consumption at the base time point.

Again, $\Delta p = p_n - p_0$

Where, p_n is the energy service consumption at the current time point and p_0 is the energy service consumption at the base time point.

The rebound was estimated for the illumination service as in this case study efficient appliances were introduced for lighting purposes only. The impact of electricity access could be estimated as the frontier rebound effect using equation (1). Thus, we were able to estimate the total increase in energy service demand resulting from the energy access intervention by comparing the pre-microgrid and post-microgrid situation. In the rebound estimation, the price mentioned in equation (1) represents the estimated price per particular "service" (e.g., illumination/cooking/heating). To estimate these prices per service, we used service-specific expenditure data. We also estimated the expenditure both before and after the introduction of the solar microgrid. We estimated the cost of a domestic solar lantern system using annualized monetary expenditures (*E(q)*) divided by the quantity of consumption (*q*) (Filippini and Pachauri 2004). *E(q)* is the total annualized cost of consumption derived from the capital cost and operating cost (including maintenance) borne by households. Capital cost includes investment and interest charges. To estimate what part of the unit cost can be attributed to capital investment, we used the method suggested by Culp (1979).[5]

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$$E(q) = total\ annualised\ cost = annualised\ capital\ cost + annual\ operation\ cost + annual\ maintenance\ cost$$

Here, $annualised\ capital\ cost = first\ cost \times annualised\ factor$

$$and\ annualised\ factor = i + \frac{1}{\{(1+i)^t - 1\}}$$ (*)

Data were collected from users who owned domestic solar lantern systems. The solar microgrid expenditure and energy consumption data were directly collected from the energy meters and payment receipts. The number of households and the names of the heads of households were first collected from the village panchayat office; then, every alternate house from the village was selected for the survey. If the selected house was vacant, or its members were unavailable or unwilling to participate in the survey, the next house was selected. Each household was given the option of exiting the survey at any time to minimize bias and erroneous responses. In conducting the survey, standard survey ethics were followed. Consent was taken from each of the stakeholders (the educational institute based in the US, private start-up, households) before the purpose of the study was explained.[6]

A key aspect of the survey was collecting data on the energy service demand pattern of households before and after they had access to the solar microgrid and efficient lamps, and how these corresponded to their energy bills. Both types of information were collected through direct interviews based on a pre-formatted, tested, and piloted questionnaire. Since the appliance usage patterns of households influence electricity demand, the technical specifications of the appliances were very important in this study. Therefore, the questionnaire[7] also collected information about the types of appliances used in households, the number of appliances, their specifications, wattage consumption, usage time in both summer and winter, whether they were energy-efficient or not, and their initial cost. Apart from this, the questionnaire also had qualitative questions on how households perceived the impact of electrification.

4. RESULTS AND DISCUSSION

The total population in the study village was approximately 100 people living in 22 households. The average family size was roughly five members. Eleven households responded to the interview. The village is situated on the banks of the river Banas, which forms a moderately rich fertile plain.

Where, t is the operating time period/lifetime of the equipment and is considered as 10 years for this calculation, and i, is the rate of interest and is assumed to be 8% for the present calculations, given the then prevailing market interest rate for long-term deposits in India. However, we also use a 3% rate (savings bank interest rate prevailing in 2013) to arrive at a range rather than a single number.

[6]We declared that all data and information were to be used for academic purposes (PhD thesis of the first author and any academic publication out of it) with due acknowledgment to the funding sources and that no information would be shared for commercial purposes.

[7] The questionnaire is provided in the Appendix.

We estimated the magnitude of the rebound effect by studying how access to efficient lighting and a solar microgrid changed energy-use patterns and the socio-economic impacts of the same.

4.1 The Socio-economic Structure of the Village

Cultivation was the major occupation in the study village. About 70% of the households in the village were engaged in cultivating different varieties of pulses. A few individuals worked as marginal labourers (21%) in various menial jobs like construction, long-distance truck driving, and intermediate short distance non-motorized cart driving (7%). Some households received a secondary source of income from wage earnings during the non-agricultural seasons. It was difficult to determine their exact incomes because householders did not have fixed monthly incomes, salary slips, or registered labour incomes. Our survey data revealed that two households were below the poverty line and the rest were only marginally above it. All the households were in the low-income category. The income from marginal labour was approximately $6.35 per day (₹400).[8] The cultivation workforce was mostly from within the family, and they mainly practised subsistence farming where they produced crops for their consumption. The average monthly expenditure per household was $97.5 (₹6,142.5). The minimum and maximum reported monthly expenditures were $31.75 (₹2,000) and $174.6 (₹11,000), respectively. Among the villagers, 62% were male and 38% female; 54% were adults and 46% were below 18 years of age. Only two adults had a formal education. Those under 18 years, however, attended school at Khareda regularly. All the households had a residential unit with an average carpet area of 871 sq ft. The predominant materials used to construct house walls were mud and unburnt bricks (93% households), whereas the predominant material used to make the roof was asbestos (86% households). About 14% of residential units had tiles on their roofs. Most of the residential units were single-storied buildings with one or two rooms and an open balcony in front of the rooms. Villagers used this balcony as a kitchen and living and dining space. We present some village characteristics vis-à-vis the state in Table 2.

[8] All conversion rates are for the year 2013.

Table 2: Socioeconomic Status of the Study Area

	Study area	**State: Rajasthan**	**Country: India**
Principal crop cultivated	Pulses	Barley, wheat, gram, pulses, and oil seeds	Wheat, rice, pulses, and jute
Main source of livelihood	Cultivation and labour	Cultivation	Cultivation
Average monthly family expenditure	$97.5 (₹6,142.5)	$50 (₹3,200)	$18–21 (₹1,175–1,350)
Gender ratio (Female: male)	666:1000	861:1000	940:1000
Literacy rate	Very low (2% approximately)	61.44%	74%
Predominant material of the wall	Mud and unburnt bricks	Stone: packed with mortar	Burnt brick
Predominant material of the roof	Asbestos cement	Stone/slate	Concrete

Source: Census of India (2011); Ministry of Statistics and Programme Implementation (2012)

4.2 Access to Energy Sources

At the time of the survey, households were either using energy sources available in the market or their own sources. They were using kerosene, wood fuel, dung cakes, solar microgrid electricity, and battery power. Each household had one ration card issued against the name of the male head of the family, which gave them access to the public distribution system (PDS). Each household, or each ration card, was allocated four litres of kerosene per month. Kerosene is widely used in cooking (Lam *et al.* 2012), but in the surveyed village, households used wood fuel and dung cakes for cooking and kerosene for agricultural purposes like operating irrigational pump-sets and spraying fertilizers. Kerosene was not used for cooking also because there was a cultural preference for *chulah* (mud-oven) cooked food. For lighting, all the households have been using solar panels and lanterns since 2003–04. While the lanterns only provide a maximum of four hours of illumination service per day, under the new solar microgrid system, a household has access to round-the-clock electricity for illumination and space-cooling (fans or room coolers could be connected). If necessary, and if they could afford to pay, they could also connect other household appliances like televisions, buttermilk machines, grinders, etc.

Table 3: Major Energy Services and their Sources of Energy

Energy service	Lighting (illumination)	Space-cooling	Other energy services
Pre-solar microgrid electricity access	Solar panel with a domestic lantern system (4 hr/day) [90%]	None [0%] (Personal hand fan only)	None [0%]
Post-solar microgrid electricity access	Solar microgrid electricity [77%] (24 hrs/day)		
Change in usage	Consumption increased [77%]	New electric ceiling fans installed [65%]	Buttermilk machines and televisions were purchased and installed in 5% of the surveyed households

Source: Household sample survey
Note: Percentage of households is in parentheses.

The solar microgrid gave households access to both illumination and cooling services. Earlier, households could not have possibly used appliances like fans or coolers/heaters because of affordability issues.

4.3 Solar Microgrids and Electricity Access

The solar microgrid system installed in the study village was of 2 kW capacity. Households paid in advance for the energy service. A 100% advanced payment helped the producer ensure that there was demand for the installed capacity, and people were used to such arrangements because they were familiar with mobile phone recharge services. The households adopted the payment system without any hesitation. The producers engaged a technician to collect the money. Based on the specific needs of households and the amount paid, the power company's controller used the house's consumer identification number to set the individual household meter through a wireless network. A connection used for a minimum of two lights bulbs could be recharged at $0.80 (₹50) and a minimum of two lights and one fan at $2.78 (₹175). On average, in a month, a household spent $0.32 (₹20) on recharges, and the modal value of recharge payment was $0.80 (₹50). This was possible because monthly recharges were not mandatory. A household could recharge again after the amount was exhausted. Thus, there was no specific monthly electricity bill in these households. Households could decide on their service demand level according to what they could afford at that time.

Before getting access to the solar microgrid, most households had just one or two solar lamps from the 2003–04 programme. They had been using these appliances for nine to ten years. A few of them needed replacement appliances (14%). During the survey, we observed that the solar microgrid company had provided all village households with new microgrid connections with two 6 W compact fluorescent lamps (CFL) worth $28.57 (₹1,800) free of cost. If a household used a 6 W CFL for one hour, it cost $0.0024 (₹0.15) under the solar microgrid scheme. Similarly, if they used a 40 W fan for one hour, it cost $0.059 (₹0.37). So, a household paid $0.40 (₹25) per unit (kWh) of solar microgrid electricity.

This amount is nearer the electricity rate in the US ($0.48/unit or ₹30/unit in March 2013) and is much higher than the cost of India's grid-connected electricity ($0.13/unit ₹8/unit in March 2013, on average). It is worth mentioning that the price of grid-connected electricity in India in 2013 included a subsidy of 20–50% at the consumer end. The installation cost of a solar microgrid system is two-and-a-half times higher than setting up a connection to the centralized grid electricity supply system (CEA 2012). In the case of energy-efficient appliances, the capital cost or initial purchase cost is also a significant catalyst for energy consumption. However, energy-efficient technologies have a higher initial cost that acts as a barrier to faster adoption, especially in developing countries (Fowlie *et al.* 2018; GEA 2012; Toman 2003; Bruckner *et al.* 2014). Therefore, the estimation process needs to consider the fixed capital cost and variable costs and calculate the annualized cost for each type of equipment for energy access.

In a supply-constrained scenario, comparing the costs of two competing systems (domestic solar lantern systems and microgrid connectivity systems) generates interesting results. The annualized cost per unit (kWh) of electricity from a community-scale solar microgrid is still much lower than the cost of the electricity generated from the solar home lantern system (Table 4). This is due to the up-front cost of the individual solar panel for the domestic lantern system. So individual households with access to community-scale solar microgrids benefit from economies of scale and get electricity at a cheaper price when compared with the domestic lantern system. In monetary terms, our estimates show that individual households can save approximately $0.21 (₹13) on one unit (kWh) of energy if they switch from individual PV-based systems to microgrid systems. Annually one household can save around $142 (₹8,946) by using the solar microgrid.

Table 4: Energy Sources and Their Corresponding Costs, Services, Appliances in Use, and Average Time of Usage

Energy sources	**Domestic solar panel lighting systems**	**Solar microgrid electricity**				
Time of access (hrs)	4	24				
Annualized cost per kWh energy ($)	0.95* 0.74**	0.64* 0.59**				
Services provided	Lighting only	Lighting	Cooling	Entertainment	Cooking	Other
Appliances in use	Solar lamp	CFL, night bulb	Fan, cooler	Television, radio, DVD player	Buttermilk machine	Mobile charging
Duration of use in a household (hrs/day)	4	4-6 (CFL) 3–5 (night bulb)	2–6 (fan) 2–4 (cooler)	2–4 (television)	1–1.5	2–4

Source: Estimates based on household sample survey data
Note: *Estimated using 8% of the discount rate.
**Estimated using 3% of the discount rate.

Therefore, for the end-users in our case study, it is economic to use community-scale microgrid electricity. This has been shown in other literature as well (Chaurey and Kandpal 2010). Our survey revealed that with 24x7 access to the solar micro-grid, households preferred to keep one light bulb outside their homes illuminated for at least eight hours after sunset for security reasons. When you consider that the domestic solar lamps only provided four hours of illumination, it is easy to see that access to energy from the microgrid and efficient electric appliances doubled the consumption of energy services in the sample households.

Above 90% of respondents agreed that the socio-economic condition of end-users has improved with 24x7 access to electricity from the solar microgrid.[9] The demand for entertainment services via television and radio

[9]Rest of the 10% of the respondent choose not to specify anything.

use have also increased. People are less afraid of insect attacks at night; public places feel more secure; women can cook food even after sundown, which gives them flexibility when it comes to other chores and has allowed them to do more productive work; students have more time to study as they can study at night too. In the village we studied, the basic need was illumination as the village layout was open enough for there to be natural ventilation. Demand for household appliances for food preparation went up when a new appliance—the buttermilk machine—was purchased by some of the households. The uptake rate was as high as 77%, signifying that what was once accomplished using women's physical labour was now being done by modern electric appliances.

Table 5: The Perceived Impact of 24x7 Electricity

Perceived impact of efficient electrification	**Yes (% of responses)**	**No (% of responses)**	**Don't know (% of responses)**
Indoor environment becomes less smoky	100%	0%	0%
Increase in demand for lighting/cooling	100%	0%	0%
Increase in study time for children	100%	0%	0%
More time allocation for daily primary jobs like cultivation	100%	0%	0%
Better livelihood practices with electricity	100%	0%	0%
Others	90% mentioned other benefits such as increased access to entertainment services via television and radio, less fear of insect attacks at night, and flexible cooking times		

Source: Estimates based on household sample survey data

4.4 Avoided Direct Emission

The total demand for energy in the village was 2 kWh per day, as determined by the maximum capacity of the system. If this same amount of energy had been generated by a centralized, thermal electricity grid, 3.56 kg of CO_2 would have been produced per day (1,299 kg of CO_2 per year), assuming an emissions factor of 0.89 tons of CO_2 for every megawatt-hour of electricity (CEA 2012). The solar microgrid system in our case study helped to avoid 3.56 kg of direct CO_2 emissions per day. However, when considering these avoided emissions, one needs to keep in mind the costs involved. From the generation company's perspective, avoiding the 3.56 kg of CO_2 caused an additional 54% generation cost compared to the centralized grid-connected power supply system in India. This was estimated based on CEA data from 2012 about the cost of power projects per megawatt.

4.5 Changes in Electricity Service Demand

A key aim of the survey was to understand the energy service demand patterns of households before and after they got access to the solar microgrid. The annualized per unit cost of electricity from the solar microgrid was found to be 32% lower than in the case of the solar lantern system. The annualized unit cost of electricity services was used to estimate the percentage change in the price of energy services at the household level. Corresponding changes in the demand for illumination services and all-encompassing electricity services have been estimated in Table 6.

Table 6: Estimated Frontier Rebound Effect

Energy services	(At 8% discount rate)	(At 5% discount rate)	Implication of estimated rebound effect
For illumination services	151%	165%	Presence of the frontier effect
For all the available energy services	192%	199%	Presence of the frontier effect

Source: Estimates based on the data from the household survey

The rebound estimates clearly show that the percentage change in the demand for energy services with respect to the price of those services was more than 100%. Thus, a 1% decrease in prices will result in a 1.51–1.65% increase in the demand for illumination services and a 1.92–1.99% increase for all other available energy services. This is because consumers earlier had unmet energy demands because of the constraints of only four hours of access to electricity. After the solar microgrid was set up, they had uninterrupted supply of electricity throughout the day. However, it must be noted that there is an upper limit to the amount of electricity that the community can draw from the microgrid system, i.e., based on its initial capacity on installation. Frontier estimates can be higher than the estimated values when supply is unlimited. The literature suggests that with the introduction of efficient appliances, the energy demand will increase manifold to satisfy unmet demand.

The frontier rebound effect arose in this case study because households increased their direct energy consumption. Their newfound access to affordable electricity allowed them to adopt new appliances (fans, radios, televisions, cell phones, and kitchen appliances) that led to these communities, who had no previous access to modern energy, to demand new energy services that can be considered welfare-enhancing (Saunder, 2013; Jenkins *et al.* 2011). Therefore, the study's estimate is conceptually equivalent to the frontier rebound estimate suggested by other literature (Jenkins *et al.* 2011; Saunders 2013; Saunders and Tsao 2012; Tsao *et al.* 2010; Sorrell 2007, 2009). A rebound case study in rural India (Roy 2000) estimated a partial rebound effect at about 50% for illumination services after introducing only solar lanterns. That was lower than this study's estimated rebound magnitude. For some households, Roy (2000) observed that the rebound effect was about 200% for both lighting and cooking services, which are quite close to the rebound estimates of this study. In another study by Burgess *et al.* (2019), the researchers found high price responsiveness for diesel, off-grid, and microgrid solar in the state of Bihar, India. Such high demand elasticities are striking when compared to those in developed countries where saturated demand levels and high-income levels mean that the demand curve is expected to be almost vertical. Thus, only extensive changes in price can induce changes in demand in those countries.

In our study, we found that 23% (or 5 out of 22) of the households had not taken a solar microgrid electricity connection because they found the costs prohibitive. These households were using the solar lantern system with a battery that let them run at least one light bulb at night; however they found the 24x7 electricity service too expensive. However, it is likely that these households will eventually switch services, either after the lifetime of their current equipment or when their incomes improve. Households that cannot afford the switch can be offered support through new policies that, for example, buy back older solar panels and lighting systems. How such policies can be operationalized, or what other alternative institutional or policy arrangements can be made, are research questions for the future.

5. CONCLUSION

The case study shows that electrification via solar microgrids offers rural households in India social, economic, and environmental benefits. Solar microgrid systems combined with energy-efficient end-use appliances result in a quick reduction in the demand gap. Lessons learned from the case study are relevant at the policy level as well. In contrast to newly emerging research (Lee *et al.*, 2020; Burgess *et al.*, 2019), this study clearly shows that poor rural households in India value round-the-clock access to electricity service. It reduces the drudgery of physical labour and provides flexibility in how time can be productively utilized, especially for women. Therefore, access to electricity, from a class and gender perspective, can be considered essential in terms of a decent standard of living and the Sustainable Development Goals (Hayward and Roy 2019; Rao and Min 2018). The study found that solar microgrids offered many additional benefits to a remote village: increased security in public places at night, access to entertainment services, pest reduction, and more time for students to study. In the village we studied, households consumed very little electricity (around 0.2 kWh per day) compared to an average household in India (12 kWh per day). This can be seen as an indicator of the electricity demand gap, where there is scope for accelerated provision of access to electricity.

The frontier rebound effect of illumination services is estimated to be more than 100%, which implies that a 100% increase in energy efficiency will increase the demand for energy services by more than 100% because of the shift in consumption. This signifies an improvement in end-user utility and thus the well-being of low-income households. This result is consistent with existing literature that postulates that the introduction of energy-efficient supplies will increase demand manifold. In the context of energy-access-equity-driven climate policy, where the goal is to reduce energy poverty and unmet energy demand, the frontier rebound effect can indicate whether the implementation of energy-efficiency policies affect the rate at which unmet demand is reduced.

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Appendix
Questionnaire for Rural Household Units

Usage pattern of lighting and space cooling in India's rural household sector

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This questionnaire collects information on ownership patterns and usage of energy-efficient appliances in India as a part of a study on estimating the rebound effect in energy consumption in the Indian economy. The research is being carried out by

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REQUEST FROM THE RESEARCHERS

It will take you approximately 15 minutes to respond to the questionnaire. Please take some time to answer the questions carefully. This will help us capture a set of crucial information. We would appreciate your responses.

We assure you that your personal information will be kept confidential and your responses will be used purely for academic purposes. We shall be thankful to you for your completing the questionnaire and helping us in our research study.

With regards,

Name of the investigator: ………………………………………………………………………..

Date: ……………………....…. *Time:* …………………. *Signature:* ....…

1. Name of the respondent:
   a) Address:
   b) Contact number:

A. Personal Details

1. Age of the respondent:
2. Highest level of education attained by any family member:[10]
3. Are you one of the earning members of the family? Yes/ No
4. How many earning members are there in your family?
5. What is the composition of your family (mention numbers)?

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[10] (a) < class 10 (b) class 10–12 (c) above 12 but not graduate (d) graduate (e) post-graduate and above

	Adult	Children
Male		
Female		

6. Carpet area of your living space (in sq ft):
7. Is the residential unit owned by you or rented? Yes/ No
8. Family monthly income level:
9. Family monthly expenditure level:
10. Major source of income/major occupation?[11]
11. What are the predominant materials of the roof and walls of your house?
    a) Wall:[12]
    b) Roof:[13]

B. Energy Consumption Details

12. Source of energy:

a) Pre-electricity access scenario:

Energy services	Fuel type used[14] (in the last 3 months)	Amount of fuel used (specify the unit) (per month)	Expenditure on fuel used (in INR) (per month)
Lighting			
Space cooling			

b) Post-electricity access scenario:

[11] (1) Cultivator, (2) main worker (< 6 months), (3) marginal worker, (4) agricultural labourer, (5) household industry worker, (6) other worker.

[12] (1) Grass/thatch/bamboo, (2) wood, (3) mud/unburnt brick, (4) plastic/polythene, (5) burnt brick, (6) stone, (7) GI metal/asbestos sheets, (8) concrete, (9) any other.

[13] (1) Grass/thatch/bamboo, wood, mud, etc, (2) plastic/polythene, (3) tiles (handmade tiles/machine-made tiles) (4) burnt brick, (5) stone, (6) G.I. metal/asbestos sheets, (7) concrete, (8) any other.

[14] (1) Coal, (2) coke, (3) electricity, (4) kerosene, (5) solar, (6) LPG, (7) petrol, (8) diesel, (9) wood fuel, (10) dung cakes, (11) others

Energy services	Fuel type used[15] (in the last 3 months)	Amount of fuel used (specify the unit) (per month)	Expenditure on fuel used (in INR) (per month)
Lighting			
Space cooling			

13. Total electricity consumption pattern:[16]

Months	Units consumed	Expenditure on electricity (in INR)
June		
May		
April		
March		
February		
January		

14. Total electricity consumed in the last 2–3 months:

[15] (1) Coal, (2) coke, (3) electricity, (4) kerosene, (5) solar, (6) LPG, (7) petrol, (8) diesel, (9) wood fuel, (10) dung cakes, (11) others

[16] Investigators are requested to fill the questions of this section himself/herself from the latest electricity bill of the respondent.

15. Consumption pattern of appliances:

Service	Specification	Wattage consumption	Hours in use in summer	Hours in use in winter	First cost/ capital cost	Remark/other details
Post electricity access consumption pattern (in 2012–2013)						
Lighting	Incandescent 100 W					
	Incandescent 60 W					
	Incandescent 40 W					
	Night bulbs 15 W					
	TFL (T5, T8, T12)					
	Tube 2 ft (narrow)					
	Tube 4 ft (narrow)					
	Tube 2 ft (regular)					
	Tube 4 ft (regular)					
	CFL (retrofit/non retrofit) (mention W-5/7/9/11/23)					
	Total					
Space cooling	Ceiling fan (32", 48", 52")					
	AC (0.75, 1, 1.5, 2 ton)					
	Total					
Other (Specify)						

C. Perception about the impact of efficient electrification

16. Do you feel that your environment has become less smoky? Yes/No/Don't know
17. Have you increased your lighting/space-cooling service consumption? Yes/No/Don't know
18. Do you think your kids now have more time for study? Yes/No/Don't know
19. Do you think you can now give more time to your daily primary job like cultivation, etc.? Yes/No/Don't know
20. Do you think now you have a better livelihood with electricity? Yes/No/Don't know
21. Any other impacts (please specify):

End of survey. Thank You!