Title

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Estimation of Potential and Value of Demand Response for Industrial and Commercial Consumers in Delhi

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Estimation of Potential and Value of Demand Response for Industrial and Commercial Consumers in Delhi

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Abstract—**Demand response (DR), especially from larger commercial and industrial consumers, can significantly contribute towards improving India's grid reliability. The industrial and commercial consumer's share of the total electricity consumption is 40%–50% for most electricity utilities in India. Automated DR (a form of DR that uses advanced metering infrastructure and automated signals between utilities and consumers) can efficiently enable these consumers to shed or shift their loads when electricity prices are high, or during times of scarcity, providing not only financial benefits for themselves, but also benefits to utilities, system operators, and other consumers. Estimating both the technical and economic potential of automated DR can enable regulators and utilities to design appropriate policies and incentives for consumers, and for system planners to consider DR as a dependable capacity resource. Using data and analysis from a DR pilot program conducted by the Tata Power Delhi Distribution Limited (TPDDL), we estimated the potential of DR for industrial and commercial customers in the state of Delhi. Further, we valued DR assuming various potential savings opportunities for utilities that include avoided high-price wholesale day-ahead market purchases, reduced unscheduled interchange exchanges during low frequency-high penalty periods, and avoidance of generation from expensive marginal generators.**

Keywords—Automated Demand Response; Demand Response Potential; Economics of Demand Response; Delhi; India

I. INTRODUCTION

Over the past several years, the Indian electricity sector has been experiencing severe energy and peak power shortages. In 2013–14, India had an average peak power deficit of 4.5% and an average energy deficit of 4.2% [1]. Demand response (DR) through the provision of incentives or varying prices can reduce peak demand by either shedding load or shifting demand to non-peak hours [2]. In the short run, reduction in peak demand can avoid high-price wholesale energy purchases, reduce penalties due to unscheduled interchanges (UI), avoid generation from high-cost marginal generators, and prevent uncompensated load shedding. In the long run, a dependable demand reduction through DR can enable capital expenditures deferral, both in generation capacity and in transmission and distribution upgrades. Demand response is also becoming an important balancing resource, with increasing shares of variable and uncertain renewable energy generation sources like wind and solar [3], especially in jurisdictions such as India's that have relatively inflexible coal generation as their dominant electricity source.

Regulatory agencies in India do note the importance of DR as a resource. The 2014 regulations of the Delhi Electricity Regulatory Commission recommends that electricity utilities implement DR programs to "reduce or shift demand away from periods of peak/higher cost electricity to periods of non-peak/ lower-cost electricity periods" [4].

Given this significance, it is important to understand the potential of DR and its value to the electricity sector. While several studies in the U.S. and elsewhere have quantified DR potential based on existing DR programs, there are few, if any, studies conducted for jurisdictions in India, mainly because pilot DR programs have only recently started being conducted in India. In this paper, we use data from one of the first DR pilot programs in India to estimate the potential of DR for commercial and industrial customers in the state of Delhi. The DR pilot program was conducted by the Tata Power Delhi Distribution Limited (TPDDL), one of the four electricity utilities in the state of Delhi. Commercial and industrial customers account for approximately 44% of the total electricity consumption in Delhi. In our study, we used data from 144 out of the total 173 commercial and industrial customers that participated in the TPDDL demand response pilot program over a period of six months (May to October 2014). We also estimated the value of DR within the context of India's electricity sector, from both the customer's and the utility's perspective, using TPDDL as an example.

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The paper is organized as follows: In Section II, we describe the methodology, data, and results for the DR potential estimation. In Section III, we discuss the methodology and approach to valuing DR in India's electricity sector. Section IV provides our conclusions.

II. ESTIMATING DEMAND RESPONSE POTENTIAL

Previous studies (specifically from U.S. jurisdictions) have estimated the DR potential during specific peak hours for a utility or a larger jurisdiction, such as a state or country [5], [6]. The Federal Energy Regulatory Commission, in its national assessment of DR potential, used two different approaches [5]. For non-price based DR options, such as direct load control or interruptible/curtailable load programs, the load impact estimates were based on average values determined through analysis of data from existing programs. For price-based DR options, the same estimates were determined using normalized load shapes for different consumer categories; and estimates of the percentage change in energy use during peak periods were estimated using price elasticities and the assumed change in prices during peak periods for DR tariffs relative to non-time varying rates. Our approach is similar to the one adopted for non-price-based DR options, given that the TPDDL pilot study used automatic demand response (AutoDR) to send signals for customers to curtail their load, without varying any price-based incentives.

In this study, we estimated the DR potential for the state of Delhi, using results from TPDDL's demand response pilot program. We briefly describe the program and its results before outlining the methodology for our study.

A. *TPDDL Demand Response Pilot Program*

The TPDDL demand response pilot program employs AutoDR with advanced metering infrastructure, smart meters, data analytics, and interoperability standards. AutoDR enables customers to receive an automated signal from the utility and automatically respond by either reducing or increasing their demand for the requested time duration. The details of TPDDL's pilot program and technologies used for AutoDR are discussed in our complementary study [7]. We used energy use data for 144 commercial and industrial customers at a 15-minute time resolution from May 2014 to October 2014. During this time period, TPDDL executed 17 AutoDR events, ranging from 0.5 to 1 hour each. We estimated the demand reduction during these AutoDR events for each consumer category by computing the 75th percentile of the maximum DR shed over all the DR events using a 5/10 (pronounced *5-in-10*) baseline with a morning adjustment factor. The details are provided in our complementary study, and the summary of the results are shown in Table I [8].

The maximum demand reduction (75th percentile) as a share of each category's coincident peak demand during May to October 2014 ranged from 2% (for Education) to 28% (for Packaging). Note that the share of demand response shown in Table I is not the reduction over the baseline peak demand, but over the six-month peak demand. We restricted our analysis to demand reduction only during the DR events, and have ignored any potential rebound effects in other periods.

TABLE I. PEAK DEMAND AND DEMAND RESPONSE ESTIMATES BY CONSUMER CATEGORY FROM THE TPDDL PILOT PROGRAM. SHARE OF DEMAND RESPONSE SHOWN IS NOT REDUCTION OVER BASELINE PEAK DEMAND, BUT OVER SIX-MONTH PEAK DEMAND.

Category ID	Customer Category	No. of customers in DR pilot (available data)	Peak demand May–Oct 2014 (kW)	Max demand reduction (75th percentile) (kW)	Demand reduction as % of peak demand
1	Auto parts	4	620	110	18%
2	Chemicals	2	430	60	14%
3	Cold Storage	6	1,100	170	15%
4	Commercial	11	4,600	350	7%
5	Education	3	1,900	40	2%
6	Flour Mills	25	7,300	1,100	16%
7	Food products	9	2,700	370	14%
8	Glass manufacturing	2	770	90	12%
9	Home products	5	1,000	250	24%
10	Hospitals	2	1,400	230	16%
11	Medical products	3	430	50	12%
12	Others	14	1,900	360	19%
13	Packaging	1	170	50	28%
14	Plastics manufacturing	18	2,200	300	14%
15	Printing	7	1,000	140	13%
16	Pumping	3	560	90	15%
17	Retail stores	3	60	20	26%
18	Shoe manufacturing	7	920	140	15%
19	Steel industry	17	2,000	160	8%

B. Methodology

Estimation of the potential of DR by extrapolation of data from a pilot study has some uncertainties, given that several different factors determine the actual DR that may be realized at a particular time that may not be represented by the results of the pilot program. However, it is useful to estimate the potential of DR to gain broader insights about the extent that DR can serve as a future resource. We outline our methodology, and then discuss the limitations.

For each customer category, the DR potential can be estimated by Equation 1.

$$DR\ potential = (Aggregate\ customer\ peak\ demand) * (DR\ as\ \%\ of\ peak\ load) * (Participation\ rate) * (Response\ rate) \tag{1}$$

The key requirements in estimating DR potential are data on aggregate load profiles, energy use during peak periods, and peak demands of different consumer categories within a utility. To estimate the DR potential in Delhi, we used different extrapolation strategies for different consumer categories, depending on the availability of data, in order to extrapolate our results from the TPDDL pilot program to the entire state. Note that Delhi is served by four utilities: TPDDL, BSES Yamuna Power Limited, BSES Rajdhani Power Limited, and the New Delhi Municipal Council.

We assumed the aggregate load profile of the participants in the pilot study from each consumer category to be representative of the aggregate load profile of the entire corresponding consumer category in Delhi. This assumption enabled us to apply the load factors of the pilot program participants that belonged to a particular customer category to the annual electricity consumption for those types of customers across Delhi, and to estimate their total coincident peak demand (See Equations 2–4).

We then estimated the total DR potential for each customer category from the peak demand for that category and the 75th percentile of the maximum DR shed determined in our complementary study, and provided in Table I [8]. The implicit assumption is that DR events happen during the same timeframe and weather conditions as the ones in the DR pilot program. Since we are using demand reduction estimates from the pilot study, the response rate of the participants (which is expected from the participants that are already enrolled in the DR program) is included in the demand reduction that we observed. However, in our estimation, we do not include the participation rate, which is the share of total utility consumers that are expected to participate in the DR program.

$$\widehat{LF}_c = \frac{\widehat{AD}_c}{\widehat{PD}_c} \tag{2}$$

$$PD_c = \frac{AE_c}{\widehat{LF}_c * 8760h} \tag{3}$$

$$DR_c = PD_c * \widehat{DR\%}_c \tag{4}$$

Where

c : Customer category

$\widehat{AD}_c$: Average aggregate demand of pilot participants

$\widehat{PD}_c$: Peak aggregate demand of pilot participants

$\widehat{LF}_c$: Load factor of pilot participants of a category

AE_c : Average electricity consumption for a category across a jurisdiction

PD_c : Peak demand for a category across a jurisdiction

$\widehat{DR\%}_c$: Demand response as percentage of peak demand estimated from the pilot program

DR_c : Technical demand response potential without considering participation rates

For most of the industrial customer categories (1, 2, 6–9, 11, 13–15, 18, and 19 from Table I), we used their corresponding National Industrial Classification codes to extract annual electricity consumption by state (Delhi) from the Annual Survey of Industries [9], [10]. The latest financial year for these electricity consumption data was 2011–12, three years before the pilot program was conducted.

Customer categories designated as "commercial" and "retail stores" in the pilot study are part of the "non-domestic" consumer category as reported by the Delhi utilities. While the small rain water pumping and sewerage loads that were part of the pilot program were not operated by the Delhi Jal Board (Delhi water utility), the main water supply and sewerage pumping loads of the Delhi Jal Board could make a significant contribution to DR in the future, making it important to estimate their DR potential. We attributed 75% of the total annual electricity consumption of the Delhi Jal Board to pumping loads (extrapolated from electricity expenditure and electricity consumption for pumping from [11]). We further assumed that these loads are similar in their characteristics as the pilot participants in the customer category of "pumping." We computed the total electricity consumption of the consumer categories of "non-domestic" and Delhi Jal Board across the state of Delhi from the tariff statements of all four utilities in Delhi [12]–[15].

For the customer category of "cold storage," we were not able to access data on total electricity consumption or aggregate peak demand in Delhi. As an alternative, we scaled the peak demand of three cold storage facilities that were part of the DR pilot program using a ratio of their aggregate cold storage capacity (13,000 metric tonnes) and the total cold storage capacity in Delhi (125,000 metric tonnes) [16], [17].

We were unable to estimate the DR potential for customer categories of "educational institutions," "hospitals," and "others" (5, 10, and 12 from Table I) due to unavailability of aggregate electricity consumption and peak demand data at the state level.

C. Demand Response Potential Results and Discussion

Figure 1 shows the DR potential estimates for the industrial customer categories included in our study. The total non-coincident technical DR potential for these industrial customer categories across Delhi is approximately 25 megawatts (MW). However, this estimate is only an illustration of the methodology, and should not be interpreted as an upper bound. Further, the total electricity consumption for these customer categories, based on the Annual Survey of

Industries [10], was only a tenth of the total electricity consumption for industrial customers in Delhi, as reported by the four utilities [12]–[15]. This difference in electricity consumption is likely due to both: an underestimation of total electricity consumption by these customer categories, and the presence of other types of industries not represented by the DR pilot participants. With greater participation rates, we may find a higher potential for DR than that estimated in our study.

In 2013–14, non-domestic customers accounted for 6,700 gigawatt-hours (GWh), or 30% of Delhi's electricity consumption [12]–[15]. Assuming load factors of 0.5 and 0.3, and demand reduction of 7% and 26% relative to their aggregate peak demand (parameters estimated from the pilot program participants), the "commercial" and "retail store" customer categories could provide a demand response of approximately 20 MW and 50 MW, respectively, if future DR participants in these categories were to account for 10% each of the total non-domestic electricity consumption.

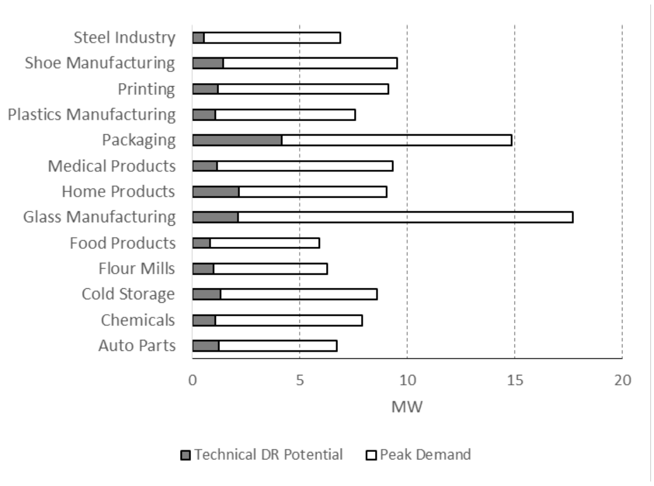

Figure 1: Demand response potential of certain industrial customers in Delhi

The Delhi Water Board's annual electricity consumption for 2013–14 was 550 gigawatt-hours (GWh), of which we attributed 75% to pumping loads. The pumping stations that participated in the pilot program provided a demand reduction of 15% relative to their aggregate coincident peak demand. Assuming a load factor of 0.25 (estimated from [11]) and participation rates between 20%–50%, the demand response potential could be in the range of 6–15 megawatts.

D. Assumptions and Limitations

Due to certain limitations, we made the following assumptions that should be considered while interpreting the results. First, we assumed that the participants in the pilot program are representative of their customer category for the entire utility or jurisdiction in terms of their load curves, strategies for demand reduction, price elasticities, behavior, and other factors. However, the peak demand and load factors for the pilot program participants were based on data that were collected over six months (May to October 2014), and not an entire year. While the peak demand estimates might not change if measured over the whole year, since Delhi customer loads peak during the summer months, the load factors can change significantly, thus affecting the estimates of the aggregate peak load for each customer category across Delhi. Given that the pilot program was in its first six months of operation, the estimates are likely to be improved as data on more DR events and additional customers are measured over a longer period of time.

Second, due to the unavailability of time-series load profile data for different customer categories aggregated at the state level, we needed to estimate the coincident peak demand for each of the customer types or categories from the load profiles of the participants from the pilot program. The number of participants in many customer categories was small, and may not be representative of the population.

Third, we assumed that the DR events in the pilot program are representative of future DR events for which the potential is being estimated, an assumption that may not hold, as utilities may design different incentives and programs in the future. Also, the DR events called during the pilot program do not all coincide with the peak demand hours of TPDDL (see Figure 2). If TPDDL were to call DR events at different times during the day or year with different weather patterns, the response rate and peak demand could be different, thus affecting the DR potential estimates.

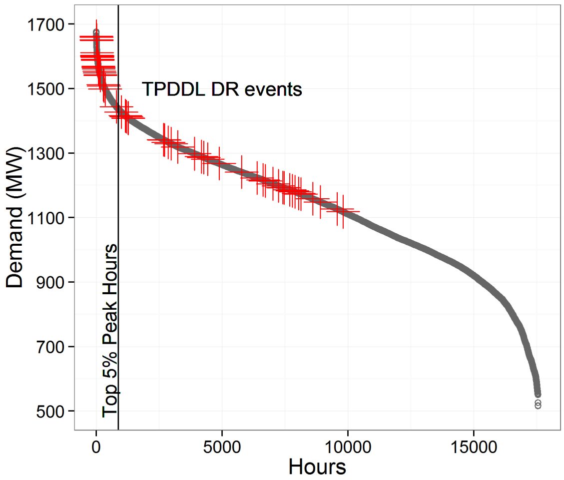

Figure 2: TPDDL's load duration curve and DR events (15-minute resolution)

Given these assumptions, our estimates should be considered as indicative, and further detailed analyses with better data are necessary to arrive at more accurate estimates.

III. ECONOMICS AND VALUATION OF DEMAND RESPONSE

Demand response can result in significant savings for both utilities and customers through reduction in demand during peak hours. However, these savings can vary depending on several factors that include, but are not limited to, utility rate structures, the utility's generation mix, supply-side markets, DR program costs, and customer participation and response rates. Understanding the economics of DR, particularly in the context of a particular utility and electricity sector, is important in order to determine the appropriate incentives for eliciting and realizing the expected levels of DR. Here we outline the methodology for valuing DR in the short run in the context of the Indian electricity sector.

A. Methodology for Valuing Demand Response

Since DR can result in savings for both the utility and the customer, we value DR from both perspectives. From a utility's perspective, the savings through the DR program need to be greater than its loss of revenue due to reduced energy sales, its share of costs for setting up and operating the DR program, and the DR incentives that it has to pay the participants (Equation 5).

$$DR\ incentives \leq (Utility\ savings - Utility\ loss\ of\ revenue - Utility\ DR\ program\ costs) \quad (5)$$

The short-run utility savings include avoided costs due to reduced unscheduled interchange (UI) drawal (or earnings due to UI injection during periods of low frequency), lower purchases on the wholesale day-ahead market (DAM), or avoiding generation from high-cost marginal generators. Unscheduled interchanges are the differences between the scheduled and actual drawal/injection of energy by a utility or generator. UI, in India, is a penalty mechanism tied to the real-time system frequency that discourages over-drawal and encourages injection during periods of low frequency, and vice versa. If the DR events result in reduction in energy consumption (DR shed), utilities could lose some revenue, especially if both fixed and variable costs are bundled in the per-unit consumer tariffs (which is the case for most utilities), and if the participant customer category cross-subsidizes other customer categories (e.g., commercial and industrial customers in India often have rates that are higher than the average cost of supply for the utility). If the DR event results in a shift in energy consumption from peak hours to non-peak hours, the utility could recoup some of these fixed costs and cross-subsidy charges. The utility share of DR costs include the fixed costs of infrastructure as well as the ongoing operating costs of the DR program. These costs will change on a per unit of energy (kVAh) basis depending on the participation and response rates of the customers, as well as on the type of DR program (AutoDR versus less infrastructure-intensive programs, which in turn may have lower reliability and response rates).

The benefits of the DR program for a participating customer include financial incentives for participating in the DR program, and also the savings that result due to reduced energy consumption during peak hours (Equation 6). In a time-of-use rate structure where tariffs during peak hours are higher than non-peak hours, customers are likely to save by shifting their consumption from peak hours to non-peak hours, assuming that they do not experience any significant rebound (i.e., the increase in energy consumption in non-peak hours becomes greater than the reduction in consumption during peak hours).

$$DR\ Incentives \geq (Customer\ opportunity\ costs + Customer\ DR\ program\ costs - Customer\ Savings) \quad (6)$$

From a customer's perspective, benefits associated with DR need to be greater than their opportunity costs, as well as their share of the actual hardware and operating costs involved in the DR program (especially in an automated demand response program) (Equation 6). Opportunity costs for the customers include costs due to inconvenience, rescheduling, loss of production, and additional maintenance, among others that the customer experiences for reducing its demand during a DR event. For a particular customer, these opportunity costs can change, depending on the time of day, frequency of DR events, and its particular activities.

There are other benefits of a DR program that are not captured by this model. These include long-run benefits from capital expenditure deferral, especially in generation capacity (in other words, providing more service through the same generation capacity), and transmission and distribution upgrades. Reducing peak demand could reduce carbon and particulate emissions, especially if the marginal generator is carbon intensive (such as an open-cycle gas turbine or an expensive coal turbine), or save precious water resources if the balancing unit is a hydropower plant. Customer audits conducted by the utility to identify DR opportunities and non-critical loads could also identify opportunities for energy efficiency, resulting in greater overall energy savings. Finally, DR has the potential to limit uncompensated load shedding, that is likely to result in both increased welfare for those who would have otherwise been left without electricity supply, and financial and carbon emissions savings for those who would have operated a diesel backup generator during deficit periods.

B. Valuing Demand Response for TPDDL

We analyzed the wholesale DAM prices, UI rates, and the generation costs for TPDDL to get insights into the valuation of demand response. We avoided estimating the savings for the actual DR events in the TPDDL pilot program for three reasons. First, the goal of the TPDDL pilot program was to establish technology effectiveness, and later to maximize the gains from DR in the interest of the customers [7]. Second, while the energy savings resulting from the DR events can be estimated, the avoided cost estimation depends on the counterfactual, which for TPDDL could have been higher purchases on the wholesale DAM, increased over-drawl (or decrease in injection) in real-time through UI, or increased generation through high marginal cost generators. Third, for the last counterfactual of potential increased generation from high marginal cost generators, we do not have data on the merit order or marginal generation unit during the actual DR events. Hence, we restricted our analysis to examining broader trends and potential savings per unit of energy avoided.

We analyzed the DAM prices from the India Energy Exchange (IEX) and the UI rates that are based on system frequency over the six-month duration of TPDDL's pilot program. Figure 3 shows the DAM prices and UI rates against TPDDL's demand, as well as the DR events (15-minute resolution) from the pilot program.

A DR event called during the top 5% peak hours for TPDDL (events that fall to the right of the vertical lines in Figure 3) would have resulted in an average savings of INR 4 per kWh from the UI mechanism or INR 4.5 per kWh from avoided purchases in the wholesale DAM (see boxplots in Figure 3). While these avoided costs are approximately equal to TPDDL's weighted average cost of generation of INR 4.2 per kWh [15], additional savings result due to avoided transmission charges and losses. From Figure 3, the hours of high DAM prices and UI rates, a sign of overall stress in the Indian national grid, are not closely correlated to the peak demand hours of TPDDL. Calling a DR event during the top 5% hours with the highest DAM prices or UI rates could have resulted in savings of at least INR 6 or INR 7 per kWh or higher through DAM or UI, respectively. Avoiding high-cost purchases in the day-ahead market, which clears 24 hours before actual dispatch may allow for sufficient time to plan a DR event. At the same time, anticipating a high UI rate (i.e., low overall system frequency dictated by the entire Indian national grid) during a specific time period may be a difficult task and may require calling a DR event at a short notice.

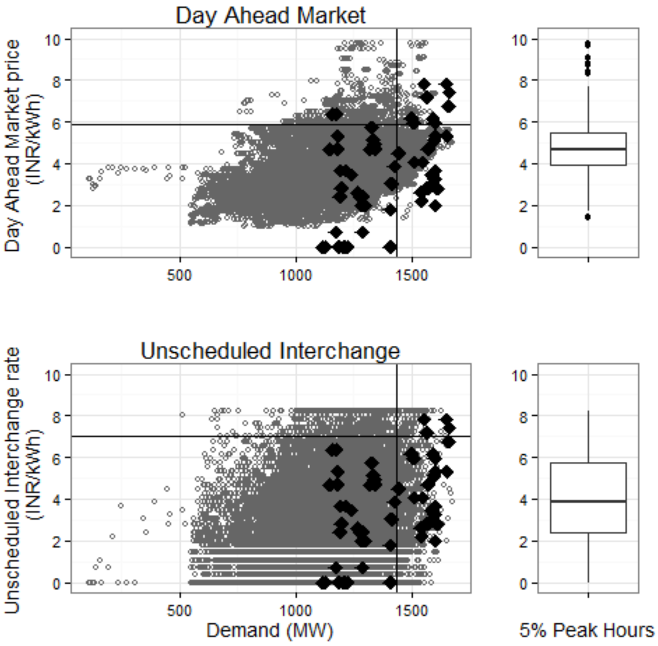

Figure 3: TPDDL's demand is slightly correlated to India Energy Exchange's day-ahead market (DAM) prices but poorly correlated to UI penalty rates based on system frequency (Data from May–Oct 2014). Vertical lines mark the top 5% peak demand hours for TPDDL. Horizontal lines mark the top 5% of hours with the highest DAM price or UI rate. Dark markers represent demand response events from the pilot program. Box plots show the distribution of DAM prices and UI rates in the top 5% peak demand hours.

TPDDL's savings can also come from the avoided generation from the marginal generation units. Often times, during peak demand hours, utilities find it difficult to purchase power through DAM or UI due to congestion in the transmission network. To avoid inadvertent load shedding, utilities are required to purchase electricity from marginal high-cost gas-based generators, which in turn may need to purchase fuel from the spot market at a high price, given the limited availability of natural gas in India. Figure 4 shows the supply curve for TPDDL's generators, along with the annual peak demand for 2013–14 and the average cost of generation [15]. TPDDL's savings would depend upon the generator that will be on the margin when the DR event is called. Savings will be especially significant when the marginal cost of supply is INR 6 per kWh and above, which is higher than the average cost of generation of INR 4.2 per kWh. TPDDL's average power purchase cost for 2012–13 was INR 5.45 per kWh, which included transmission charges and losses [15]. Avoided energy purchases from marginal generators, DAM, or UI will result in additional savings by avoiding transmission charges and losses.

Note that the savings in UI and DAM prices assumes that the frequency of the system and DAM prices are determined exogenously. In other words, we assumed that the utility's reduction in peak demand is small enough to not affect these two parameters. However, as larger and a higher number of utilities call coordinated DR events, greater reductions in demand could lead to increases in system frequency or suppress the DAM price, an effect that will need to be incorporated to better estimate the utility savings due to demand response.

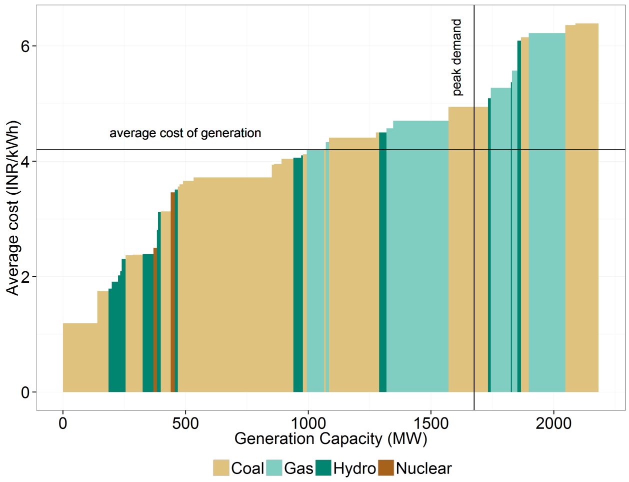

Figure 4: TPDDL's supply curve for available generation capacity in 2013–14, peak demand during 2014, and actual weighted average cost of generation for 2012–13.

In this study, we did not estimate utility loss of revenue and customer savings, since both these parameters depend not only on demand reduction during the DR event, but also on the rebound effect and shift in energy consumption to non-peak hours. Further, we do not estimate the opportunity costs for customers, since these would require elaborate research designs that vary incentives in a randomized control trial setting, a subject for future research.

IV. CONCLUSIONS

Demand response can provide significant benefits to both utilities and consumers by reducing consumption during peak hours. We estimated the DR potential by customer categories in the state of Delhi, which provides the scale of DR as a resource, and also understand the data requirements that would increase the accuracy of our results. We also provided an approach to value DR in the short run that provides useful insights to utilities that they can use to schedule their DR events to help reduce their own peak and maximize the value of DR while improving the overall reliability of the larger interconnected grid. In TPDDL's case, DR events that were called during the top 5% hours with the highest DAM prices or UI rates, which may not always coincide with TPDDL's peak demand hours, could result in savings of INR 6 per kWh and above in generation costs, as well as avoided transmission charges and losses during the DR events. The overall realized savings will depend on the extent of the shift in energy consumption to non-peak hours, and their associated costs.

Commercial and industrial customers have a significant potential to provide DR services. Better datasets in terms of larger samples (more customers), longer durations to capture all seasons, and more events at different times of the day will enable better analysis. Further, the quantum of DR that can be elicited from their customers depends highly on the incentives provided by the utility. While the pilot study did not offer varying prices for DR, in the future, TPDDL and other utilities may offer price-based incentives to elicit different levels of DR, in which case, determining price elasticities for different consumer categories during peak hours will be a significant area of research. Future research can include quantifying customer response rates by varying the number and frequency of events, pricing, type of signal, and information content. Quantifying both demand reduction and demand shift to non-peak hours, and rebound effects can enable more realistic estimates of realizable DR. Finally, innovative pilot programs using AutoDR with fast responses, specifically to balance variability introduced by increasing shares of renewables such as wind and solar, should be designed as DR plays a more prominent role as a resource to improve grid reliability.

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