Evidence-based Cooling Strategies for a Warming World: Assessing Supply and Demand Conditions in India's Ceiling Fan Market

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Abstract

As global temperatures rise, extreme heat poses a particular risk for households with limited access to cooling. Improving access to sustainable and affordable cooling services has become a global priority. We assess the supply and demand conditions for super-efficient fans in India, focusing in particular on harder-to-access markets where a majority of India's poorest households live. We first assess the real-world performance of ceiling fans in a small-scale technology trial. The super-efficient fans perform well in settings characterized by frequent supply interruptions and voltage fluctuations. Efficient fans use a third of the energy consumed by standard fans. We use field trial data to calibrate estimates of the benefits that accrue when an efficient fan displaces a standard fan. From a social perspective, a discounted sum of benefits easily exceeds the additional technology costs. However, from the perspective of a low income household paying a subsidized electricity price, discounted electricity bill savings may not offset the additional investment cost. We conduct an experimental sales trial to assess the demand for energy-efficient fans at different price points in a real-world transaction setting. Less than 3 percent of low income households purchase the fan at the current procurement price ($30 USD). However, at subsidy levels that can be easily rationalized on the basis of benefits that households do not capture, adoption rates exceed 90 percent.

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1 Introduction

More than 320 million people in India are at high risk from extreme heat (Sustainable Energy for All 2022). Rising temperatures pose a particular risk for vulnerable populations with limited access to cooling technologies. India faces the formidable challenge of helping at-risk households adapt to hotter temperatures, while at the same time reducing the local air pollution and greenhouse gas emissions generated by increased electricity production and managing the impacts of increased electricity demand on power system infrastructure.[1]

To address this challenge, the Indian Ministry of Environment, Forests and Climate Change recently launched the India Cooling Action Plan (ICAP). The stated goal of ICAP is to "provide sustainable cooling and thermal comfort for all while securing environmental and socio-economic benefits for the society".[2] Improving access to – and accelerating the adoption of- more efficient cooling technologies is one promising path to this goal.

Ceiling fans are, by far, the most common space cooling appliance used by Indian households. Ceiling fan sales exceeds 60 million annually. This demand is expected to increase rapidly in the coming years as purchasing power increases and temperatures rise. If this increase in demand for space cooling is met using the fans that currently dominate the Indian residential market, the impact on electricity demand will be large. These standard fans use 65-75W induction motors. Super-efficient Brushless Direct Current (BLDC) fans that consume only 28-35W are also available in urban markets. These energy savings notwithstanding, the market penetration of efficient BLDC fans remains stubbornly low.[3]

This study provides a first-of-its kind- assessment of the demand potential for BLDC fans in rural and peri-urban market settings where access to sustainable cooling solutions is limited. We begin with a small-scale technology trial that measures the performance of BLDC fans in set-

1. Electricity demand has been surging during extreme heat events, triggering cascading outages across the country (Kay 2022).

2. This quote was taken from a press release found here: https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1568328. (Ministry of Environment, Forest and Climate Change 2019).

3. Of the 90 per cent of Indian households who use ceiling fans, it is estimated that less than 3 percent use efficient fans (Agrawal et al. 2020).

tings characterized by frequent power outages and low voltage events. Prior research (e.g. Shah et al. 2015; Phadke, Park, and Abhyankar 2019) has relied on technology performance specifications provided by manufacturers and optimistic assumptions about utilization rates to assess the market potential for BLDC fans. One advantage of our approach is that our analysis uses data we collected from representative households on relative fan performance and utilization rates.

The technology trial involved replacing households' standard fans with BLDC fans. We find that BLDC fans use 67-83% less electricity (as compared to the control group that did not get a fan replacement). Anecdotally, we observe a 17 percent increase in average utilization rates among households who received a BLDC fan.

We use these field-based measurements to assess the potential benefits of displacing a standard fan with an an energy-efficient BLDC fan. We compare the estimated present discounted value of future benefits against the efficiency premium (i.e. the difference between the cost of purchasing a standard fan and the higher cost of an efficient BLDC fan). If we account for all of the social benefits, including reduced electricity generation and supply costs, reduced air quality impacts, and avoided climate impacts, present value discounted social benefits easily offset the efficiency premium across a range of assumed investment time horizons, utilization rates, etc. From the perspective of a distribution company selling electricity to low-income households at a subsidized rate, the present value of the reductions in future electricity consumption subsidy obligations exceed the efficiency premium. However, from the perspective of a low-income household paying subsidized electricity rates, the discounted present value of electricity bill savings need not offset the upfront efficiency premium.

Our stylized model of the ceiling fan investment decision suggests that households paying subsidized electricity rates will generally find that BLDC investment benefits do not offset the cost. To evaluate household fan choices in a real-world setting, we implement a randomized sales trial. We focus on rural and peri-urban areas of Bihar where, prior to our intervention, energy-efficient fans were unavailable.

Our primary objective is to understand how consumer demand for efficient fans varies with the efficiency price premium. We assess household demand for BLDC fans across a range of purchase prices using an incentive-compatible demand elicitation mechanism in a real transaction setting. We are also interested in evaluating the extent to which local warranty support increased BLDC fan adoption. For a subset of households in the trial, we augmented the standard manufacturer's warranty with a local warranty supported by local shop owners.

Consistent with the predictions of our investment model, demand for BLDC fans at the current market price is very low (less than 3 percent). However, adoption rates increase significantly at lower BLDC fan prices. When we reduce the BLDC fan price by INR 1000, fan adoption exceeds 75 percent. To put this subsidy into context, our conservative estimates of the future electricity consumption subsidy savings that accrue when a BPL household chooses a BLDC fan over a standard fan exceed INR 2000. Whereas price reductions have large effects on adoption rates, we do not see a significant increase in adoption rates among households who were offered the local warranty.

Finally, our research design lays the foundation for a promising partnership concept between India's largest energy service company, Energy Efficiency Services Limited (EESL), and a well-established network of women's self-help groups in Bihar (JEEViKA). We worked with JEEViKA to provide training and support for a sample of women who own and operate local shops. Participants acquired the skills they needed to procure fans from EESL and sell these fans in their shops which serve hard-to-reach markets. If BLDC fan prices can be brought down, this partnership model could be scaled up to distribute, market, and sell efficient fans across thousands of local markets.

This report provides more details about the research design, implementation, and empirical findings. Section 1 provides some background and context. Section 2 summarizes the technology trial. Section 3 uses primary and secondary data to calibrate a basic cost-benefit analysis for BLDC fan investments. Section 4 provides describes the field experiment in detail. Section 5 summarizes the empirical findings. Section 6 concludes.

2 Energy Access and Energy Efficiency in India

The point of departure for this research is the hypothesis that electricity price subsidies for low income households will lead to under-investment in energy efficiency. Fans are long-lived investments. Every time a household chooses a standard IM fan over a BLDC fan, inefficiency attributes are locked in for decades to come. To put this line of empirical inquiry into context, we provide a brief overview of electricity price subsidies in India. We then introduce an unintended consequences of these subsidies: under-investment in energy efficiency.

2.1 Electricity subsidies for low-income households in India

Affordable access to energy services is broadly viewed as a necessary input into poverty eradication and accelerated economic growth. It is estimated that almost 98% of Indian households now have access to grid electricity (Agrawal et al. 2020). In order to achieve this level of grid access, electricity prices have been heavily subsidized for low income households.

These large electricity subsidies, together with some tolerance for non-payment, have played a large role in ensuring that electricity is affordable and accessible to all households. However, this regime is widely viewed as unsustainable (IISD, 2020). Direct tariff subsidies from state governments amounted to INR 110,391 crore (USD 15 billion) in 2019 (PFC, 2020). Cross-subsidies add another INR 75,027 crore (USD 10.2 billion) (IISD, 2020). In most states, distribution company (DISCOM) revenues do not cover the costs of supply. Unrecovered DISCOM costs are only partly remunerated by transfers from state governments.

Our research project was conducted in Southern Bihar, India. The average cost incurred by the Southern Bihar DISCOM per kWh procured and delivered to a customer is INR 7.44 in 2021-2022. Low-income consumers who fall below the poverty line pay a highly subsidized electricity price. Unmetered customers pay a volumetric price of 0. Metered BPL customers pay a tiered volumetric price that increases with cumulative consumption over the billing period. These tiered prices range between INR 2 - 3.15 per kWh. Collection efficiency across the Southern Bihar service territory has been estimated at 74% . In sum, whereas the DISCOM incurs a cost of INR 7.44 per kWh delivered to a BPL customer, they recover less than INR 2 per kWh on average from households.

The prior literature has identified some unfortunate and unintended consequences of electricity subsidies. If distribution companies lose money when they serve low income households, they may restrict hours of supply and/or under-invest in reliability in order to remain solvent (McCrae 2015), (Burgess et al. 2020)). Poor power quality undermines consumers' willingness to pay, perpetuating a vicious cycle of under-investment, neglect, and insolvency. Fowlie and Meeks (2021) argue that electricity subsidies can also lead to under-investment in demand-side energy efficiency. Because households incur only a fraction of the costs of consuming energy, they realize only a fraction of the benefits from using energy more efficiently.

2.2 Energy subsidies and energy efficiency

Electricity price subsidies notwithstanding, India has made some encouraging progress with respect to accelerating the adoption of energy efficient household appliances in recent years. An approach developed by state-owned Energy Efficiency Services Limited (EESL) leverages India's massive purchasing power and industry competition through a bulk procurement process to significantly reduce appliance prices.

EESL's most successful program has been the Unnat Jyoti by Affordable LED for All (UJALA) program. Since the program launched in 2015, the retail price of LED bulbs has been reduced from UNR 300-350 to INR 40. Over 370 million LED bulbs have been distributed across India. And UJALA has helped increase domestic manufacturing of LED bulbs from 100,000 to 40 million per month. Given the success of UJALA, EESL has been working to extend the scope of this bulk procurement and mass marketing approach to other appliances, including ceiling fans. The ceiling fan program has proven to be more difficult because fans are more complex and more expensive. A recent report identifies several challenges (Aggarwal and Agrawal 2022):

- **High costs:** In low income areas, demand for BLDC fans at current prices is expected to be very limited.

- **"Last mile" supply chain challenges**: Sales and marketing of fans is more complex. requiring more technical knowledge, installation support, repair and maintenance support. These services can be costly to extend to markets outside urban centers.
- **Information:** Lack of awareness about the benefits of BLDC fans and warranty support programs.
- **Limited access to credit:** Lack of flexible financing and purchase options will likely limit demand for efficient fans.

EESL has demonstrated core competencies in bulk appliance procurement and mass market distribution. However, it has had limited impacts in peri-urban and rural markets where demand for efficient appliances is perceived to be low and the costs of building supply chains is likely to be high (**prayas**).

With these limitations in mind, we developed a partnership with a well-established network of village organizations in rural and peri-urban areas of Bihar. JEEViKA supports livelihood opportunities for low income women across the State of Bihar. As part of this work, JEEViKA supports female entrepreneurs operating small electronics shops serving local, often remote, markets. Historically, these shops have had limited inventory: small solar lamps, flashlights, light bulbs. We posit that, with some additional training, this network of shop owners could be highly effective partners in the distribution, marketing, sales, and support of efficient fans.

3 The Technology Trial

Before embarking on a campaign to encourage low-income households to adopt energy efficient fans, we wanted to first ensure that these fans will perform well for households that regularly experience frequent supply interruptions and low voltage conditions. Our target population is low-income, grid-connected households. We recruited 36 representative households to participate in the trial.

3.1 Control and treatment groups

We randomly assigned the 36 participating households to control and treatment groups. For the 12 households assigned to the control group, we did not provide any new appliances. With the consent of these control households, we installed data loggers to monitor the electricity consumption of the most frequently used fan. All households in our control group were using induction-motor based fans that consume 75 W power.

The 24 households assigned to treatment groups were randomly allocated across 4 treatment arms. For all treatment groups, we replaced the household's most frequently used fan with a new technology configuration. All of the fans we replaced were of the standard variety (i.e. AC fans rated at 75W). Table 1 summarizes how configuration specifications varied across groups.

Table 1: **Technology Configurations in Treatment and Control Groups**

Group	Control	Treatment 1	Treatment 2	Treatment 3	Treatment 4
Existing/new Fan	Existing	New	New	New	New
Supply	AC	AC	AC	AC	DC
Technology	Induction motor	Induction motor	BLDC	BLDC + storage	BLDC + storage
Rated Power	$\sim$70-75W	55W	28W	28W	25W
Battery storage	No	No	No	Yes	Yes
Sample size	12	6	6	6	6

Notes: Treatment 1 received an induction motor-based EE fan operating on AC supply with a power rating of 55W. Treatment 2 received a BLDC motor technology ceiling fan, operating on AC supply with a power rating of 28W. Treatment 3 received the same fans as Treatment 2. In addition, these households received a battery storage device. Lastly, Treatment group 4 received a different model of a BLDC motor technology ceiling fan, with a rating of 25 W, powered by a 12V DC supply and a battery storage device. Its power rating was 25 W. The battery storage device provided to Treatment groups 3 and 4 is a LiFePO4 battery with a rating of 200Wh.

3.2 Data collection

To measure the electricity consumption of individual appliances, we developed customized data loggers and deployed them in participating households. These data loggers recorded the date, time, voltage, current, power, and power factor for each ceiling fan. For treatment groups 3 and 4, the battery voltage, battery charge/discharge current, and mains supply status were also recorded. The data loggers recorded data at approximately 1 minute intervals. Data were retrieved manually from each HH after every 15 days.

We measured the average fan power consumption and the duration of fan operation for each household. As we are interested in assessing the extent to which additional reliability provided by the battery storage device impacts fan usage, we also tracked supply interruptions by measuring grid voltage. We tracked fan usage during supply interruptions for households in treatment groups that had been allocated battery storage devices. There was not battery storage used by households at baseline.

Data were collected October to July, 2021. Over these 10 months, data loggers recorded the electricity consumption of each fan and the charging and discharging of battery storage devices. Table 2 summarizes the metrics we use to estimate energy savings from EE fans and increase in reliability due to battery storage during power outages.

On average, the measured power consumption of the energy efficient fans was significantly lower than that of the induction motor fans owned and operated by the control group. Figure 1 summarizes the range of power consumption across treatment and control groups.

Treatment groups 2 and 3 households, which were equipped the same AC BLDC fan model rated at 28 W, experienced similar power savings— 67% and 69% compared to the control group. Treatment group 4 households had DC BLDC fans rated at 25 W. These fans delivered the largest power savings (83%) relative to the control group fans. Notably, measured power consumption for these energy efficient fans was significantly less on average than the manufacturer power

Table 2: **Metrics Calibrated**

Metric	Unit	Description
Fan utilization rate	hours	Total number of minutes fan was used by households in a group.
Average power consumption	power (W)	When the fan is in use, power draw is measured We average power across all fans in a group
Average utilization during supply interruptions	hours	Duration of fan use during power supply interruptions (treatment groups 3 and 4 only).

ratings of the fans. Presumably, this is because households sometimes operate the fans at lower settings.

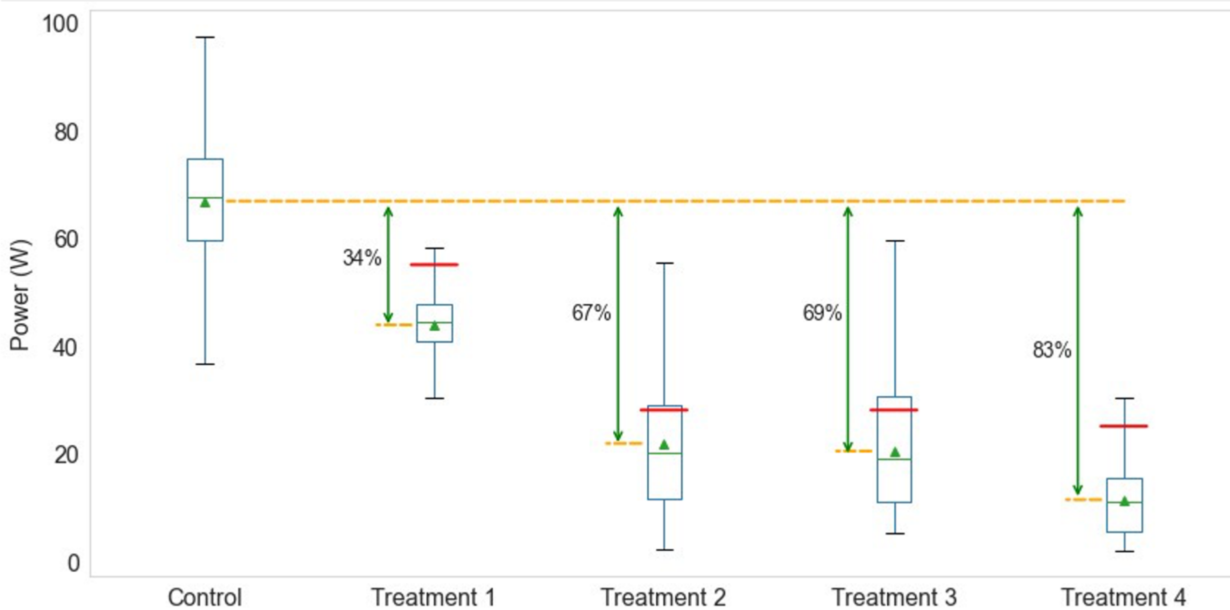
Figure 2 shows the average ceiling fan usage across the control and treatment groups. Conventional fans in the control group were used for an average of 6.9 hours per day. DC BLDC fans with storage (treatment 4) were used for an average of 9.4 hours per day. Treatment 2, wherein households were allocated BLDC fans without storage, is most relevant to the subsequent field experiment. These fans were used 8 hours per day on average. Because the sample sizes of these trial groups are small, measured differences in utilization across groups are merely suggestive.

4 Are BLDC fans a good investment for India?

Investing in an efficient BLDC fan over a standard induction motor fan will be cost effective if the present discounted value of the returns on the BLDC fan investment (accruing over the investment time horizon) exceed the additional cost of the BLDC fan (i.e. the energy efficiency premium). In this section, we bring primary and secondary data to bear on the question of whether BLDC fans look like good investments for low income households. We find that the answer to this question really hinges on the perspective we take.

We estimate the discounted sum of net benefits generated by a BLDC fan (relative to a standard

Figure 1: Power Consumption of Ceiling Fans



Notes: Horizontal red line markers indicate design power ratings of ceiling fans assigned to each group. Green triangle markers show average power consumption for each group. Box plots show the range of fan power consumption during operation across time. Percentages indicate differences in average fan power consumption between energy-efficient fans assigned to treatment groups and conventional fans in control group households.

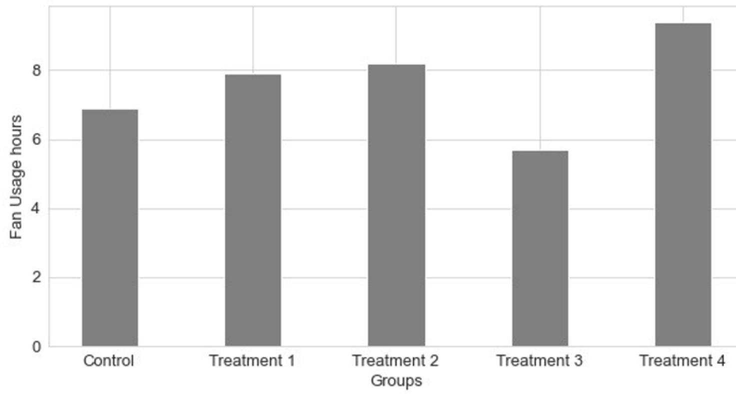
fan) over a conservative investment time horizon of 5 years. To calibrate this analysis, we use data collected during the technology trial, together with additional data sources. These additional sources include:

- **Rural Electricity Demand in India (REDI) survey**: Researchers at the Johns Hopkins University conducted the Rural Electricity Demand in India (REDI) survey in 2019. This survey covered 100,000 households and 2,000 businesses across 200 villages. We use the survey responses collected from 833 households in Bihar.

- **Scoping Survey:** In June 2019, we conducted a baseline survey of 130 households to collect information about appliance ownership and usage, electricity consumption, technology costs, electricity expenditures, and energy literacy.

- **South Bihar Power Distribution Company Limited (SBDCL):** The DISCOM reports

Figure 2: Average fan utilization across control and treatment groups



Notes: This figure summarizes the average utilization rates of fans by group.

detailed data on production costs, tariffs, and revenues in annual reports and rate cases.

We formulate an expression for the net present value (NPV) of discounted benefits as follows:

$$NPV = \sum_{t=0}^{T} \frac{P_t \cdot \Delta PR \cdot H \cdot 365}{(1-r)^t} - \underbrace{(IC_{BLDC} - IC_{IM})}_{\text{efficiency premium}} \tag{1}$$

We use the data summarized above to inform our parameter value choices. Table 3 summarizes the range of parameter values we consider.

Technology costs and the efficiency premium: We collect data on induction motor (IM) ceiling fan prices from a survey of local markets in Bihar. In our scoping survey, we also asked households to recall what the investment cost paid for their most recently purchased ceiling fan. The investment cost for IM fans is denoted IC_{IM}.

Survey responses indicate that the most popular brands of ceiling fans can be purchased locally at prices ranging from INR 1200- INR 1600. Prior to our intervention, BLDC fans were not commercially available in the local markets we worked in. As we write this report, these fans are currently being procured by EESL at a price of INR 2399. This implies an efficiency premium on the order of INR 999.

Power rating improvement (△ PR): Standard induction motor fans have manufacturer power ratings of 70-75 Watts. More efficient BLDC fans have power ratings in the range of 28W-

Table 3: **Cost-Benefit Parameter Value Assumptions**

Variable	Values
Standard fan cost	INR 1200-1400
BLDC fan cost	INR 2300-2300
Standard fan rating	75W
BLDC fan rating	30-35W
Utilization rate	5-10 hours/day
BPL marginal electricity price	INR 1-3/kWh
Discom procurement price	INR 7-8
Social marginal cost	INR 9-13/kWh
Household interest rate	15-100%
Social/DISCOM discount rate	10-20%

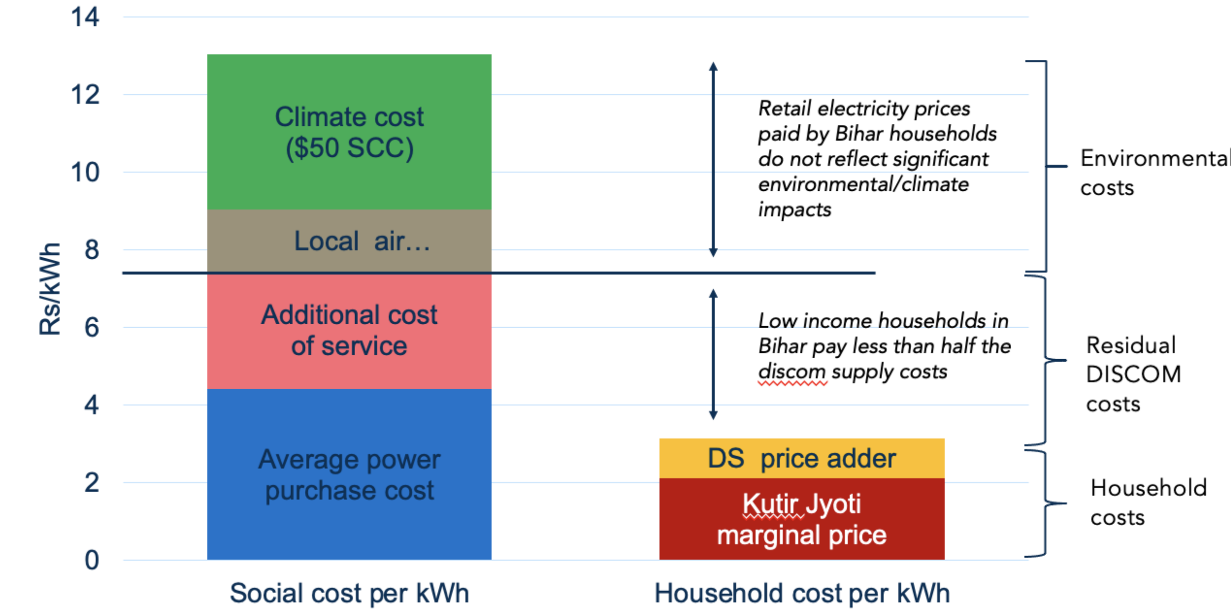
35W. [4]

Appliance utilization rate (H): The REDI survey asked households to report the number of hours per day they use their fans. Across the 833 survey respondents in Bihar, the average response was 8.2 hours with an lower and upper quartile of 5 hours and 11 hours, respectively. In our smaller technology trial, ceiling fan usage varied from 5.8 to 9.4 hours across the control and treatment groups (Figure 2). We find suggestive evidence that power supply interruptions constrain utilization rates. If power supply becomes more reliable in the future, fan utilization rates will presumably increase. We therefore consider a range of annual utilization rates varying between 5-10 hours per day.

Electricity savings ($\Delta PR \cdot H \cdot 356$): We estimate electricity savings as the product of the change in power rating and the number of hours the fan is used per year. This assumes that the utilization rate does not depend on the energy efficiency attributes of the fan. As noted above, households might demand more cooling when the cost of cooling is reduced. If there is

4. The BLDC fans tested in our technology trial are somewhat different from the BLDC EESL fans we use in the field experiment.

Figure 3: Social Marginal Cost of Electricity versus Household Cost Net of Subsidy



This figure compares BPL electricity rates and the social marginal cost. Unmetered households pay a marginal price of 0. For metered customers, BPL prices range from INR 2.12 (the Kutir Jyoti schedule) to 3.15 (the DS schedule) per kWh.

an efficiency-induced rebound in cooling demand, our benefits formulation will overstate the electricity saving and omit an important source of benefits (i.e. enhanced comfort).

Electricity cost per kWh (P_t): To monetize the estimated electricity savings, we need to estimate the costs that are avoided when electricity consumption levels are reduced. The assumed costs will vary depending on the perspective we take. For example, from the perspective of a BPL household, we assume that electricity savings are valued at the subsidized electricity rate.

Figure 3 contrasts the subsidized electricity price paid by a BPL household with the cost incurred by society as a whole when an additional kWh of electricity is consumed. This social marginal cost includes the costs that distribution companies incur to generate and deliver electricity to households, in addition to the environmental costs. Recent work by Chakravarty and Somanathan (2021) estimates that air pollution related health damages (given the current marginal emissions intensity of electricity production) is approximately INR 1.5 per kWh (Chakravarty and Somanathan, 2021). A recent paper by Sengupta et al. (2022) estimates state-specific marginal

GHG emissions rates from electricity generation. In Bihar, this carbon intensity is estimated to be between 0.95 - 1.05 tons per MWh. If we assume a $50/ton social cost of CO2, this implies an additional cost of INR 3.8-4.6 per kWh.

Discount/ interest rates (r): The discount rate used by private households will partly reflect their cost of borrowing. Traditional money lenders in Bihar charge between 12 and 150% annual interest (RBI, 2011). Self Help Groups charge an annual interest rate of approximately 265-30%. The rate at which a social planner should be willing to trade off current versus future consumption should reflect the social rate of time preference or the social opportunity cost of capital. We consider a range of social discount rates from 10-20%.

4.1 Cost-effectiveness analysis

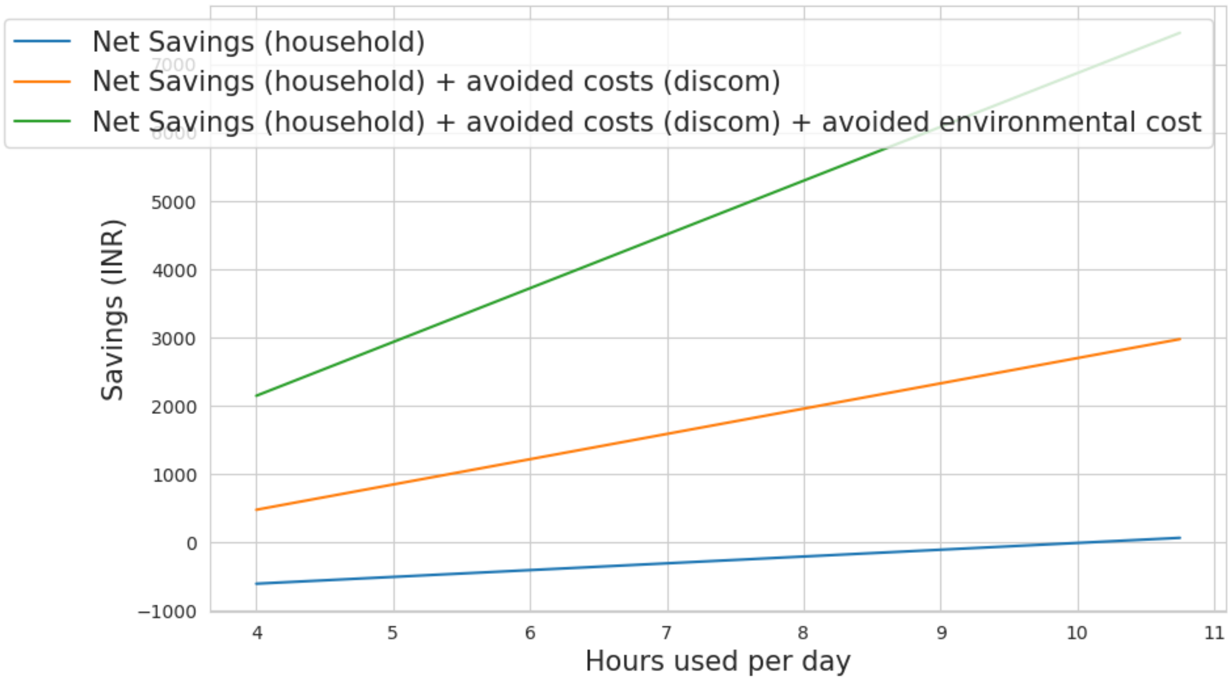
We begin with a set of calculations that illustrate how net benefits of BLDC fan adoption vary with the assumed utilization rate, holding other parameters of Equation (1) constant. We then summarize how these net benefit estimates vary across the range of assumptions in Table 3.

Figure 4 plots the net savings associated with purchasing and operating the more efficient fan versus a standard fan as a function of daily hours of usage. To calibrate the efficiency premium, we subtract the mid-range price of standard fans (INR 1400) from the current BLDC procurement price (INR 2399). We assume a mid-range efficiency gain of 43W.

The blue line in Figure 4 shows how the net present benefits of choosing a BLDC fan over a standard fan (i.e. the discounted electricity bill savings less efficiency premium) increase with the assumed utilization rate. We assume an electricity price of INR 2/kWh and a discount rate of 30%. We assume that this subsidized price prevails over the five year horizon. Under these assumptions, the discounted electricity bill savings over a five year time horizon do not offset the energy efficiency investment premium from the household perspective.

The orange line adds the discounted benefits that accrue to the DISCOM when a household chooses a BLDC fan over a standard fan. The additional benefits accruing to the DISCOM (over and above household benefits) manifest in the form of a reduced subsidy obligation. As noted

Figure 4: Net Present Benefits of BLDC Fan Adoption



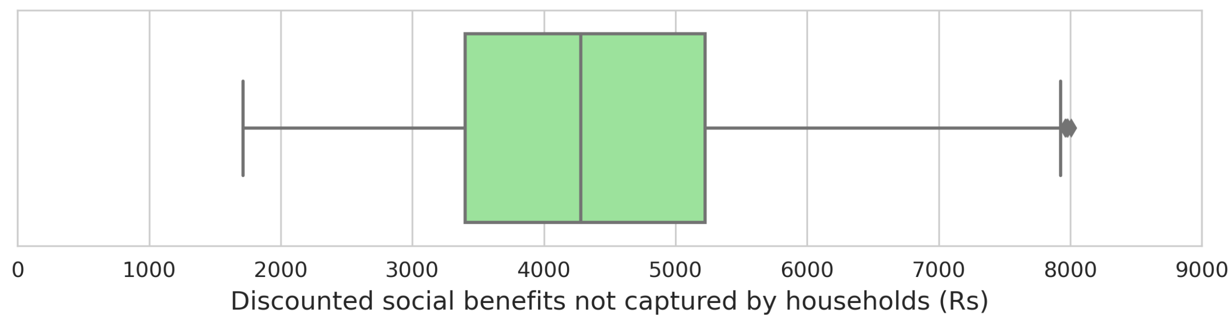
Notes: This figure plots the discounted present value of cost savings associated with the BLDC fan versus the standard fan. Savings captured by households are plotted in blue. Total social savings are plotted in green. The orange line lots the net present value of the DISCOM savings that manifest as reduced electricity consumption subsidies. In practice, these benefits accrue to some combination of the DISCOM and the state government.

above, distribution companies incur supply costs that are significantly higher than subsidized BPL electricity prices. The average cost currently incurred by the DISCOM to supply a kWh of electricity to a household is INR 7.44 per kWh. This number reflects power procurement costs and technical losses The government is supposed to reimburse DISCOMS for the costs that DISCOMS do not collect from BPL customers. In practice, DISCOMS often fall short. Thus, both the state government and the DISCOM stand to benefit from accelerated adoption of more efficient fans.

To estimate the net present value of social benefits from BLDC fan adoption, we add the external health and climate-related benefits (the green line). We assume a social marginal cost of INR 12/kWh and we use a social discount rate of 15%. The BLDC fan is highly cost effective from a social perspective, even at lower fan utilization rates. The social benefits from reducing the electricity inputs required for residential space cooling exceed the efficiency premium costs by almost INR 5000 over a 5 year time horizon if fans are used 7 hours per day.

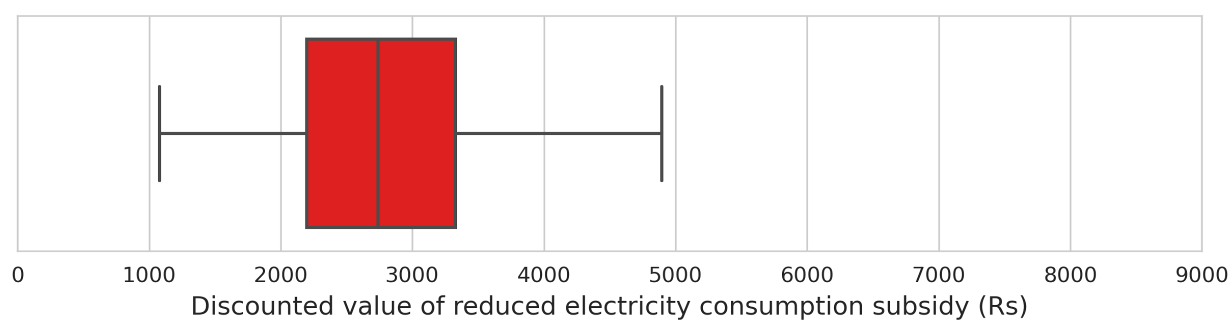
Thus far, our calibration exercise has assumed specific values for uncertain parameters. To assess how NPV estimates vary with alternative parameter value assumptions, we calibrate these NPV values using the range of parameter values summarized in Table 4. We sample randomly (and independently) from each of these ranges to generate a distribution of NPV values.

Figure 5: Social Net Benefit - Private Net Benefit (Rs)



Notes: This box-and-whisker plot summarizes the range of external benefits we obtain across 1000 simulations. For each simulation, we draw randomly and independently from the parameter value ranges summarized in Table 3. External benefits are estimated by subtracting the NPV from a private household perspective from the NPV from a social perspective.

Figure 6: Net Benefits Accruing to DISCOM/State Government (Rs)



Notes: This box-and-whisker plot summarizes the range of DISCOM benefits we obtain across 1000 simulations. For each simulation, we draw randomly and independently from the parameter value ranges summarized in Table 3. DISCOM benefits are calculated as the present discounted electricity savings valued at the difference between the DISCOM cost of service and the subsidized BPL rate.

We evaluate the difference between the estimated social net benefits of BLDC fan adoption and the net benefits captured by households. We refer to this difference as a measure of the 'external' benefits. Figure 5 shows that these external benefits are large. One implication of these estimates: Absent a policy intervention that brings down BLDC fan prices, we should expect to see significant *under*-investment in efficient fans.

Next, we evaluate the discounted benefits that the DISCOM/state government realizes when a BLDC fan displaces a standard fan across a range of parameter assumptions. Figure 6 summarizes our estimates of the present value discounted benefits (in the form of reductions in future electricity price subsidy obligation). The average value of benefits realized by the DISCOM is INR 2800. We note that these calculations ignore the potential for cooling demand rebound and assume that current electricity consumption subsidies will remain in place over the investment time horizon. Even if rebound were to reduce the benefits realized by DISCOMS in half, these estimates suggest that DISCOMS could reduce their long run subsidy costs by incentivizing BLP households to adopt BLDC fans.

One implication of these calculations is that an economically significant technology subsidy targeted at low income consumers could be justified on the basis of external benefits that are not captured by these households. Whether such a subsidy would actually increase BLDC fan adoption is an empirical question we investigate with a field experiment.

5 The Field Experiment

We conducted our field experiment in the Gaya district of Bihar. This is a low-income area of Bihar that has not been targeted by EESL appliance programs in the past. We worked in close collaboration with two local organizations to design and implement the field research. JEEViKA is a World Bank supported program that works to create livelihood opportunities for low income women, primarily in rural areas, across the State of Bihar. JWires is a company that JEEViKA started in 2020 to support local entrepreneurship and market development of solar and other technology products.

JEEViKA supports over 1 million self-help groups and a large network of female-operated small businesses. This network of entrepreneurial women could be well-positioned to distribute, market, and sell efficient appliances in local markets across Bihar. JEEViKA and JWires expressed great interest in exploring the local market potential for BLDC fans.

Our field experiment was designed to investigate two potential barriers to BLDC adoption: high appliance costs and limited local warranty support. BLDC fan prices were randomized across households using a demand elicitation mechanism developed by Becker, Degroot, and Marschak (1964) (BDM). Local warranty support was varied across geographically distant shops (to avoid warranty information exchange or confusion across control and treatment groups).

The following sections describe partner selection, the randomized treatments, the implementation timeline, and the empirical findings. A target sample size was calculated using statistical power calculations and registered in the pre-analysis plan. The final sample size exceeds the numbers listed in the plan due to a high-level of local interest in purchasing a fan.

5.1 Partner selection

Our first step involved selecting a representative group of shop owners to work with. We identified the following short list of criteria for selecting our partner shops:

- Shops should be located in local markets that can be reached using local transport.
- Shops should be located in close proximity to other electrical shops selling standard fans.
- Shop should have sufficient space to store 10 fans boxes and accommodate at least 3 persons at a time for survey.
- Shop ceiling should have the space to install a BLDC fan for demonstration purposes.

Many shop owners expressed interest in participating. We only had capacity to partner with 8 shops. These shops are located in Amas, Barachatti, Dhobi and Manpur blocks of Bihar. These are all blocks where shop owners have an active presence in the community. Each shop serves a non-overlapping cluster of villages and/or peri-urban settlements. Once we had selected the shops, we conducted a baseline assessment of the local market conditions. Field staff surveyed local electrical shops to assess the available inventory and collect information about local prices. Table 4 summarizes some responses to these surveys.

Table 4: Local Markets for Ceiling Fans

Shop	Nearest Electrical Shop (distance)	BLDC fan available?	Top selling ceiling fan	Typical sales price (INR)
1	200m	No	Toofan/Orient	1200-1400/1400-1600
2	150m	No	Toofan/Orient	1200-1400/1400-1600
3	400m	No	Toofan/Oreva	1300-1450/1300-1400
4	300m	No	Toofan/Khaitan	1300-1450/1400-1600
5	100m	No	Toofan/Usha	1200-1400/1600-1700
6	200m	No	Usha/Toofan	1600-1700/1200-1400
7	200m	No	Usha/Halonix	1300-1500/1600-1900
8	100m	No	Usha/Halonix	1300-1500/1600-1900

Notes: The most common fan was a 75W Toofan which sold for 1200-1400 INR. Higher quality models (e,g, Orient, Halonix models) All of the available fans had similar power ratings of 70-75 W.

BLDC fans were not available in any of the markets we surveyed. At the time of our study, EESL had not officially launched their BLDC fan program. However, they had started procuring BLDC fans from manufacturers. We worked with J-wires to purchase BLDC fans from EESL. Prior to our field experiment, these fans were installed in all participating shops for demonstration purposes.

5.2 Experiment design

We implement a 2-by-2 experimental design, cross-randomizing the price discount treatments and the extended warranty intervention.

Randomization of BLDC fan prices: We elicit households' willingness-to-pay (WTP) for a BLDC fan in a real transaction setting. BLDC fans were randomly varied across participants using a Becker, Degroot, and Marschak (BDM) mechanism. This mechanism can be challenging to understand at first. Thus, we made sure that study participants had multiple opportunities to observe and practice this game during demonstration meetings and in practice rounds conducted during the sales appointment.

Randomization of local warranty support: We also varied local warranty support. To avoid warranty information exchange between control and treatment groups, the warranty intervention was randomized across geographically distant blocks. Four of the shops were assigned to a "control" group where households were offered only the standard manufacturer warranty. The other four shops were assigned to a local warranty support treatment group. Customers were offered an additional three-month warranty that could be readily activated through the local shop. Shop owners were allocated surplus inventory such that any technical problems that arose within the three month period could be resolved conveniently through the local shop. Shop owners were allocated surplus inventory so they were prepared to honor this local warranty.

5.3 Field implementation

To participate in the study, respondents had to attend a demonstration meeting, complete an enrollment process, signal some interest in buying a fan in the next year, and arrive at a scheduled appointment at the local solar shop with funds to purchase a BLDC fan. All of these activities are summarized below. Table 5 summarizes the implementation timeline.

Table 5: **Field Implementation Timeline**

Date	Activity	Number of participants
Feb/2022	Training sessions	72 participants
Feb/2022 - Apr/2022	Awareness creation	8719 participants in 385 sessions
Feb/2022 - May/2022	Demonstration meetings	6595 participants in 367 sessions
Feb/2022 - May/2022	Enrollment	2074 participants
Mar/2022 - Jun/2022	Sales appointments	1,709 participants

Figure 7: Local field staff facilitating a training session

5.3.1 Training Session

A five day residential training was conducted by the IIT Bombay team for the local research team that was responsible for scheduling sales appointments, conducting the surveys, and coordinating with local field staff. Local JEEViKA J-WIRES staff helped us identify and recruit 'Local Resource Persons' (LRPs) to work on the project. These are local women who were responsible for awareness creation, communications, and local data entry.

On the first day of training, our field directors provided an introduction to the project and an overview of the different activities we would be engaging in. The second and third days of the training focused on the awareness creation activities. The fourth day of training covered the demonstration activities. The last day of the training concentrated on conducting the survey, record keeping, and data entry.

Throughout the training there was lots of opportunity for participants to ask questions, make suggestions, and build relationships with fellow team members.

5.3.2 Awareness raising

After the training session, participating SHG members (LRPs) disseminated information about our project at local SHG meetings. Information campaigns included pamphlets, posters, and

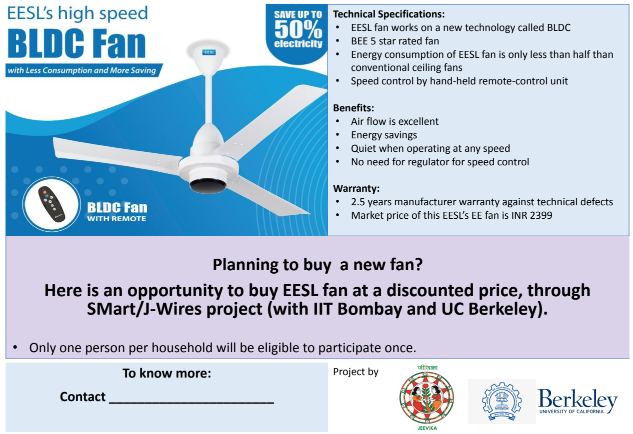


Figure 8: Marketing Materials (English translation)

Figure 9: Local women at an awareness raising meeting

demonstration fans. The format and content of posters and materials was based on the kind of information that EESL provides in marketing materials.

Meetings were convened to share information about our research project. Local households were educated about this opportunity to purchase an energy-efficient fan. These meetings were facilitated and supported by local Village Organizations (VOs). LRPs adopted very creative ways to explain the project and generate interest in the fans. This included a song that conveyed key attributes of the fans we were selling!

All potential participants were informed about the standard warranty support provided by the manufacturer. As noted above, this warranty support can be hard to access from remote markets. In the villages that had been assigned to our warranty treatment group, SHG members educated potential participants about the additional local warranty support.

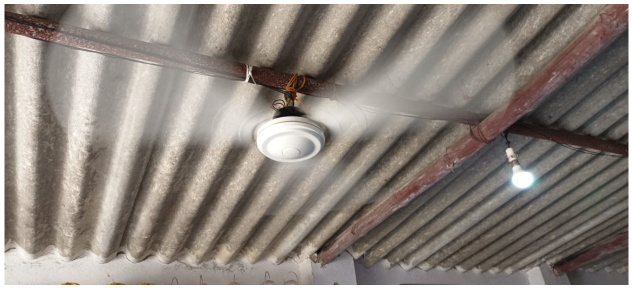


Figure 10: A BLDC fan in action

Figure 11: Local women watch a demonstration of the BDM transaction game

5.3.3 Demonstration Activities

Once local community members had been made aware of our project, we convened demonstration events at local village offices or Cluster-level Federation (CLF) offices. BLDC fans were installed and operated so that people could inspect the fans (and cool off on a hot day!)

Demonstration meetings were convened by the LRPs. Meeting locations and times were announced well in advance. Participants had many opportunities to ask questions about the various aspects of the project.

Demonstration events provided additional information on the BLDC fans, the opportunity to purchase a fan, and the demand elicitation exercise we would be using during the sales appointments. At each event, field staff demonstrated a 'mock' game so people could understand how the BDM mechanism works. The game was framed as a lottery – a fair way to randomly allocate BLDC fan discounts.

5.3.4 Program Enrollment

After the mock game demonstration, attendees had the opportunity to apply to participate in the study. The first step in the application process involved completing a short survey. Enrollment priority was given to those respondents who indicated that they were very likely to purchase a ceiling fan in the next year and willing to travel to a participating shop for a sales appointment.

Research staff explained that participants would need to bring the funds to purchase the fan to the sales appointment. Interested and qualified participants made sales appointments, completed a consent form, and shared contact information so they could be contacted and reminded about the appointment. Paper-pen based enrollment forms, each having a unique identification (UID) number, were used to enroll participants and make sales appointments. Completed enrollment forms were sent to the local data entry operator who would enter data in a shared database, and upload pictures of consent forms and enrollment forms.

5.3.5 Sales appointments

Sales appointments were scheduled at participating SHG shops. The surveys were conducted by local research staff who attend all sales appointments. At the appointment, field staff confirmed the identity of the respondent and checked that they had brought an electricity bill and funds to purchase a fan. Participants completed a consent form. A photograph of the electricity bill was collected. At shops assigned to the control arm, participants were reminded of the manufacturer's warranty (using manufacturers language). For the treatment group participants were reminded about the local warranty offer.

The researcher, with the help of the shop owner, conducted the survey (included in Appendix). Once the survey questions had been answered, the

5.3.6 The BDM mechanism

We use a demand elicitation mechanism that was originally developed by Becker, Degroot and Marshak (BDM, 1964). This is an incentive-compatible approach to eliciting participant's willing-

Figure 12: The demand elicitation game

ness (or ability) to pay for the BLDC fan.

Prior to the appointment, each participant identification number was randomly assigned a discount lottery card. Each card contained a practice exercise and a series of 6 randomly generated offer prices (hidden under scratch off stickers) ranging from 1200 INR to 2390 INR. A demonstration fan was on display at all participating shops. Participants were also reminded that standard IM fans were available from nearby shops (less than 400 m away).

The prices on each card were drawn randomly from a range of prices between INR 1200 and INR 2390. Neither the respondent nor the research staff administering the survey knew what prices were offered on any given card. Participants were able to purchase the fan if and only if their bid price was higher than (or equal to) to the price she blindly chose on her randomly assigned scratch card.

After the participant quoted their final WTP price, the research staff noted the maximum bid on the card and took a photo as a record. The participant then chooses one of the six scratch-off squares on the card, and scratches the square to reveal the offer price. At this time, a second photo was taken. If the offer price on the scratch card was the same or less than the participant's bid, then the participant 'won' the game and was able to purchase the fan at the offer price on the scratch card. However, if the offer price on the scratch card was higher than the participant's bid, then the participant cannot purchase the fan. No negotiations permitted.

After the fan had been won or lost, the participants were invited to scratch all other squares to confirm that a range of offer prices were displayed on the card. A final photo of the scratch card was then taken. The photo documentation was used to assess compliance with the experiment protocols.

5.3.7 Data Entry and Validation

The consent forms, enrollment and surveys were recorded on paper, and then entered online using Kobo survey tool by the local research team. The photos of the scratch cards taken were also uploaded on Kobo. The IIT research team cross-checked and verified all the data entered. A continuous monitoring approach, through random inspection, via phone calls, videos and photos, was undertaken to ensure that the survey/WTP game was conducted exactly as designed without any bias. The research team also examined all the photos of scratch cards of all participants for possible discrepancies (i.e., scratch-off of more than one square; possible alteration in the quoted price). A very small number of discrepancies (five surveys) were found and subsequently removed from our analysis.

6 Empirical results

The demographics of the 1,709 households that participated in our demand elicitation exercise are summarized in Table 6. As we worked closely with women's SHGs to raise awareness about the study and recruit participants, the survey respondents are disproportionately female (79%). The median self-reported monthly household income is INR 6000 (USD $75 per month). About 76 percent of respondents have a Public Distribution System (PDS) card that is issued to the economically weakest section of the societies by the government of India. The average self reported monthly electricity bill expenditure was INR 294.

The survey asked a series of questions about household electricity consumption and the qual-

Table 6: **Survey Summary Statistics**

Variable	Mean	Standard deviation	25th	50th	75th
Household size	5.96	2.26	5	5	7
Age	34.90	9.95	28	35	40
Female respondent	0.79	0.40	1	1	1
Completed Class 10 education	0.63	0.48	0	1	1
Monthly household income (INR)	7455	5625	5000	6000	10000
PDS card	0.76	0.43	1	1	1
Number of rooms in house	3.8	2.0	2	4	5
Scheduled caste/tribe	0.40	0.49	0	0	1
Monthly electricity bill (INR) (self reported)	294	401	150	200	300

Notes: Summary statistics of key socioeconomic characteristics for all 1,709 study participants.

ity of electricity supply. Table 7 summarizes the responses to these questions. 23% of the participants are unmetered customers who pay a marginal price of zero. Of those households that have an electricity meter, all pay a subsidized rate. Most households report receiving an electricity bill each month.

Respondents were asked to estimate their monthly electricity expenditures. The average self-reported bill is INR 294. Expressed as a share of (self-reported) monthly income, participants report spending 5% of their income on electricity, on average.[5]

Most participants own one ceiling fan. Respondents report operating their ceiling fans for an average of 8 hours per day.[6] Respondents were asked to estimate the cost of operating a fan (in terms of INR per month). A standard fan owned by these households consumes between 65-75 W. Assuming a utilization rate of 8 hours per day, monthly electricity consumption by the

5. Households were also asked to share a recent electricity bill. We are in the process of scraping bill information from these documents. This exercise will help us to ground-truth self-reported expenditures. 94% of households brought sample bills for our research team to photograph and review.

6. Our survey was conducted during the warmer months, and thus, estimates could be biased upward from the annual average fan utilization rates.

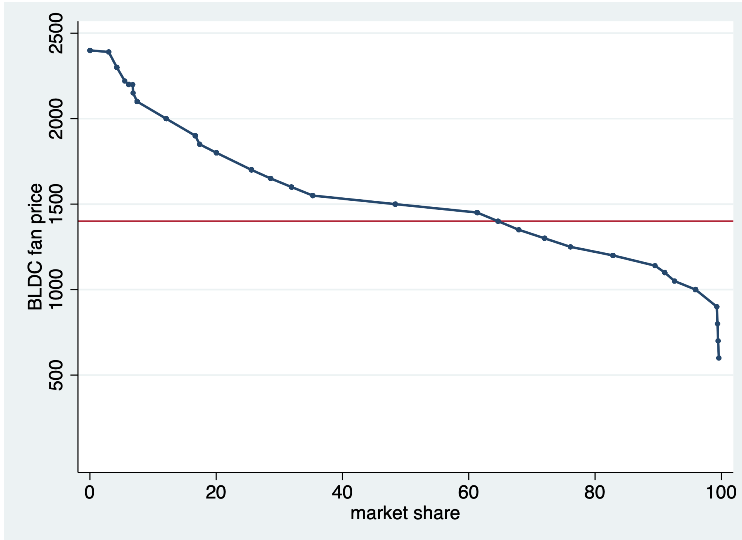
fan is approximately 16.8 kWh. At a subsidized electricity rate of 3 INR per kWh, it should cost households approximately INR 50 per month to operate a fan. A majority of survey respondents (80%) declined to answer this question, suggesting that these households are not well-informed about fan electricity consumption or operating costs. Of those providing a response, the median estimate of fan operation costs is INR 100.

In the interest of assessing energy literacy, we asked participants to complete two tasks. First, respondents were asked to look at their electricity bill and figure out what price they pay per kWh of electricity consumed. Only 7 percent of respondents were able to do this successfully. The second task involved arranging photos of three appliances (a CFL, a Fan, and a Television) in ascending order of energy consumption per hour of use. Two thirds of the respondents were able to correctly rank appliances in order of increasing electricity consumption.

Table 7: **Survey Response Summary**

Variable	Mean	Median	Standard deviation
Metered customer (yes=1)	0.77	0.5	0.42
Monthly electric bill (INR) (self-reported)	294	200	401
Electricity bill share of income (self-reported)	5.0%	3.3%	6.2%
Billing frequency (bills received per year)	11.40	12	2.32
Brought electricity bill? (yes=1)	0.94	1	0.24
Energy literacy			
Locate marginal price on bill? (yes=1)	0.07	0	0.26
Appliance ranking correct? (yes=1)	0.66	1	0.47
Reliability			
Power outages? (yes=1)	0.95	1	0.22
Typical daily power supply (hours)	18.98	20	2.3
Voltage problems? (yes=1)	0.69	1	0.46
Appliance holdings			
How many fans owned?	1.58	1	1.21
Fan utilization rate (hours/day)	7.47	7	5.04
Estimated fan cost (INR/month)	143	100	108

Figure 13: **Household demand for BLDC fans**



Notes: This graph summarizes how demand for BLDC fans increases as the fan offer price decreases. A standard 75W induction motor fan sells in local markets at prices between INR 1200-1450. The red line represents a reference price of INR 1400 for comparison purposes.

6.1 Household demand for the BLDC fan

After answering survey questions and completing multiple practice rounds of the BDM game, study participants had the opportunity to submit a bid to purchase the BLDC fan. The average bid price was INR 1554.

Offer prices were determined by the random scratch card process. The average across the realized offer prices was INR 1804. Of the 1,709 households that participated in our WTP experiment, 35% purchased the fans (and 'won' the game). All participants' submitting bids that exceeded the offer price they received followed through and purchased fans. None of the participants who submitted bids below their randomly chosen offer price were able to purchase fans. This suggests that the WTP survey mechanism worked as intended, and that the bids reflect participant's maximum ability to pay for a new fan. The figure below summarizes the results from this choice experiment.

As expected, adoption rates at the current BLDC price of INR 2399 is very low; less than 3 percent of households in our study were willing to pay this price. Fan adoption increases from 20% at a price of INR 1800 ($22.60 USD) to 60% at a price of INR 1450 ($18.20 USD). As no credit or financing was provided, so these bids reflect households' ability to pay at the time of transaction.

Bids to purchase the BLDC fan varied across participants. The mean bid was INR 1556 with a standard deviation of INR 372. To investigate what type of households value these fans more or less, we regress the household-level bids on households demographics and other factors. Table 8 summarizes these results.

Table 8: **What explains variation in WTP?**

VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5
Constant	1,775***	1,796***	1,719***	1,790***	1,711***
	(94.67	(112.3)	(116.0)	(128.5)	(111.1)
female	-177.8***	-174.9***	-167.7***	-150.8***	-153.2***
	(29.19)	(28.39)	(28.82)	(27.72)	(25.66)
BPL	-19.87	-18.90	-16.48	-20.99	-22.09
	(27.46)	(27.31)	(26.74)	(25.41)	(23.26)
Unmetered	-88.61***	-90.31***	-78.85**	-71.32**	-81.73**
	(32.56)	(33.05)	(33.60)	(31.31)	(38.19)
Voltage problems		-35.64*	-38.88**	-37.64**	-23.11
		(19.35)	(18.54)	(18.05)	(19.64)
Longer outages		-21.24	-21.87	-14.05	-42.50
		(26.27)	(25.51)	(24.25)	(30.83)
Fan ownership			83.32***	75.84***	61.35***
			(23.59)	(22.04)	(20.07)
Fan hours			1.092	2.127	6.619**
			(3.097)	(2.839)	(2.536)
Risk averse				-104.3***	-59.79**
				(27.91)	(24.58)
Warranty treatment					-15.18
					(64.99)
Observations	1,709	1,709	1,709	1,709	1,709
R-squared	0.082	0.085	0.093	0.108	0.086

All regressions include block fixed effects.
Robust standard errors are clustered at the block level.
$***p$¡0.01, $**p$¡0.05, $*p$¡0.1.

All regressions include block-level fixed effects. Across all specifications, we find a strong correlation between the gender of the participant and bid prices. Conditional on other observables listed in Table 8, male participants are able to pay approximately 10 percent more than female participants. Participants with electricity meters are also willing and able to pay more. Because it is difficult to control precisely for income, this effect is likely driven both by the fact that un-metered households cannot reduce their energy expenditures by reducing energy consumption and the fact that un-metered households have lower incomes on average.

All else equal, households that experience longer supply interruptions and low voltage events should be willing to pay less for a BLDC fan because poor power quality can limit the hours the fan can be used and could increase the probability of fan failure. We find that households that report experience low voltage problems and/or longer outage durations also submit lower bids. Households who own fans already are also willing to pay significantly more for a BLDC fan.

To construct a measure of risk aversion, we used data we collected during a simple investment game. Each respondent receives INR 100 to compensate them for the effort they invested in the aforementioned tasks. As anyone who has ever tried to understand their electricity bill can attest, this is an arduous task. Respondents are given the option to "invest" some of their earnings in a game of chance. A 2 x 2 scratch card had two "win" entries and two "lose" entries. If the player scratches a win, she triples her investment. If she loses, she loses her investment. Participants knew they had a 50% chance of winning. Those who choose to invest scratch off one square to determine their investment fate. They are then encouraged to scratch the second square to confirm this was a fair 50/50 odds game.

We construct an indicator for risk aversion that equals one if the participant wagered more than half their compensation (for an effortful task performed during our survey) in an investment game. This indicator was set to zero if the participant bet less than half of her earnings. Risk averse participants have a lower willingness to pay for the BLDC fan. We find no significant correlation between our measure of energy literacy and participant's willingness to pay for a BLDC fan.

7 Conclusion

Through an initial technology trial, we find that BLDC fans perform very well in settings characterized by supply interruptions and low voltage events. BLDC fans use less than half as much electricity as standard IM fans. We also found a high rate of consumer satisfaction with the BLDC fans used in our trial. A majority of households purchased the fans at the end of the trial. The strong performance of BLDC fans is necessary, but not sufficient, for increasing adoption in a low income setting.

Using data collected from the technology trial, in addition to secondary data sources, we analyze the cost-effectiveness of BLDC fans (versus standard fans) from a private and social perspective. This analysis suggests that these BLDC fans are highly cost effective from a social perspective; energy savings easily offset the additional upfront cost using a range of discount rates and time horizons. However, because low-income households pay highly subsidized electricity rates, they capture only a fraction of the energy savings benefits. Thus, from a private household perspective, the returns on a BLDC fan investment may not justify the additional upfront cost. On this basis, we anticipate that adoption rates at current fan prices will be low among low income households.

Working closely with local SHGs, we design and implement a field experiment to assess household demand for BLDC fans in hard to reach markets across a range of price points. In addition to the high purchase price, limited "last mile" support and services (e.g. limited repair and maintenance support) has been cited as a potentially important barrier to investment. To investigate this claim empirically, our field experiment varied both purchase price and access to an extended (and locally supported) warranty.

As expected, there is very limited demand for BLDC fans at the current retail price among households paying subsidized electricity rates. However, at subsidy levels that can be justified on the basis of benefits that private households do not capture, we see significantly higher adoption rates. Fan adoption rates increase to (20%) with a subsidy of INR 600 and 80% with a subsidy of INR 1200.

One important implication of these findings is that, absent additional policy intervention, India will see significant under-investment in energy inefficient fans, particularly among households who pay subsidized electricity rates. This under-investment will "lock-in" energy inefficient cooling for decades. This will impose larger-than-necessary costs to households, distribution companies, and the environment.

To incentivize efficient investments in harder-to-reach markets, policy makers need to find viable ways to reduce the cost of purchasing BLDC fans and other efficient appliances. Bulk procurement programs will be necessary, but not sufficient.

This research finds that state governments and discoms could substantially reduce their overall subsidy costs by providing incentives that increase BLDC fan adoption among low-income households. Researchers find that lowering BLDC fan prices by INR 1000 increased BLDC fan adoption by almost 65 percentage points. This INR 1000 subsidy could be quickly offset by reductions in future electricity subsidy costs which are estimated to be on the order of INR 2000 per fan over a five-year time horizon.

Policy makers have a number of tools they could use to reduce BLDC fan prices offered to low-income households. These include targeted direct benefits transfers, fan replacement programs, and on-bill financing. More work is needed to assess the impacts that these alternative strategies would have on BLDC fan adoption and electricity consumption. This work should start now. In the absence of effective policy intervention, households will continue to purchase inefficient fans, locking in higher costs for consumers, the power sector, and the environment for decades to come.

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