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Providing reliable and financially sustainable electricity access in India using super-efficient appliances

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ABSTRACT

In India, 46 million, mostly rural, households lack access to electricity – over 50% of those are in the states of Bihar and Uttar Pradesh. While India has set an aggressive goal of extending the grid to all households by 2019, grid extension does not necessarily imply reliable electricity access. Indian utilities face a financial disincentive to supplying reliable electricity in rural areas because of subsidized tariffs and low consumer willingness-to-pay. Tariff subsidies for full household electrification in these states would be about Rs 15,000 Cr per year, which is two-times the existing subsidies and equivalent to 20–30% of their annual utility revenues. We find that super-efficient lamps, TVs, and fans can reduce the energy consumption of a rural household by over 70% cost-effectively, resulting in a net reduction in the total subsidy burden. Reduced consumption offers an opportunity to raise consumer tariffs while ensuring consumers' monthly electricity bills reduced. We also argue that super-efficient appliances make consumer-side storage cost-effective, leading to greater consumer willingness-to-pay. We recommend adoption of super-efficient appliances as part of the electricity access initiative in India, and electricity service based tariff setting as the next policy steps towards providing a reliable and sustainable electricity access.

1. Introduction - utility and consumer incentive challenges to grid-based electricity access

Globally, nearly 300 million households lack access to electricity. Nearly 20% of those, or about 46 million households are in India (REC India, 2017).[1] Over the last several decades, India has made significant progress in village electrification. As of April 2018, 100% of the villages in the country have been electrified[2] (DDUGJY, 2017). Household electrification, however, remains a challenge. To address this issue, the Government of India (GOI) launched the "Power for All" initiative in June 2014, a joint effort between the federal Ministry of Power (MOP) and the state utilities or governments to achieve universal electricity access by 2019 (Banerjee et al., 2015). This initiative is primarily implemented through the Deendayal Upadhyaya Gram Jyoti Yojana program for rural electrification (DDUGJY-RE) and involves extending electricity to un-electrified villages, separating the agricultural and household feeders in rural areas, and providing free electricity connections to nearly 40 million below-poverty-line (BPL) households in the rural areas (MOP, 2017). GOI is also working with several state governments to provide subsidized connections to above-poverty-line (APL) households.

However, electrification, or providing an electricity connection, does not necessarily mean reliable electricity access for households. Currently, electricity supply is highly unreliable for most rural consumers. The Electricity Supply Monitoring Initiative (ESMI) by Prayas Energy Group has been monitoring hourly power supply quality since 2013 across India—covering more than 50 districts and 350 locations as of April 2017—and is finding significant power-quality issues, especially in rural areas, despite the significant increase in power availability. More specifically, ESMI data shows that rural areas in several states continue to face regular power-cuts that last for several hours, while urban areas receive reliable power supply during the same time. For example, there was no evening (5 PM to 11 PM) electricity supply in the rural villages monitored for more than 58% (Uttar Pradesh) and 39% (Bihar) of the time, on average, during all of 2016. In the same period, in an urban area such as the state capital Lucknow, average

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[1] More than half of these un-electrified households are in the states of Uttar Pradesh and Bihar.

[2] A village is declared electrified if basic infrastructure such as a distribution transformer and lines exist in the inhabited locality, the electricity connection is provided to public places (such as schools, local government offices, and health centers) and at least 10% of all households.

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power-cuts were nearly absent.[3] It is pertinent to note that in 2016, Uttar Pradesh (UP) had no shortage of power procurement capacity (CEA, 2017). Also, UP is not an isolated example of unreliable power supply to rural areas - its neighboring state of Bihar as well as many other states share a similar story.

Typically, average tariff for rural consumers in India (especially BPL connections) is significantly below utilities' cost of supply, making utilities unwilling to procure and supply additional power to these consumers. For many utilities, state governments cover the difference between utilities' average cost of supply and BPL tariffs as subsidy paid to the utilities (Aklin et al., 2016). Despite this, utilities are unable to recover their full costs owing to two major problems. First, there is metering and billing inefficiency. For example, in the state of Bihar, only 20%–25% of the BPL connection electricity meters are actually read, and only 90% of consumers actually receive a bill, which may result in inaccurate billing and revenue recovery (BERC, 2016). This also has a significant impact on accounting for the government subsidy, which is based on actual energy consumption by the subsidized categories. Second, because of poor-quality electricity supply and service, consumers are likely to be less willing to accept higher tariffs and pay their bills. A survey of about 8,500 Indian households shows that consumers' satisfaction with their electricity supply is highly correlated with hours of electricity supply.[4] Note that these two problems compound one another, resulting in large losses to utilities and a vicious cycle of financial disincentive leading to low-quality supply, low willingness to pay, and low revenue realization (Schnitzer et al., 2014). See Fig. 1 for a summary. As electricity access is extended to additional 46 million, primarily rural households, the vicious cycle is likely to continue.

In fact, this cycle may worsen because most of the newly connected consumers likely will be subsidized. Note that financial disincentive is not the only reason why supply is poor in rural areas, but addressing the financial disincentive is likely to improve the quality of supply for newly connected consumers or rural consumers more broadly. Our hypothesis is that significant efficiency improvement in key appliances used by the rural households could address the utility financial disincentive in the following two ways (Fig. 2). First, super-efficient appliances, while maintaining the service quality, could lower the electricity consumption by rural households significantly, thereby reducing the overall quantum of utility's financial loss and subsidy burden on the state government. Second, super-efficient appliances, owing to their low consumption, would enable battery storage as an affordable strategy for enhancing supply reliability at the household level. Improved reliability would likely increase rural consumers' willingness to pay their bills resulting in better revenue recovery for the utility. Also, utility costs of maintaining reliability (through expensive peak power purchase etc.) go down significantly. State governments or utilities can potentially finance the rural households for purchasing super-efficient appliances and batteries from avoided subsidies/losses. The costs of super-efficient technologies and reliable storage have dropped significantly in recent years, and bulk procurement could reduce these costs further.

The objective of this paper is to conduct detailed techno-economic analysis of this hypothesis and present two case studies from the states of Bihar and UP, where more than 50% of the un-electrified households in India are located. Also, although the paper is focused on India, it would also be applicable to other emerging economies with low electrification rates and unreliable supply. The remainder of the paper is organized as follows. Section 2 gives an overview of the data, assumptions, and methodology. Section 3 shows the key results from our techno-economic analysis. Section 4 presents a case study of reducing subsidy requirements for electricity access through super-efficient

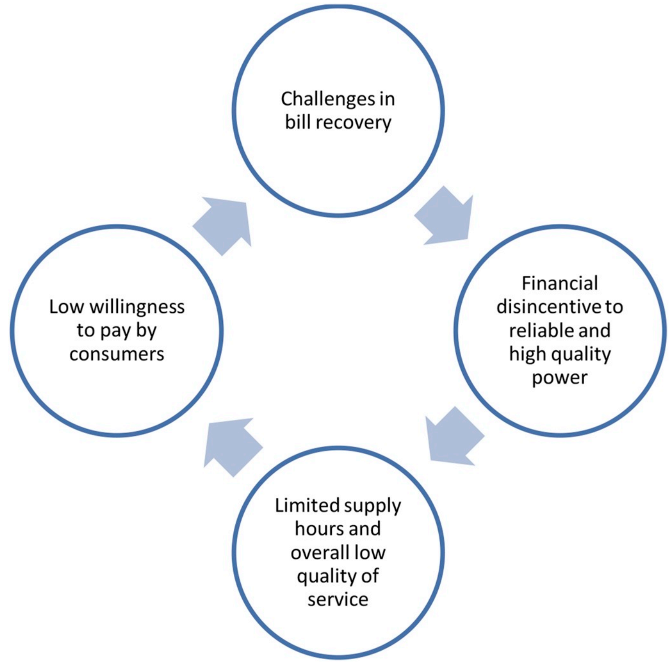


Fig. 1. Cycle of financial disincentive leading to low-quality supply, low willingness to pay, and low revenue realization.

Fig. 2. Two-pronged strategy to break the cycle of low-quality supply and low revenue realization.

[3] We discuss the findings from ESMI in more detail in Appendix A.

[4] Aklin et al. (2016) surveyed 8,568 households in 714 villages in six Indian states: Bihar, Jharkhand, Madhya Pradesh, Odisha, Uttar Pradesh and West Bengal. They found a strong and almost linear correlation between electricity satisfaction and the number of hours of electricity access. More specifically, they find the electricity satisfaction increases by 36% with an increase in the supply hours by 6.5 h per day.

appliances and battery backup in Bihar and UP. Section 5 offers conclusions and policy implications.

2. Data, assumptions, and methods

To analyze performance and cost of super-efficient appliances, we use the data obtained from the Global Lighting and Energy Access Partnership (Global LEAP) awards competition.[5] To estimate retail price of appliances from the manufacturing costs, we use a factor of 1.8 used for two off-grid-focused market-development programs, Lighting Global and Global LEAP. The following subsections describe the two developments in technologies and policy programs.

2.1. Data and assumptions on end-use and storage technologies

Most of the rural households in Bihar and UP use bare minimum appliances. For example, according to Jain et al. (2018), in Bihar, 38% rural households did not have access to electricity while 60% used either only lamps or lamps, TV, and fan. Only 2% of the households owned other heavier appliances such as washing machines and microwaves, air conditioners etc. In UP, about 42% rural households lacked access to electricity while 57% used either only lamps or lamps, TV, and fan. Only 1% of the households used heavier appliances such as washing machine, air conditioners, and microwaves etc. In both states, residential electricity consumption is over 40–50% of the total electricity sales by utilities. In 2018, in Bihar, energy sales to residential consumers were 50% of the total residential sales. Over 60% of the residential electricity consumption is by subsidized consumers consuming less than 100 kWh/month (BERC, 2019). Similarly, in UP, the residential electricity sales were 42% of the total electricity sales in 2018 (UPERC 2019). Therefore, this paper takes into account the key appliances commonly used in the rural households of UP and Bihar (lights, TVs, and fans), set-top boxes which is the dominant way of getting TV content in rural area, and the most commonly used technology for battery backup systems. Below we discuss the technologies and trends that enable deep appliance energy-consumption reductions as well as battery improvements.

Traditional incandescent bulbs are the most inefficient, because 90% of the energy they consume is lost as heat; for example, they consume 60 W to emit 800 lumens [lm], resulting in 13 lm/W. These are still widely used particularly in rural areas (The Economic Times, 2017). Compact fluorescent lamps (CFLs) consume only 10–15 W to produce 800 lm, yielding 53–80 lm/W (Bijli Bijli Bachao, 2016; US DOE, 2016; Phadke et al., 2015). Light-emitting diode (LED) technology has emerged as the most efficient lighting technology. Commercially available LED bulbs consume 8–10 W to produce 800 lumens (80–100 lm/W), and additional efficiency improvements are expected (US DOE, 2016; Phadke et al., 2015; Bijli Bachao, 2015). In March 2017, an average global retail price of 60-W-equivalent LED lamps was about $8.1/klm, or $6.5 for an 800-lm LED bulb (LEDinside, 2017). In India, under the UJALA program, LED bulb prices have dropped by more than 80% since 2015 to Rs 65 per bulb (retail price in November 2016) and Rs 38 (bulk procurement in August 2016), while the retail price of incandescent light bulbs is about Rs 27 per unit (The Economic Times, 2016).

Along with the trend in lighting application, energy-saving LED technologies have already penetrated significantly into mobile device, standalone monitor, laptop, and TV products, on top of the transition to liquid crystal display (LCD) technology which has significantly reduced power requirements compared with cathode ray tube (CRT) TVs. The Global LEAP Awards identified the world's highest-quality, most energy-efficient, and affordable off-grid TVs (Global LEAP, 2016). Based on the findings from the award competition, we estimate that a 23-in, 11-W, LED-backlit LCD TV can be considered to replace a 22-in, 70-W CRT TV. The price of an energy-efficient LED-LCD TV that consumes 11 W in on-mode is about Rs 9,700 (retail) and Rs 5,400 (bulk purchase), while the retail price of a 22-in CRT TV is about Rs 6,800. In most rural areas direct-to-home (DTH, TV content via satellite) is becoming the dominant way of getting TV content (Dasgupta, 2017). DTH requires a set-top box for most existing TVs, and these boxes consume 8–50 W, depending on features (Bijli Bachao, 2015; Park et al., 2016). However, most new TVs come with built-in digital tuners and do not need a separate set-top box to receive TV content via terrestrial signal. Further, some commercially available TVs include tuners that receive content via both satellite and terrestrial signal (Niwa, 2016). TVs with built-in satellite and digital terrestrial tuners do not need a set-top box to receive free-to-air channels, thereby lowering the overall electricity consumption significantly.

Commercially available most-efficient fan technology employs efficiency improvements associated with blade design, motors, drives, and controls and achieves up to a 50% efficiency improvement compared with the commonly used technology (Shah et al., 2015). Using brushless direct current (DC) motors—which employ permanent magnets and are electronically commutated—instead of the typical induction motors can improve fan efficiency by 50%. Improving the design of fan blades can improve efficiency further by 15% (Shah et al., 2015). A super-efficient 48-in ceiling fan consumes 24 W (compared with 70 W for a conventional fan) and is priced at about Rs 2,800 (retail) and Rs. 1,560 (bulk purchase). Similar efficiency gains have been observed in smaller table fans. For example, high-efficiency pedestal fans with 16-in blade diameters consume 10 W instead of 50 W for similarly sized conventional fans.

Commercially available super-efficient appliances of lights, TVs, and fans can reduce the electricity consumption of some commonly used devices by up to 80% (Fig. 3), resulting in significant consumer bill savings. Although they cost more compared with conventional devices, their prices could be reduced below the price of conventional devices through procurement incentives such as bulk procurement programs (Table 1).

The usage of key appliances is an important factor to realistically estimate energy consumption in those appliances. Abhyankar et al. (2017) assumed 5 h, 5 h, and 4 h of daily usage for lights, TVs, and fans, respectively, for assessing the energy and peak impact of appliances in India. TV usage patterns vary by region, sector of use, consumer lifestyle, and power management scheme applied to the system. According to Park et al. (2017), average daily usage of TVs is estimated to range from 3.5 to 6.5 h, e.g., 3.5 h in India. Shah et al. (2015) studied efficiency improvement opportunities for ceiling fans on the global market. Given a lower range (3–5 h per day) and a higher range (10–16 h per day) of use identified by literature review, they assumed 8.7 h on average of use per day. We in this analysis assume that storages are used with super-efficient appliances, potentially leading to reliable electricity service despite unreliable grid supply, and people use 5, 4, and 8 h per day on average for lights, TVs, and fans, respectively. The assumed level of usage and consumption is comparable with that under the circumstance with reliable supply of electricity. We also perform a sensitivity analysis in the range of 3 to 5 h for TVs and 4 to 12 h for fans.

The information on power consumption and usage of appliances enables estimate battery capacity required to support the appliances. Lead-acid batteries are the most commonly used technology for battery backup systems in India, but Li-ion battery technology likely will dominate in the future because of its higher performance and declining cost. Li-ion batteries last much longer than lead-acid batteries do (e.g., more than 2,000 cycles for a Li-ion battery vs. 500–1,000 cycles for a

[5] Since 2013 when the inaugural Global LEAP Awards identified best-in class off-grid televisions and LED lighting, the Global LEAP Awards have held annual competitions, with industry engagement growing with each successive round. Each round of the Awards expanded to include additional off-grid products, including fans, refrigerators and solar water pumps. See details for the Award competitions at https://globalleapawards.org/.

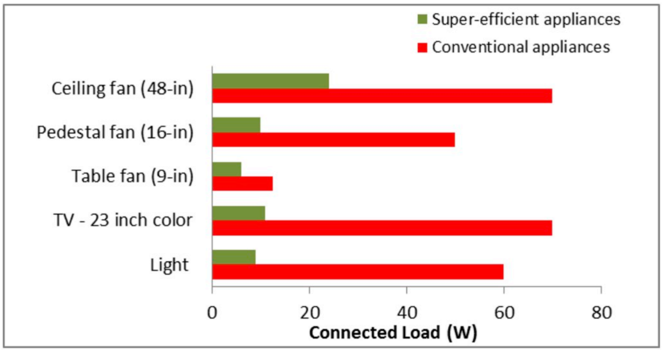


Fig. 3. Load from conventional and super-efficient appliances
Source: authors' work based on Phadke et al. (2015) and Global LEAP (2016).

lead-acid battery), have much higher depths of discharge, and have lower maintenance requirements, and are more environmentally friendly (Gretz, 2016; USAID, 2014; Akhil et al., 2013). Currently, the upfront costs of Li-ion batteries ($150–175/kWh) are only marginally higher than those of the lead-acid batteries ($125–150/kWh), albeit with more than double the battery life. The Li-ion costs have dropped by more than 80% in the last 10 years and are projected to decline by another 30%–50% in the next 5 years (IRENA, 2015; PV Magazine, 2015). Even at current costs, per charge-discharge cycle cost of Li-ion batteries is about 40% lower than the lead-acid batteries.[6] In addition, the use of super-efficient appliances reduces the battery size and cost required for backup power (see Section 3.2).

2.2. Approach to reducing the cost of efficient end-use and storage technologies via bulk procurement

The Unnat Jyoti By Affordable LED's for All (UJALA) program—implemented by Energy Efficiency Services Limited (EESL) to accelerate the adoption of LED bulbs in India—shows how bulk procurement can reduce the cost of efficient technologies. As of February 1, 2017, more than 200 million bulbs had been sold to consumers through this program, and LED prices have dropped by more than 90% since the start of the program. The UJALA program transfers deep reductions in LED prices achieved through bulk procurement directly to consumers, offers on-bill financing to consumers who do not pay the full LED bulb cost up front, and leverages government's brand and bill-collection centers of state distribution utilities to reach consumers. The program involves no direct government subsidy, although EESL used its initial capital to conduct bulk procurement. EESL is implementing a UJALA-type program for super-efficient ceiling fans and is considering a program for super-efficient air conditioners.

This type of program design could be used to reduce the cost of super-efficient devices and battery backup systems further. Based on the information from the Global LEAP Awards TV and fan competitions, bulk discounts of 50%–60% seem available for quantities above 1,000. Similar or much deeper discounts might be available for much larger order sizes. However, note that the appliances considered in this analysis are significantly more capital intensive than LED lamps. Also, these appliances may require repair or maintenance value chains. Therefore, the super-efficient appliance program design needs to be different than that for UJALA. For example, EESL can provide volume or loan guarantees to manufacturers instead of actual procurement of appliances.

[6] Assumptions: Battery life of 1000 cycles for Lead-Acid and 2000 cycles for Li-ion, 1 charge/discharge cycle per day, interest rate of 12%.

2.3. Life-cycle cost and subsidy requirement estimate

For consumers, the cost of electricity service consists of the up-front cost of the equipment (appliances and battery system) and the cost of electricity used by them. We assess how the life-cycle cost (LCC) of electricity service changes as equipment efficiency improves and electricity consumption reduces. Installation and maintenance costs are not considered for the appliances and battery system discussed here.

$$LCC = Equipment\ Cost + \sum_{n=1}^{L} \frac{Operating\ Cost}{(1 + Discount\ Rate)^n}$$

where equipment cost is purchase price, n is the year since purchase, and operating cost is the annual operating cost represented by consumer electricity bill. Operating cost is summed over each year of the appliance lifetime L.

This paper assumes a lifetime of 750 h for incandescent light bulb and 7 years for other equipment, a discount rate of 7%. Based on the existing data from Bihar (NBPDCL, 2016), we assume electricity tariff of Rs 1.78/kWh and electricity subsidy of Rs 3.82/kWh – the total electricity cost is assumed to be Rs 5.6/kWh.

The impact of new household electrification on the state government's subsidy burden, if all households are electrified, is estimated by the following equation:

$$\begin{aligned} &Total\ Subsidy\ Requirement\ for\ New\ Households \\ &= Total\ Number\ of\ subsidized\ households\ (electrified\ and\ yet\ to\ be \\ &\quad electrified)\ x\ Annual\ Electricity\ Consumption \left(\frac{kWh}{yr}\right) x \\ &\quad Subsidy \left(\frac{Rs}{kWh}\right) \end{aligned}$$

If households use super-efficient appliances instead of conventional appliances, their annual electricity consumption would reduce significantly and so would the subsidy requirement. The difference in the subsidy requirement with conventional appliances and that with the super-efficient appliances, gives the net savings in state government's subsidy burden.

The next section estimates the cost of providing a battery backup/super-efficient appliance package through a bulk procurement program.

3. Results: techno-economic analysis of providing a battery backup/super-efficient appliance package through a bulk procurement program like UJALA

In this section, we assess the reduction in electricity consumption and electricity supply costs if the most-efficient commercially available technologies presented in the previous section are deployed in the rural households. We also show how efficient appliances could reduce consumer bills and electricity subsidy requirements, and compare the cost savings with their incremental upfront costs.

3.1. Rationale for including specific appliances in analyzed packages

After lighting, TVs and fans appear to be the most commonly owned appliances in rural Indian households. Income and electricity access appear to be the two key drivers for ownership of TVs and fans (Parikh et al., 2016; Rathi et al., 2012; NSSO, 2012). In this section, we show why we think newly connected rural households will likely own a fan and a TV in addition to lights.

In FY 2009–10, in rural areas, fan ownership was over 20% even in the lowest income decile (measured by the monthly per capita expenditure [MPCE]) and was about 30% in the next decile (NSSO, 2012). However, the penetration of fans is highly correlated to access to electricity. For example, rural fan ownership was over 60% in the state

Table 1
Per-unit price (Rs) of conventional and super-efficient end-use devices.

	Conventional appliances (retail)	Super-efficient appliances (retail)	Super-efficient appliances (wholesale)
Ceiling fan (48-in)	1,279	2,814	1,563
Pedestal fan (16-in)[a]	965	1,072	596
Table fan (9-in)[a]	335	362	201
TV (23-in color)	6,800	9,715	5,397
Light	27	65	38

Source: authors' work based on Phadke et al. (2015), Global LEAP (2015), and internet searches.

[a] Retail prices of the selected super-efficient fans (9-in/16-in) are lower than the retail prices of many conventional/inefficient fans in the same size. Only a few conventional models appear to be similar to or slightly lower than the super-efficient models in purchase price. We here assumed a conservative case that conventional fans are cheaper than super-efficient ones.

of Chhattisgarh that has high levels of electricity access but has very low MPCE levels (Rathi et al., 2012). In urban areas, fan ownership was 66% and 82% in the bottom two income deciles. Hence, it is likely that newly connected urban as well as rural consumers will own fans.

TV is another appliance with rapidly increasing penetration in recent years. In 2009–2010, TV ownership was 10% and 16%, respectively, in the bottom two income deciles in rural areas; in urban areas, TV ownership was 43% and 60% in the bottom two income deciles (NSSO, 2012). One of the major factors for lower TV ownership in rural areas could be lower access to electricity. For example, in the state of Chhattisgarh, more than 70% of rural areas have access to electricity, and the TV ownership rate is more than 40% (NSSO, 2012). This is more than double the rate in Bihar, where only 20% of rural areas have access to electricity, even though Chhattisgarh's MPCE is slightly lower than Bihar's (NSSO, 2012). The economy of Bihar has grown rapidly in the last several years, with the gross state domestic product (GSDP) increasing from $30 billion in 2009 to $90 billion in 2017 (projected). At an MPCE of about Rs 1,000, more than 70% of urban households appeared to own TVs in FY 2010. If the MPCE of Bihar has followed the broad GSDP trend, it is likely to have surpassed Rs 1,000 by 2017. Since 2009–2010, TV prices have dropped by 50% in real terms. As a result, relative to 2009, increased ownership of TVs would be expected now at the same income level. Hence, most newly connected households are likely to buy TVs as well.

Note that the combination of appliances used by BPL and APL houses may vary from those we assess here. But our conclusions are unlikely to differ qualitatively for a different combination of appliances. This is because for all end-uses considered, the reduction in energy consumption due to super-efficient appliances is greater than 70%.

3.2. *Incremental cost and savings due to super-efficient appliances and batteries*

We evaluate two appliance packages. One, which is likely to be relevant for newly connected BPL or Kutir consumers (BPL package), consists of a light, a TV, and a table fan. The other, which is relevant for newly connected APL consumers, consists of two lights, a TV, and a ceiling fan (APL package).

Table 2 summarizes our appliance and battery assumptions and show estimates of the connected load and monthly electricity consumption for the BPL and APL appliance packages with conventional and super-efficient appliances. We assume the battery needs to provide the flexibility of having either alternating current (AC) or DC input as well as output. Most appliances available in the market require an AC input (although TVs and LEDs are inherently DC technologies), and highly efficient appliances that can take a DC input are becoming available, so the ability to provide a DC or AC output will not restrict consumer choice. The ability to have AC or DC input will enable the battery to be charged through the grid or solar panels (see for Figs. 3 and 4 for connected load and monthly electricity consumption per household with conventional and super-efficient appliances).

Fig. 6 shows the upfront consumer costs for conventional and super-efficient appliance packages with and without battery back-up. Based on the information from the Global LEAP Awards, the bulk purchase discount is 56% for a quantity more than 1,000, and we use this factor to calculate wholesale costs. Although the scale of bulk procurement for a program similar to DELP is significantly larger, potentially leading to a greater bulk purchase discount, we use the estimate for quantities more than 1,000 as a conservative assumption for the discount because we do not have data on discounts available at larger scales.

The super-efficient BPL appliance package consisting of a light, a table fan, and a 23-in color TV with 3-h battery backup will cost about Rs 7,400 at the wholesale price, which is only about Rs 300 more than the retail price of conventional appliances without any battery backup (Fig. 7). In addition, the super-efficient BPL package reduces electricity consumption from about 21 kWh/month to about 4 kWh/month (Fig. 5) and will result in avoided utility subsidy of Rs 4,100 over a 7-year lifetime (Fig. 7). The 3-h battery backup also significantly enhances the reliability of the service provided compared with the reliability experienced today.

If financed over the life of these appliances through a program such as utility on-bill financing, the super-efficient BPL package will cost consumers Rs 115/month under a discount rate of 7% (including the cost of battery backup) and will save Rs 92/month (non-discounted Rs 29 as consumer bill savings and Rs 63 as utility subsidy savings) (Fig. 8).

4. Case study: reducing subsidy requirements for electricity access through super-efficient appliances and battery backup in Bihar and Uttar Pradesh

Between Bihar and UP, about 30 million households (over 50% of the total un-electrified households in India) remain to be electrified. In collaboration with GOI, Bihar has developed a 24x7 Power for All plan that proposes electrification of 14 million un-electrified households (urban and rural) by FY 2018–2019. The UP Power for All plan is currently being developed. Such aggressive electrification will likely change the utility cost and sales structure significantly.

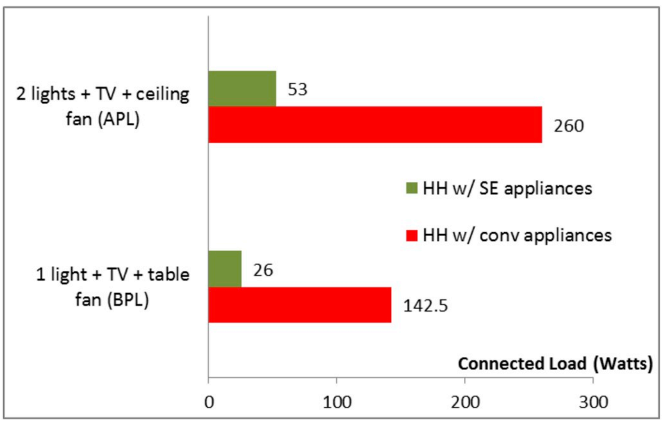
For the last several years, Bihar and UP utilities have been running significant financial losses (8%–10% of revenue) despite significant subsidy support from the state governments (40%–50% of revenue). Costs, especially power-purchase costs, have been rising, and tariff and subsidy increases have been unable to keep up. The residential sector constitutes nearly 40% of energy consumption in Bihar and UP, whereas the total industrial and commercial consumption constitutes about 25%–30%.[7] This leaves the state utilities with very limited options for increasing electricity tariffs and thus revenue. First, the Electricity Act and the National Tariff Policy limit the cross-subsidy by any customer class to 20%. In Bihar and UP, industrial and commercial

[7] This is in sharp contrast to the national average, where residential consumption is about 20% and industrial and commercial consumption is about 45%–50%.

Table 2
Assumptions for battery technical specifications and costs of appliance packages.

Battery	APL Appliance Package	BPL Appliance Package
· Technology: Li-ion · Efficiency: 90% · Depth of discharge: 90% · Cost: Rs 19/Wh · AC-DC conversion efficiency: 90% · Battery capacity required:APL package (conventional 867 Wh, super-efficient 177 Wh)BPL Package (conventional 475 Wh, Super-efficient 87 Wh)	· Two lights · One 23-in TV · One 48-in ceiling fan · Price of conventional appliances package:Rs 8,133 (retail) · Price of super-efficient appliances package:Rs 12,659/7,037 (retail/wholesale	· One light · One 23-in TV · One 9-in table fan · Price of conventional appliances package:Rs 7,162 (retail) · Package of super-efficient appliances:Rs 10,142/5,636 (retail/wholesale)

Note: See section 2.1, Table 1, and Fig. 3 for detailed assumptions and costs of individual appliances. Approximate battery prices for super-efficient appliances for the APL package are about Rs 2,500/1,700 (retail/wholesale) and for the BPL package are about Rs 1,200/850 (retail/wholesale).



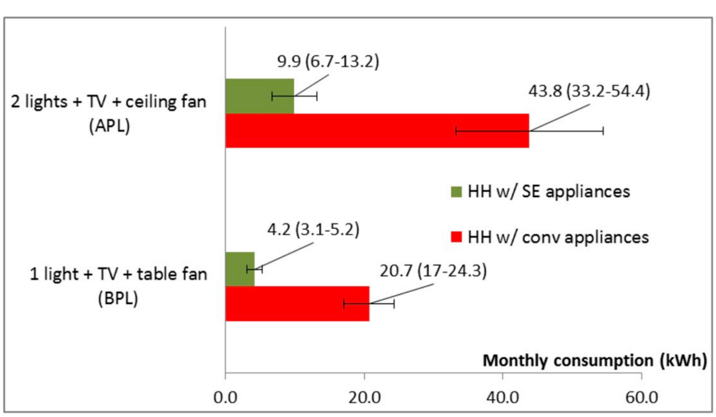
Note: See section 2.1 and Figure 3 for detailed assumptions.

Fig. 4. Connected load per household (HH) with conventional and super-efficient (SE) appliances.

customers are already paying significantly above the average cost of supply. Second, if the tariff is too high, large industrial and commercial customers may leave the utility by opting to generate their own electricity or open access; this has already been observed in certain urban areas in other states. Finally, because of the various governance issues—such as low willingness to pay owing to poor-quality service, metering and billing inefficiency, welfare/development objectives, etc.—the scope for raising residential tariffs is highly restricted.

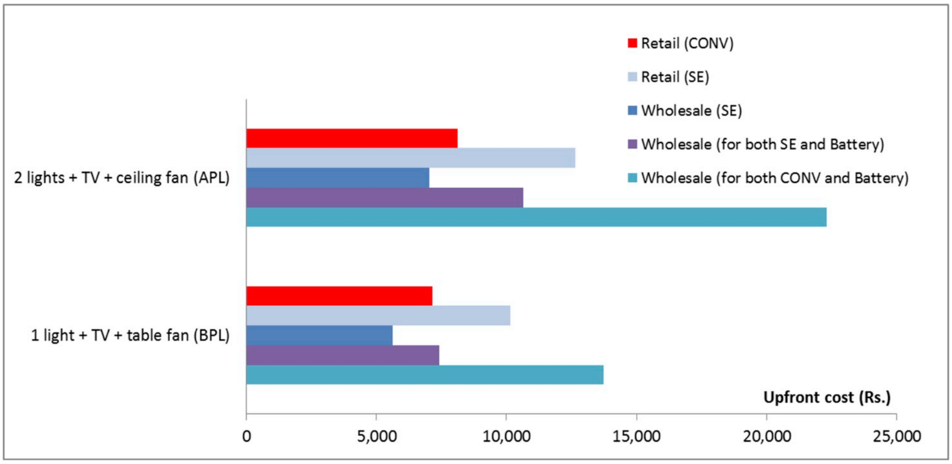
Aggressive electrification means a sharp increase in the number of residential consumers, especially subsidized consumers. For example, utilities in Bihar are targeting extending access to 15 million new households, out of which 5 million households will be in the Kutir Jyoti category and 10 million in the DS1 category (NBPDCL, 2016). For these two categories, tariffs and revenue realization are significantly below the cost of supply and will require significant subsidization (see Figure A3 in Appendix A). Currently, the Bihar state distribution utilities provide power to 3.5 million Kutir Jyoti and 8.5 million DS1 households, requiring a subsidy of about Rs 2,700 Cr/yr, which is about 1.8 times the tariff revenue from these categories (BERC, 2019). Adding 15 million consumers will likely add about Rs 3,400 Cr/year to this subsidy requirement, representing over 30% of the projected annual revenue requirement (ARR) of the utilities in Bihar by FY 2018–2019. In UP, the distribution utilities currently serve about 15 million rural households subsidized at nearly Rs 5,000 Cr/year (UPERC, 2016a; 2016b). If all unelectrified households (15 million remaining) are electrified by FY 2018–2019 (MOP's Power for All goal), 10 million households likely will be added to the subsidized category, increasing the subsidy burden to about Rs 3,380 Cr/yr (about 13% of the projected ARR by FY, 2018–2019). However, if super-efficient appliances are deployed to the new households, the subsidized consumption for providing the same level of service can be reduced by more than 70%—reducing the subsidy burden from Rs 3,400 Cr/year to Rs 760 Cr/yr in Bihar and from Rs 3,380 Cr/yr to Rs 760 Cr/yr in UP (see Table 3).

If subsidized BPL and APL consumers are limiting their consumption to be eligible for the subsidized rates, then the use of super-efficient appliances will enable them to access more electricity services while staying under the limit. Although consumers using additional electricity services while staying under the consumption limit may not reduce subsidized consumption as much, it may increase the willingness to pay for electricity, because consumers are now accessing more services for the same or somewhat-reduced electricity bill. This may be true especially if super-efficient appliances are provided in conjunction with



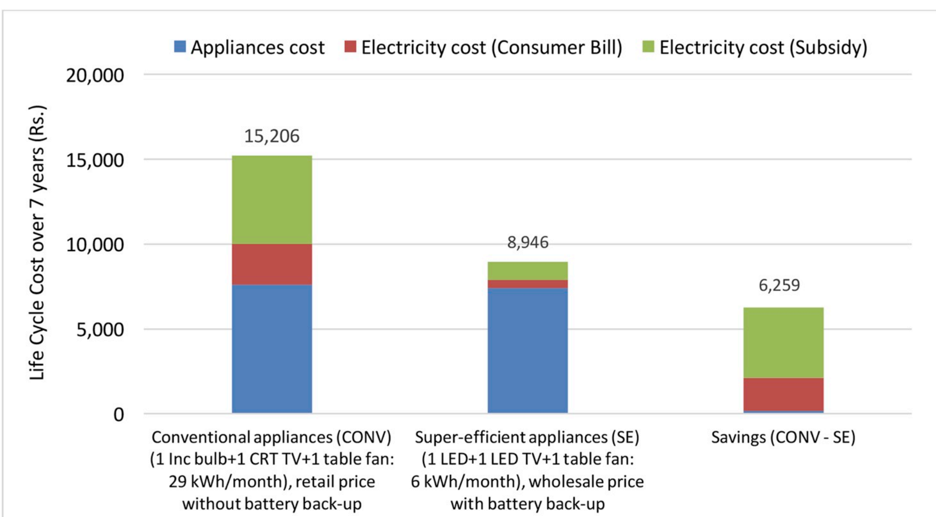
Assumptions on hours of use per day: (Light, TV, Fan) = min (5 h, 3 h, 4 h) / average (5 h, 4 h, 8 h) / max (5 h, 5 h, 12 h).

Fig. 5. Monthly electricity consumption per household (HH) with conventional and super-efficient (SE) appliances Assumptions on hours of use per day: (Light, TV, Fan) = min (5 h, 3 h, 4 h)/average (5 h,4 h, 8 h)/max (5 h, 5 h, 12 h).



SE: super-efficient appliances package; CONV: conventional appliances package

Fig. 6. Upfront consumer costs for conventional and super-efficient appliance packages with and without battery back-up SE: super-efficient appliances package; CONV: conventional appliances package.

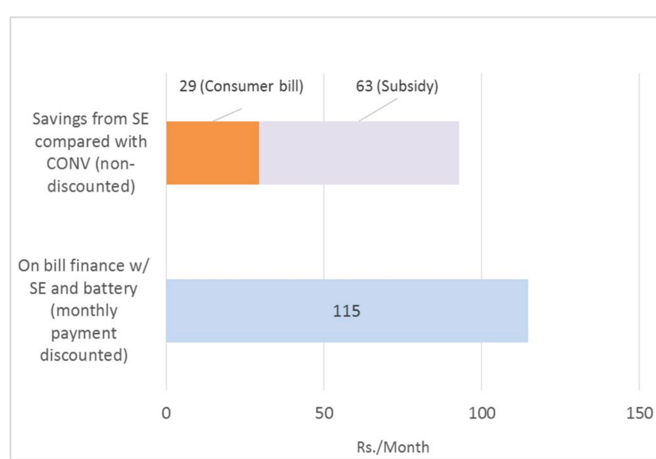


Assumptions: electricity subsidy: Rs 3.82/kWh; electricity tariff: Rs 1.78/kWh; lifetime: 7 years, except incandescent light bulb (750 h); annual increase rate of electricity price: 6%; discount rate: 7%, based on data on tariffs and subsidy in Bihar NBPDCL (2016).

Fig. 7. Lifecycle costs of BPL package with conventional (no battery backup) versus super-efficient appliances (with battery backup). Assumptions: electricity subsidy: Rs 3.82/kWh; electricity tariff: Rs1.78/kWh; lifetime: 7 years, except incandescent light bulb (750 h); annual increase rate of electricity price: 6%; discount rate: 7%, based on data on tariffs and subsidy in Bihar NBPDCL (2016).

battery backup that significantly increases the reliability of electricity services.

One of the common concerns when assessing the cost-benefit of appliance efficiency improvement is the rebound effect.[8] If the rebound effect is large, the energy consumption and thus, subsidy requirement, may not reduce significantly. Note that most APL rural consumers in UP and Bihar are eligible for subsidized rates irrespective of their monthly energy consumption. Also, based on the data from Bihar, for more than 70% of the rural consumers (APL and BPL), meters are not regularly read by the utility – implying that their electricity bills do not reflect their actual energy consumption. Hence it is unlikely that most rural consumers are limiting their consumption to be eligible for subsidized rates. Also, due to their highly subsidized tariffs, for an individual consumer, the difference in the monthly electricity bill of efficient



Assumptions: 7-year financing and 7% discount rate.

Fig. 8. Monthly savings from BPL package of super-efficient appliances compared with conventional appliances and cost of on-bill financing with bulk purchase of super-efficient appliances plus battery backup Assumptions: 7-year financing and 7% discount rate.

[8] Typically, rebound effect is classified into two categories – (a) direct rebound effect (increase in energy use as a result of effective increase in consumers' disposable income because of increased energy efficiency) and, (b) indirect rebound effect (increase in the consumption of other commodities resulting from the reduction in energy expenditures).

Table 3
Impact of new household electrification on the subsidy burden in UP and Bihar.

	UP		Bihar	
	Conventional Appliances	Super-EE appliances	Conventional Appliances	Super-EE appliances
Number of households to be electrified millions	10		DS 1: 10, Kutir: 5	
Average electricity tariff of rural households (DS1 or Kutir Category) Rs/kWh	1.67		DS 1: 2.4, Kutir: 1.8	
Average subsidy requirement for the DS1 or Kutir Category Rs/kWh	4.7		DS 1: 3.22, Kutir: 3.84	
Average monthly energy consumption kWh/month	60	13	DS 1: 70 Kutir: 30	DS 1: 16 Kutir: 6
Total subsidy requirement if new households are electrified Rs Cr/yr	~3,380	~730	~3,400	~760

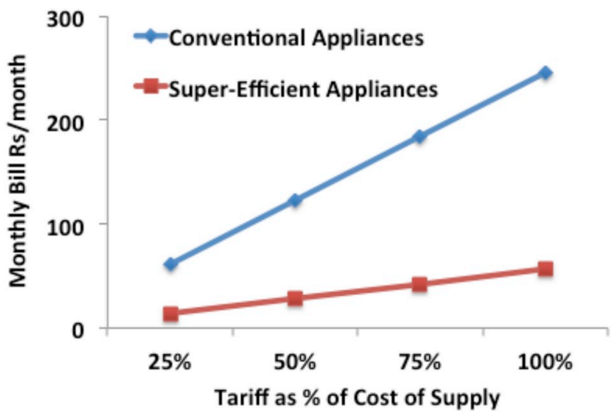


Fig. 9. Monthly bill for newly electrified households in Bihar using conventional and super-efficient appliances for multiple tariff levels (as percentage of cost of supply).

appliances and conventional appliances would be small (Fig. 9). This leads us to believe that the rebound effect due to efficient appliances will be very small in Bihar and UP, especially among rural consumers. Additional empirical assessment is required on this topic in order to more precisely estimate the reduction in subsidy requirements considering the potential rebound effect.

With super-efficient appliances, consumers' monthly electricity bill can drop by as much as 80%, from about Rs 70 to Rs 15 per month (for consumers whose bills are read). Even if these consumers are charged the full cost of supply, their electricity bills will not be higher than Rs 40/month, which is still lower than the monthly bill with subsidized tariffs using conventional appliances (Fig. 9). If the consumer monthly electricity bill does not change because its consumption is not read by the utility, their effective tariff will increase beyond the cost of supply leading to elimination of subsidy.

Based on the number of new connections planned in Bihar and UP, Table 4 shows the total annualized upfront capital requirement of about Rs 8,600 Cr/yr for such a bulk procurement program assuming the devices are financed over 3 years. Table 4 also shows the reduced government subsidy requirement of about Rs 15,000 Cr/yr. Thus the program cost (including appliances and batteries) is significantly lower than the reduced subsidy requirement—that is, the program could be financed through avoided government subsidies.

It appears that—if newly connected consumers are provided a package of super-efficient appliances with a battery backup—their electricity consumption, bills, and subsidy requirements could decrease substantially. In addition, consumers would get significantly more reliable electricity service, potentially increasing their willingness to pay for electricity. Given these potential benefits to consumers and utilities, there appears to be a strong rationale for a government intervention supporting the deployment of packages of super-efficient appliances with battery backup.

The broad contours of a super-efficient appliance plus storage program for Bihar and UP may include the following:

(a) **Bulk procurement for reducing system cost**: A program similar to UJALA could transfer deep bulk-procurement discounts on super-efficient appliances and battery backup to consumers. However, the entities conducting the bulk procurement take on uptake and repayment risks. Uptake risk could be significant because of the high first cost of the battery backup and super-efficient appliances relative to the typical cash available to the rural poor. If these products are financed on a monthly payment plan to address the high first cost, the repayment risk could be significant or unknown.

(b) **Pay-as-you-go systems to address uptake and repayment risk**: There is some evidence that pay-as-you-go (PayGo) technology, which enables consumers to pay for a device easily (through mobile payments) as they use it and allows the device to be turned off in case of a default, reduces uptake and repayment risk. Uptake risk is reduced by enabling monthly payments. PayGo technology vendors claim that sales go up 3–5 times while the payment default rate is less than 5%. If the device is turned off owing to a payment default, consumers cannot easily bypass the PayGo technology to turn the device on—in contrast to smart meters, which can be bypassed relatively easily—because circuitry in the microprocessor that drives the device is turned off. PayGo technology offers varying degrees of tamper proofing. PayGo also reduces the transaction cost of providing financing and builds confidence in the technology, because the technology vendor is providing the financing. Such systems are becoming increasingly popular for providing off-grid energy access solutions in Africa as well as other developing countries. Note that the default risk can be priced in by not passing on all the savings due to bulk procurement to consumers. For example, if the expected default risk is 10%, the products can be priced 10% higher compared with their prices under an assumption of no defaults.

5. Conclusion and policy implications

In India, providing access to reliable, financially sustainable electricity services for all is one of the toughest challenges before the power sector. Major progress is being made to extend the grid to millions of un-electrified households. However, these rural households may not receive reliable electricity service, because utilities typically lose money for providing such service. Currently, most rural households pay a highly subsidized tariff, especially in states like UP and Bihar where most un-electrified households exist. Given the potentially limited value of grid extension to these consumers due to unreliable supply, the grid infrastructure may be used for other purposes, leading to its deterioration. However, deep cost reductions for super-efficient appliances and Li-ion batteries, proven additional cost-reduction potential through use of a bulk procurement program, and development of PayGo systems to reduce uptake and repayment risk create a large opportunity to address India's electricity-access challenge.

We find that super-efficient appliances can reduce the consumption of a rural household by up to 80% while providing the same level of electricity services. This may significantly reduce the financial burden on utilities and state governments of providing electricity access. Customer-side storage—the size and cost of which can be reduced

Table 4
Annualized upfront capital requirement and reduction in government subsidy in UP and Bihar owing to use of super-efficient appliances.

	New Connections Planned (millions)	Super-Efficient Appliances Only	
		Annualized cost of upfront investment (Rs Cr/yr)	Reduction in government subsidy (Rs Cr/yr)
UP	15	4,582	10,500
Bihar	14	4,050	4,700
Total (UP + Bihar)	30	8,632	15,200

Totals may not match due to rounding.

dramatically if coupled with super-efficient appliances—can provide the much-needed reliable electricity service despite unreliable grid supply, likely increasing consumer willingness to pay for electricity and thus reducing overall utility losses.

Bulk procurement programs similar to UJALA LED program could enable deep reductions in super-efficient appliance prices, and such appliances could be provided at similar or lower cost compared with conventional appliances. Uptake and repayment risk could be reduced via PayGo technology (or any prepaid technology), which enables consumers to make monthly mobile payments as they use the appliance and allows the appliance to be turned off in case of a default. Note that super-efficient appliances are significantly more capital intensive than LED lamps. Therefore, the appliance program needs to be designed differently. For example, EESL/Central government can offer volume or loan guarantees to manufacturers instead of actual procurement.

If successfully deployed, a program based on super-efficient appliances, battery backup, and bulk procurement could address the cycle of financial disincentive leading to low-quality electricity supply, low willingness to pay, and low revenue realization—thus contributing significantly to a financially sustainable power sector.

The analysis results suggest the specific policy and programmatic actions for large-scale deployment of the super-efficient appliance program in India. First, in order to gain insights on the key hypotheses presented in this paper and develop technology confidence, the immediate next step is conducting several pilots spanning multiple regions. The pilots would help assess the real-world performance of the super-efficient appliances, battery technologies, and prepaid PAYGO systems. They would also develop insights on the key questions on consumer's willingness-to-pay for enhanced reliability, willingness of the utilities to undertake such programs for enhancing financial viability etc. Multiple stakeholders such as academic institutes, utilities, regulators, local civil society groups, and bulk procurement agencies such as EESL need to partner in running these pilots. GOI has set ambitious targets for building affordable housing in the rural and urban areas. Such housing projects could be potential candidates for large-scale pilots, where in partnership with the local utilities, super-efficient appliances and battery storage could be offered as default installations in them. Second, leveraging the previous experience on running successful bulk procurement programs for LEDs (UJALA) and room ACs, EESL should run a bulk procurement program for the super-efficient appliances and batteries in order to lower the upfront costs. Utilities could potentially facilitate the sale of these appliances to final consumers and offer on-bill financing for the efficient appliances and batteries. Alternatively, the state governments could finance the purchase of appliances (or at least the incremental cost over conventional appliances) through avoided subsidy payments. GOI has been offering significant capital subsidies to utilities for the rural electrification program; part of those subsidies could also be diverted to the purchase/financing of this program. Third, deep reduction in the energy consumption offers an opportunity to increase the electricity tariffs while still lowering the monthly bills. However, that would be applicable only to the program participants i.e. consumers who use super-efficient appliances. Therefore, if regulators wish to increase the tariffs of the rural household consumers, they will have to set different tariffs for program participants and non-participants. Also, per India's national tariff policy, electricity tariffs cannot be raised beyond 20% of the average cost of supply, which could be much lower than the true cost of supply in the remote rural areas due to long distribution networks; tariff increase may not be enough to make a dent in the utility financial disincentive.

While this paper suggests to leverage the experiences on running bulk procurement programs for LEDs, super-efficient appliances are significantly more capital intensive than LED lamps. Therefore, the appliance program needs to be designed differently. There needs future research ensuring reliable electricity access for productive appliances such as refrigeration, motors, pumps etc., which are crucial for enhancing the overall economic activity in the rural areas. Also, significant additional work needs to happen in the potential solution area of creating electricity service based tariffs rather than energy consumption based tariffs.

Acknowledgement

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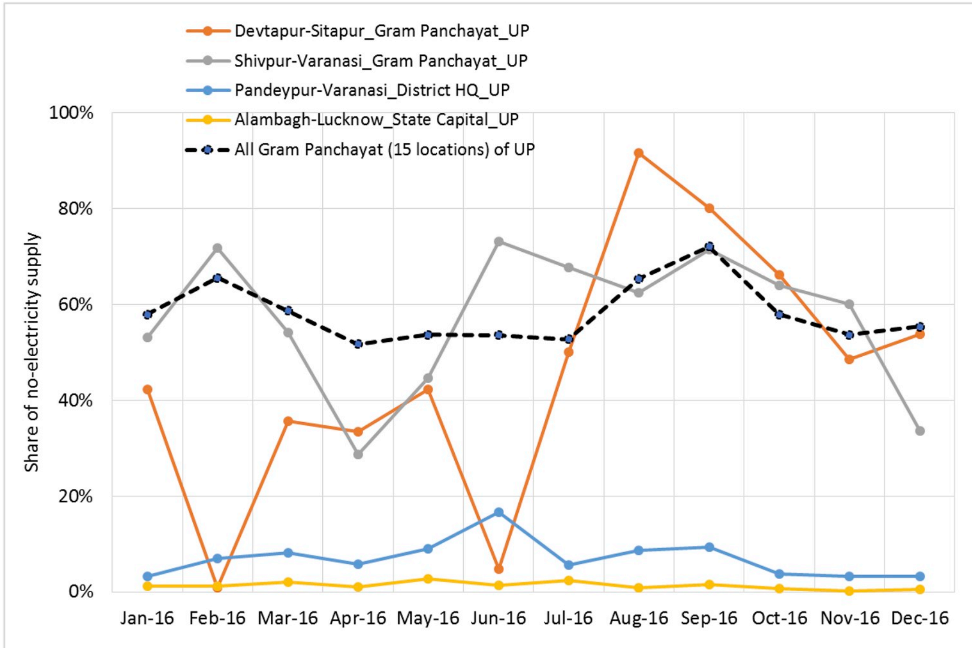
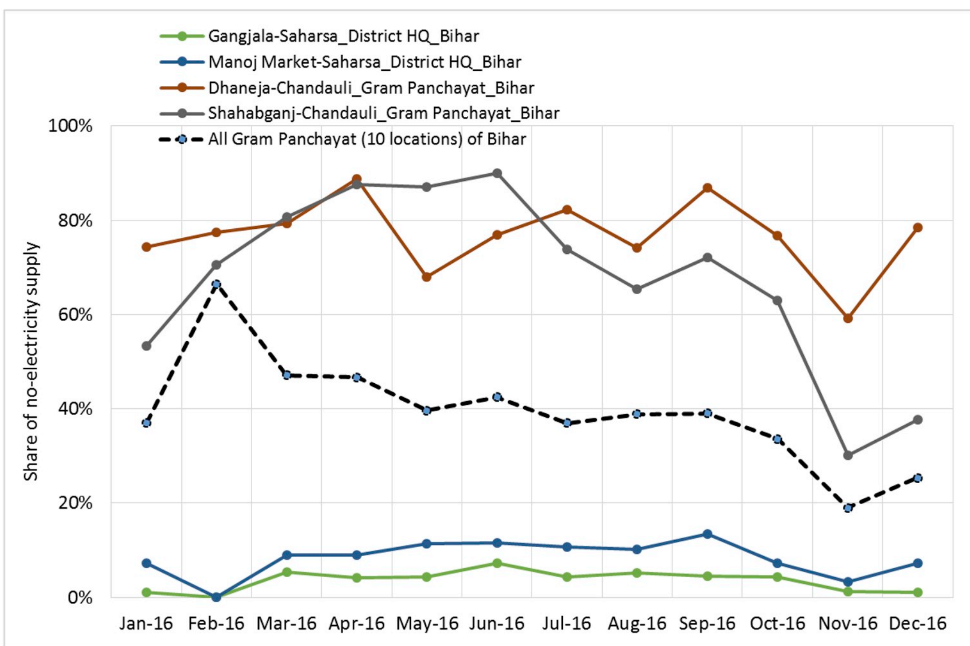
Appendix A. Electricity supply monitoring results in India

Electrification, or providing an electricity connection, does not necessarily mean reliable electricity access for households. Currently, electricity supply is highly unreliable for most rural consumers. The Electricity Supply Monitoring Initiative (ESMI) by Prayas Energy Group has been monitoring hourly power supply quality since 2013 across India—covering more than 50 districts and 350 locations as of April 2017—and is finding significant power-quality issues, especially in rural areas, despite the significant increase in power availability. More specifically, ESMI data shows that rural areas in several states continue to face regular power-cuts that last for several hours, while urban areas receive reliable power supply during the same time. For example, from January to December 2016, only 14% on average (ranging from 6% to 22%) of 28–45 rural locations monitored received their entire 6 h [h] of evening (5–11 PM) supply, compared with 61% on average (ranging from 32% to 85%) of mega cities (based on authors' calculation using data from (Prayas, 2016). Figure A1 shows the average percentage of evening time without electricity supply in selected villages and of all rural villages monitored in UP and Bihar. There was no evening electricity supply in the rural villages monitored for more than 58% (UP) and 39% (Bihar) of the time, on average, during all of 2016 (see black dash lines in Figure A1). Note that the major cities in Bihar and UP and had significantly more reliable supply than in that in rural areas. For example, in the state capital city of Lucknow, share of no electricity supply hours was less than 5%.



(a) Uttar Pradesh (UP)



(b) Bihar

Fig. A1. Average percentage of evening (5–11 PM) time with no electricity supply in monitored UP and Bihar villages, January–December 2016
Source: Authors' work based on Prayas (2016). The y-axis represents the monthly average share of no electricity supply in locations monitored every month. The number of locations monitored varies by month.

Over the last 3 years, the Central Electricity Authority (CEA) of India reported a significant increase in the available generation capacity and a steady decline in the reported peak power deficit at the national level and in most states, including UP and Bihar (Figure A2). For example, from 2012–2013 to 2016–2017, the peak demand met by utilities nationally increased by about 50 GW, whereas the thermal generation capacity increased by more than 100 GW (CEA, 2014–2016). In fiscal year (FY) 2016–2017, India's total peak load was about 160 GW, with a total installed capacity of about 315 GW. Further, there appears to be surplus power available in the day-ahead electricity markets—such as the India Energy Exchange (IEX) and Power Exchange (PX)—at relatively low prices (see, for example, the MOP data at http://www.vidyutpravah.in/). Therefore, it appears that generation availability is not the main constraint on providing reliable supply in rural areas.

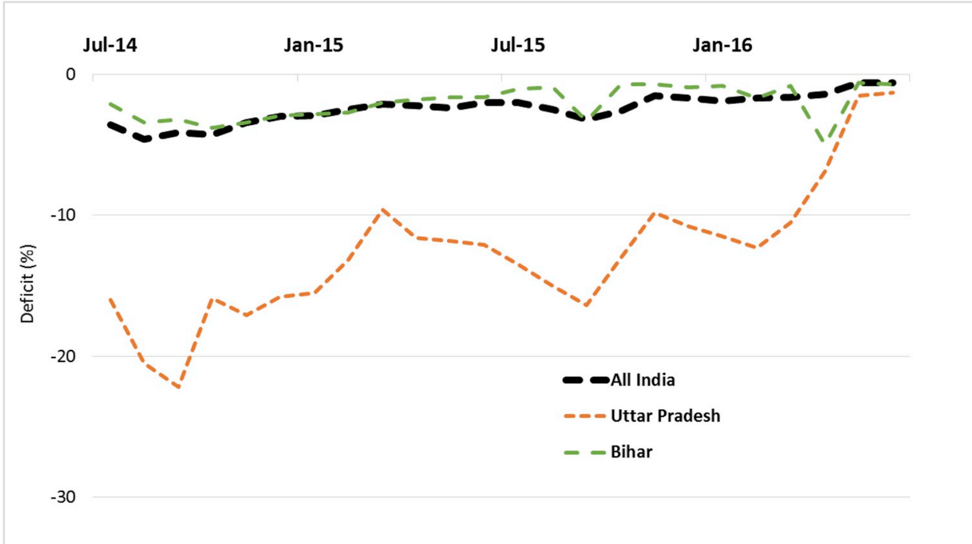


Fig. A2. Monthly power deficit in India, Bihar, and UP (July 2014–June 2016)
Source: Authors' estimate based on CEA (2014–2016)

One of the main reasons for unreliable supply is the financial disincentive faced by utilities for providing power to rural consumers. Typically, average revenue collected from rural consumers (especially BPL connections) is significantly below utilities' cost of supply, making utilities unwilling to procure and supply additional power to these consumers even though surplus power seems to be available. For example, Figure A3 shows the average tariff, cost of supply, and required subsidy for subsidized residential consumers in Bihar for the fiscal year (FY) 2016–17. These numbers are for North Bihar Power Distribution Company Limited; numbers for the other distribution utility in the state, South Bihar Power Distribution Company Limited, are similar. Figure A4 shows the average tariff, cost of supply, and required subsidy for subsidized residential consumers in UP for FY 2016–17. Most of the subsidy is applicable only to rural households, nearly 80% of which are not metered; they pay a fixed monthly bill based on their connected load. Non-rural BPL consumers with monthly consumption less than 150 kWh/month pay a reduced tariff, but they do not receive a direct tariff subsidy from the state government.

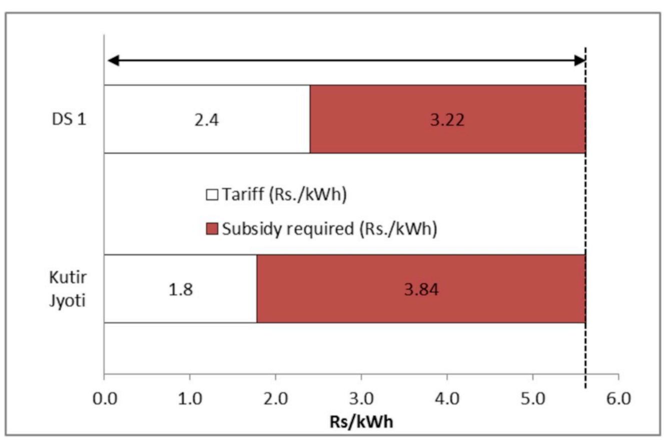


Fig. A3. Electricity cost of supply, tariff, and subsidy in Bihar for FY 2016-17
Source: Authors' work based on BERC (2016, 2017)
Notes: BPL household connections, known as Kutir connections, have consumption limits of 60 W of connected load and 30 kWh/month. The DS1 category includes other subsidized households, with consumption limits 100 W of connected load and 75 kWh/month.

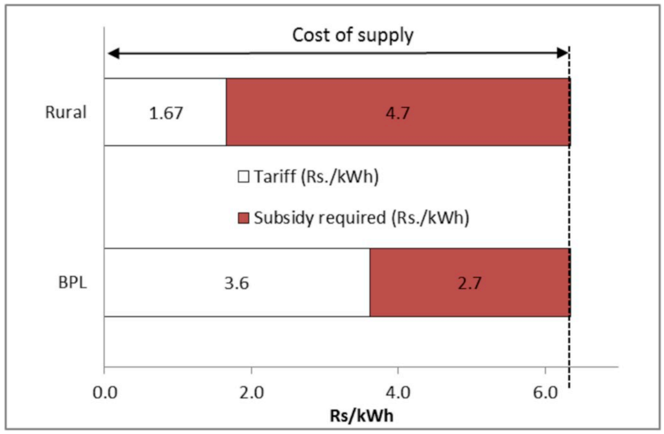


Fig. A4. Electricity cost of supply, tariff, and subsidy in UP for FY 2016-17
Source: Authors' work based on UPERC (2016a, 2016b)

Given the large difference between average tariffs and costs of supply, the state government subsidy support in UP and Bihar is significant. For example, in FY 2015–2016, the UP state government paid a total subsidy of Rs 8,500 Cr to the distribution utilities (28% of their sales revenue), most of which was for rural households (UPERC, 2016b). In the same year, Bihar's government paid a total subsidy of Rs 4,390 Cr to the distribution utilities (75% of their sales revenue), most of which was for Kutir Jyoti and DS1 residential consumers (BERC, 2016; UPERC, 2016b).

Although the average tariffs for subsidized consumers are low, utilities cannot recover those in full owing to two major problems. First, there is metering and billing inefficiency. For example, in Bihar, only 20%–25% of the Kutir and DS1 meters are actually read, and only 90% of consumers actually receive a bill, which may result in inaccurate billing and revenue recovery (BERC, 2016). This also has a significant impact on accounting for the government subsidy, which is based on actual energy consumption by the subsidized categories. Second, because of poor-quality supply and service, consumers are likely to be less willing to accept higher tariffs and pay their bills. A survey of about 8,500 Indian households shows that consumers' satisfaction with their electricity supply is highly correlated with hours of electricity supply (PFC, 2017).[9]

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