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Leveraging automated demand response for the clean energy transition: Evidence from urban India

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- In partnership with a large electricity supplier in India, we study the extent to which a combination of incentives and smart technologies can shift household power demand over time.
- We find an 8.5% reduction in household-level electricity consumption during automatic switch-off events that we trigger to a single household appliance connected to a smart switch controller. The effects increase to a 15% load reduction in the evening hours when aggregate electricity consumption is the highest.
- The level of the incentive offered has virtually no effect on the load reductions we observe, indicating that incentives have a limited impact on user behaviour once demand response is automated.
- Appliance-level electricity use does not return to pre-event levels after the switch-off event, and the absence of compensatory effects indicates a degree of wastage in how electricity is used.
- Demand-side management programmes can benefit the energy system while helping to improve the efficiency of household energy usage.

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The untapped potential of demand-side management

In recent years, India has made significant progress in increasing renewable energy generation while expanding access to electricity across its population and closing its power deficit. With its economy poised to grow rapidly in the coming decades, electricity demand will continue to surge. To achieve its climate aspirations, India will need to decouple energy demand from emissions by displacing coal-fired electricity generation from the energy mix.

While investments in supply-side infrastructure, including energy storage and transmission, will be necessary to provide energy security, a potentially cost-effective approach to accelerate the clean energy transition involves shifting energy demand from periods when renewable energy is scarce to periods when it is more available. By making energy demand more flexible, one can avoid the need to dispatch expensive and polluting power plants, thereby lowering the carbon content of the grid. With higher levels of variable renewable energy on the grid, peak demand will not necessarily coincide with the times when the marginal cost of generation or marginal grid carbon intensity is the lowest. As the times when consumption should be avoided will vary on such a grid, automated solutions may be more effective in shifting the load away from those periods than using price incentives alone. To the extent that load shifting can reduce aggregate peak demand, the cost of balancing and network reinforcement could decrease substantially, particularly since electricity suppliers often forward contract additional generation capacity to meet the expected demand of a small fraction of hours in the year. Finally, greater demand flexibility can help system operators avoid outages at times when margins are tight.

Overview of research

We began a randomised controlled trial in the spring of 2023 to study how automation and incentives can enhance flexibility in residential energy demand. We implemented the trial in partnership with a large electricity company in India that operates the power distribution network in Delhi and Mumbai. As part of the trial, we offered residential consumers of the company simple Wi-Fi-enabled smart switches. These devices control the operation of an appliance, such as a room air conditioner, an electric water heater or a refrigerator, and enable users to monitor the energy use of their appliance in real time via a smartphone app. We developed a web platform called POWBAL that allowed us to monitor power flowing through the smart switch in real time and trigger 30-minute automated switch-off events to different devices at different times, for which participants were rewarded per unit of electricity they avoided consuming during those events. We sent a text alert before each event so that users could opt out via a smartphone app if they wished, but this meant they would not earn a reward. We randomly varied whether an individual smart switch turns off automatically for a given half-hour interval between 8 am and midnight, subject to constraints (i.e., no more than two events per day and eight times per week per device). We also randomised the level of the financial incentive offered for the event among users and the amount of notice time we gave users prior to each event to examine how those factors impacted electricity use.

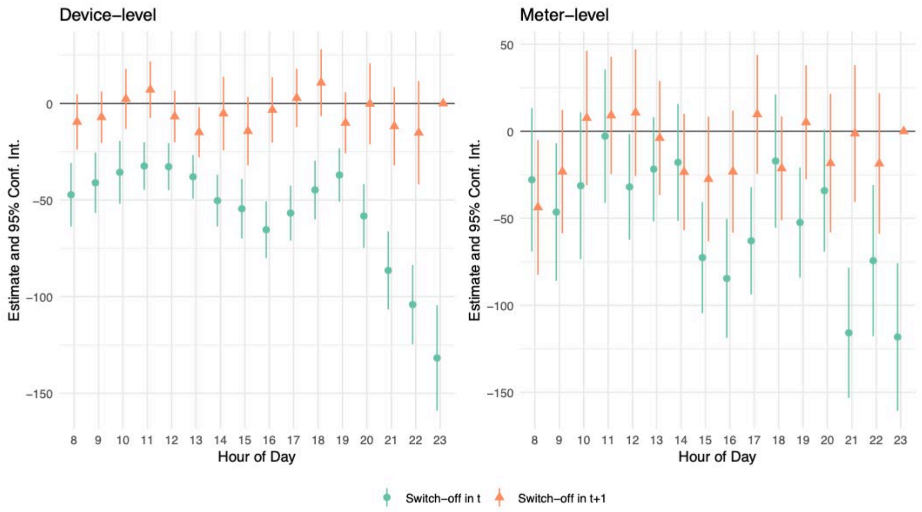
This research directly informs how electricity regulators and suppliers should design and implement automated demand response programmes to minimise the cost of power procurement and balancing while maximising the decarbonisation benefits to the energy system.

How do automated switch-off events impact appliance and household-level energy use?

As of 30 June 2024, 930 households had a Wi-Fi-enabled smart switch installed as part of the project. Households could choose which appliance to connect to the smart switch. More than 80% of participants connected their device to a window/wall air conditioning unit. By triggering random 30-minute switch-off events to the smart switch, we found that automated switch-off events could reduce appliance-level power demand by 69% during the event and by 74% within an hour of the event. Using data from the smart meters, we found that switch-off events reduced household power demand by 8.5%, a sizeable effect considering that the appliance connected to the switch accounted for 13% of household electricity consumption on average. The size of the effect increased to 15% during the late afternoon and evening hours, which coincided with higher power demand on aggregate.

To the extent that high aggregate power demand increases the likelihood of outages, these results suggest that automated load control can lower outage probabilities by reducing peak demand. In the long run, it could alleviate the need to forward contract additional generation capacity and lower prices. As shown in Figure 1, the absolute load reductions at the device level closely match those at the meter level, indicating that device readings may be enough to implement automated demand response even across consumers who do not have smart meters without compromising the benefits to the grid. We explored these effects separately for consumers in each quartile of annual baseline household electricity use. We found that the percentage reduction in appliance-level electricity use was similar across all quartiles, while the percentage reduction in household-level electricity use was higher among larger electricity consumers.

FIGURE 1: Effect of switch-off events on electricity use at the appliance- and household-level during the event and in the preceding half-hour



Impacts of the level of incentive and notice period on energy use

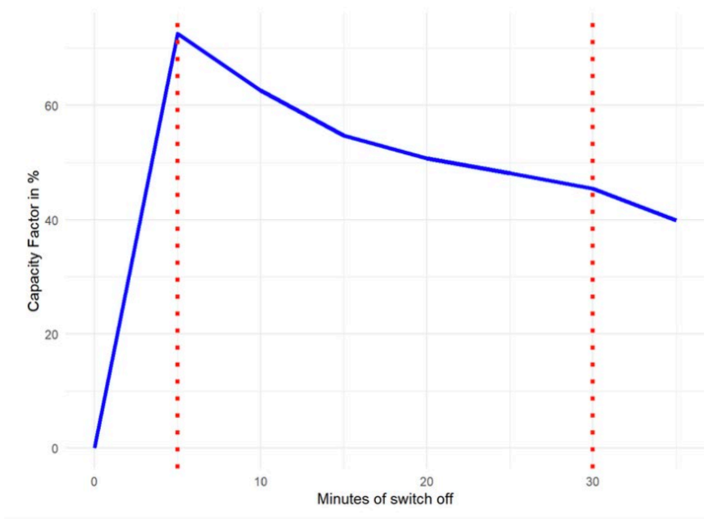
We also examined how the notice period and reward rates impacted device energy use and overriding, where users opted out of events entirely. We found that providing a short two-hour notice period created a perverse anticipation effect, where users manually turned off their devices before the event began, expecting to maximise their rewards. However, given that households opted into the event (and could opt out if they wished), there was no need to take manual action to participate in switch-off events; as such, this behaviour indicates that users misunderstood how rewards were earned. Giving a longer eight-hour notice period did not create a perverse anticipatory effect, suggesting that text alerts should be sent several hours before the event or not at all. Given the novelty of automated load control programmes in this context, creating awareness about the uses and potential benefits of smart technologies for load balancing is important.

Households were rewarded in proportion to the avoided power consumption or the power their appliance would most likely have consumed if there was no switch-off event. We varied these reward rates throughout the trial, with the lowest offered rate equal to Rs 6 per kWh, approximately the average wholesale price of electricity during this period, and the highest offered reward rate at five times that level. While a higher reward rate modestly reduced the probability of overriding the event entirely, we did not find any evidence that households respond more strongly to higher reward rates, indicating that offering volumetric price incentives higher than the average wholesale price of electricity does not deliver additional benefit when demand response is automated.

Virtual power plant

Demand response can be characterised as a virtual power plant where power generation corresponds to the energy consumption avoided due to switch-off events. Figure 2 displays the computed capacity factor of our implicit virtual power plant, which has generated over three MWh of power since the trial began in the spring of 2023. The capacity factor measures the fraction of potential implied power generation that has been realised across all switch-off events. We calculated this capacity factor at five-minute intervals before and during the switch-off events. The dotted lines indicate the beginning and end of switch-off periods. On average, the power delivered to the grid was highest in the first five minutes of a switch-off event, where the capacity factor was 73%, and then dropped to 45% towards the end of the event, reflecting consumers overriding the switch-off event. Even after the switch-off event was over, we found that, on average, devices did not return to consumption levels before the switch-off event started. After 30 minutes, our virtual power plant provided power as shown by a positive capacity factor, reflecting that some devices remained off, but even those that turned back on typically did not compensate for the switch-off period. This finding suggests that electricity may be used inefficiently by these households. It highlights the potential of automated demand response to not only deliver benefits to the energy system but also to make household power usage more efficient.

FIGURE 2: Capacity factor of virtual power plant



Conclusion

Demand-side management includes a broad class of programmes aimed at modifying patterns of electricity use. In the retail market, these programmes include various forms of dynamic pricing, such as time-of-use, critical peak pricing, or real-time price, as well as programmes that incentivise consumers to shut off parts of their electricity consumption at specified times (i.e. dynamic rewards). These measures could be optimised to provide climate and local environmental benefits while reducing the cost of supply and the likelihood of forced outages. However, attempting to make demand more flexible by either pricing electricity dynamically or offering dynamic rewards may be insufficient as residential consumers have been shown to be inattentive to electricity prices in a variety of contexts (Parrish et al., 2019; Sexton, 2015; Jessoe et al., 2014; Gilbert and Zivin, 2014; Houde et al., 2013). In such cases, incentives alone may not be enough to harness the existing latent demand flexibility.

With smart meters, utilities can control load at the meter level directly and, in exchange, offer discounted tariffs to consumers who sign up for interruptible or curtailable service contracts. However, the feasibility of this approach remains uncertain, given the inconvenience it may cause consumers. The advent of IoT technologies has ushered in the possibility of automating demand-side management while offering greater control to consumers. Automation is increasingly being considered a low-cost opportunity to make small changes in electricity demand with potentially large electricity supply cost reductions (Blonz et al., 2021; Bailey et al., 2023; Coutellier et al., 2020). In principle, flexible prices could encourage users to adopt automation themselves. However, there may be technical barriers, such as difficulty in finding installers with the requisite skills, or it may simply be a low priority for some consumers. The deployment of IoT technologies may also raise concerns about safety and data security (Alaa et al., 2017; Nicholls et al., 2020; Parrish et al., 2020). These factors may constrain the large-scale take-up needed to increase responsiveness to time-of-use pricing (Fabra et al., 2021). This study builds on this literature by developing experimental estimates on the potential for demand flexibility that could inform the design of policies on retail pricing and automated load control in the Indian context.

Our results suggest that automation technologies coupled with incentives could reduce demand by up to 15% at the household level – significantly larger effects than incentives alone (Sudarshan, 2017). We observe effects of similar magnitudes on device and household-level electricity consumption, indicating limited substitution to other electricity uses during switch-off events. This finding suggests that, unlike in the case of using a dynamic price, we can implement automated load control programmes across consumers who do not have smart meters without compromising on the benefits to the grid. Note that a smart meter currently costs a few hundred dollars while a smart device costs 10-20 USD. Furthermore, we find that higher incentives deliver limited additional benefits when using automation, suggesting that scaling up automation load control programmes may be more cost-effective than scaling up dynamic pricing. However, further research is needed on the relative benefits of these programmes. The absence of compensating effects in electricity use around the switch-off event suggests that demand-side management programmes could benefit the grid while improving the efficiency of household energy usage.

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