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Characterization and Effectiveness of Technologies for India's Electric Grid Reliability and Energy Security

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***Abstract*—India's electricity grid is aging, and the transmission and distribution (T&D) losses amount to 25%, with $5.7 billion in financial losses to the utilities. In 2013–14, India had an average peak power deficit of 9% and an average energy deficit of 8.7% due to insufficient generation and transmission capacity, resulting in rolling blackouts. Technologies and interoperability standards have enabled utilities and systems operators in the United States (U.S.) to engage customers for electricity reliability. The Indian Government's Restructured Accelerated Power Development and Reforms Program established the need for automated systems to collect baseline data and information technology adoption for grid reliability. Tata Power Delhi Distribution Limited's (TPDDL) advanced Smart Grid project plans to increase reliability and readiness of customers for automated demand response (AutoDR). The project includes smart meters and interoperable communications for data analytics and automated dispatch for load reduction during power deficiency. This study characterizes TPDDL's integrated AutoDR system, including advanced metering infrastructure, data analytics, smart meters, and interoperability standards. We evaluate the technology effectiveness where the analyses show a 75th percentile load reduction of 10% for 144 commercial and industrial facilities with an aggregated coincident total peak load of 25 megawatts (MW). AutoDR can improve customers' responsiveness and a utility's arbitrage for electricity shortfall and high cost of peak power. A well-designed program can accelerate technology use and encourage customer participation. Innovative technology solutions can enhance the grid reliability by minimizing the instances of outages in India, and improve energy security by enabling integration of renewable generation to scale.**

Keywords— *Smart Grid Transactions; Automated Demand Response; Open Standards; Communication Technologies*

I. INTRODUCTION AND BACKGROUND

Technology impacts on electricity reliability, energy security, and carbon reduction can be significant. In 2012–13, India had an average peak power deficit of 9% and an average energy deficit of 8.7% [1]. In 2014, India had the world's fourth largest installed generation capacity—255 gigawatts (GW)—of which about 70% is from fossil-based fuels, with coal being the dominant power source [2]. While India has plans to improve electricity reliability by increasing generation with abundant coal, it is also pursuing aggressive renewable energy generation to improve energy security.

Enabling technologies, as well as policies that engage customers and efficiently manage the electricity system and its use, will play a key role in achieving these goals. India lacks sound policies and a technology roadmap for customer participation in electricity grid programs. One utility in India, Tata Power Delhi Distribution Limited (TPDDL), recently concluded a demand response (DR) automation project using Smart Grid technologies. The U.S. Department of Energy's (DOE) report to the Congress defines DR as short-term changes in electricity usage by end-use customers, from their normal consumption patterns. Demand response may be in response to: (a) changes in the price of electricity, and (b) participation in programs or services designed to modify electricity use in response to wholesale market prices or when system reliability is jeopardized [3]. While DR can be manual, a fully automated DR (AutoDR) does not involve human intervention, but is initiated at a building through the receipt of external communication signals [4]. Automation technologies that allow customers to transact with the electric grid at different time scales are successfully deployed in the U.S. and other countries [5]. Technology applications in India can support low-carbon growth and cost-effective market structures to reduce peak power and improve resiliency by better integration of variable generation (e.g., solar) [6].

This study evaluates TPDDL's project from the context of an AutoDR system, which includes advanced metering infrastructure, smart meters, data analytics, and open interoperability standards. We characterize the technology effectiveness where the analyses have shown a 75th percentile load reduction of about 10% for 144 commercial and industrial facilities with an aggregated coincident total peak loads of 25 MW. With Delhi's total generation capacity of 8.2 GW and its consideration as one of the 100 Smart Cities in India, there is an opportunity to leverage technologies and flexibility in energy use. Two other symbiotic studies provide insights on: (1) Customer characteristics and DR performance, and (2) potential for scaling and valuation [7, 8]. Earlier studies have reviewed India's Smart Grid initiatives and have proposed a technology framework for the integrated energy efficiency and DR action plans [9], and identified grid integration technologies, knowledge transfer, and their market potential for the U.S.-India collaboration in the broader context for efficient, responsive, and resilient buildings [10].

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The U.S. federal and state initiatives are promoting grid-integrated technologies and standards that enable electricity demand to transact with supply as a cost-effective and carbon friendly solution to ever-increasing demand. The U.S. Federal Energy Regulatory Commission (FERC) estimated the 2019 U.S. potential for reduction in peak demand with full participation as 138 GW, or 14%, relative to a scenario with no DR programs [11]. These FERC estimates assume universal deployment of advanced metering and default dynamic pricing tariffs with advanced technologies for grid transactions. In a recent study, the contribution of DR for ancillary services or fast dispatch markets by the independent system operators was 28.3 GW, or 6% of peak load [12]. These technologies for automation are deployed in commercial DR programs for over 1,200 customers with a total enrolled DR capacity of over 250 MW [13]. Select constituents in the U.S. are also aggressively pursuing using energy efficiency building codes and communication standards as a mechanism to increase DR participation and cost-effectiveness [14].

In India, the following key initiatives offer significant opportunity for technology applications: (1) the National Smart Grid Mission (NSGM) in the power sector, (2) the Ministry of Power's (MoP) Restructured Accelerated Power Development and Reforms Program (R-APDRP), (3) 100 Smart Cities, and (4) aggressive renewable generation. The recent initiative, NSGM, highlights the challenges with increasing distributed and variable generation and an electric vehicle (EV) rollout, and the need for dynamic management of load and generation. In addition to automation, the NSGM recommends communication and information technology (IT) systems to monitor the power flows, real-time demand management to match generation, and allowing customers who produce and consume electricity (prosumers) to safely connect to the electric grid. The NSGM builds upon the R-APDRP implementation, which uses advanced technologies within the distribution systems and in cities. India has ambitious plans to generate 100 GW of solar power by 2020. This is significant considering that nearly 30% of this capacity will be achieved through customer-side rooftop solar panels. Studies suggest that wind and solar integration require enabling technologies, frequency regulation markets, and utility cooperation for reliable grid operations, especially during peak demand [15].

II. Advanced Technologies for Grid Transactions

This section describes advanced technologies that are deployed in the U.S. to enable customers to transact with the electricity grid. In particular, it describes three key technology areas that enable customers, distributed energy resources (DER), and electric vehicles (EV) to participate in the electricity markets and support India's electricity reliability goals. Smart Grid standards, essential for communications interoperability and cyber-security, are also reviewed.

The technologies used by the customers to transact with the electric grid must be based on the paradigm of interoperability standards. Such standards when integrated with information and communication technologies can accelerate and leapfrog deployments, reduce integration costs, and improve adaptation to new programs and market structures. These technologies can also be used to facilitate the integration of the DER into the grid and allow two-way communications and cyber-security. The following technology applications are characterized for the Indian context:

a. Customer transactions with the electric grid and markets
b. Customer-side distributed energy resources integration
c. Electric vehicle integration in a distribution system
d. Smart Grid Interoperability Standards

A. *Customer Transactions with the Electric Grid and Markets*

Research and data from commercial deployment suggests that customers with automation technologies provide higher average load reduction compared to those customers who did not have automation [16]. AutoDR customers have a higher participation rate, and their enrollment "improves operational efficiency and reduces operational costs," which are primarily driven by avoiding the non-performance penalties and higher energy costs for peak power [17].

The U.S. electricity markets for transmission and distribution (T&D) systems are diverse. The independent system operators (ISO) and regional transmission operators (RTO) oversee the bulk electric power systems and wholesale electricity markets. In most cases, the member utilities manage the distribution systems and DR programs at the customer-level or retail markets. Grid-integrated technologies must allow both loads and customer-side distributed generation to participate in either of the electricity markets to maximize their effectiveness.

Figure 1 shows two-way AutoDR technologies to automate prosumer control systems with both ISO and utility markets. A "client" with a controller in a building energy management and control system (EMCS) interacts with either the utility or ISO market signals for DR transactions. A DR automation "server" in the grid enables the utility or ISO to dispatch grid reliability (including emergency) and price signals to the client, which initiates pre-programmed DR strategies that are chosen by the customers. Examples of two-way signals include prices, operation modes, and telemetry for load data, among others.

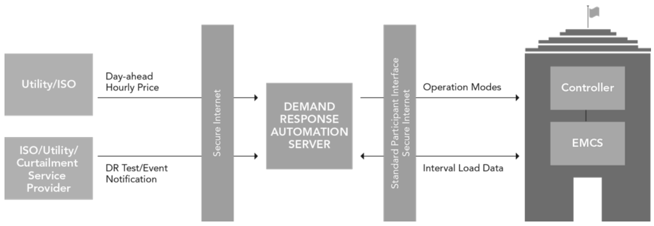

Fig. 1. Customer-side Transactions with Utilities and System Operators (*Source: Lawrence Berkeley National Laboratory, DRRC Annual Report*)

Table I shows that California utilities, which have the highest number of AutoDR customers in the U.S., offer different incentive levels to their customers [18]. The three major utilities—Pacific Gas & Electric Company (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E)—provide incentives ranging from $200 to $400 per kilowatt (kW) of estimated load reductions. PG&E offers greater incentives for advanced AutoDR technologies (e.g., dimmable lighting controls) to encourage their adoption.

TABLE I. UTILITIES' 2012–14 INCENTIVES FOR DEMAND RESPONSE ($/KW)

Technology Category	PG&E	SCE	SDG&E
Automated Demand Response	$200	$300	$300
Emerging & Advanced Technology HVAC/R	$350	NA	NA
Emerging & Advanced Technology Lighting	$400	NA	NA

B. Customer-Side Distributed Energy Resources Integration

Historically, DR technologies were used to reduce peak power, and in the case of ISOs, to balance the centralized generation and demand changes using ancillary services [5]. With the increase in distributed and customer-side DER, technologies that dynamically manage customer's electricity reliability, distribution grid safety, and two-way power flows are gaining momentum. To optimize customer resource capabilities and operation schedules, simulation and modeling tools, shown in Figure 2, are used for optimization using external and internal data parameters such as electricity costs and prices, weather, and load forecast using distributed energy resources customer adoption model [19]. Integration of market-based signals empowers the customer decisions for local reliability (e.g., microgrids) and provisioning grid transactions.

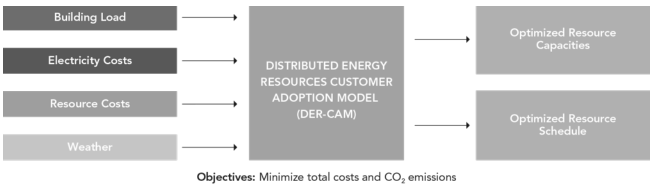

Fig. 2. Dynamic Optimization of Customer's Distributed Energy Resources (*Source: Lawrence Berkeley National Laboratory, DRRC Annual Report*)

C. Electric Vehicle Integration in a Distribution System

The U.S. has aggressive goals to deploy 1 million electric vehicles (EV) by 2015 to lower emissions from the transportation sector [20]. While large-scale deployment and charging of EVs can put more strain on the grid, they offer unique opportunities to improve grid reliability. Using the technologies and tools mentioned above, Figure 3 shows forecasting and schedule optimization for real-time control, EV fleet charge management, and vehicle-to-grid resources [21]. The technologies have allowed the ISOs and distribution utilities to use EVs as a grid resource while maintaining the EV customer's benefits and mobility needs in mind.

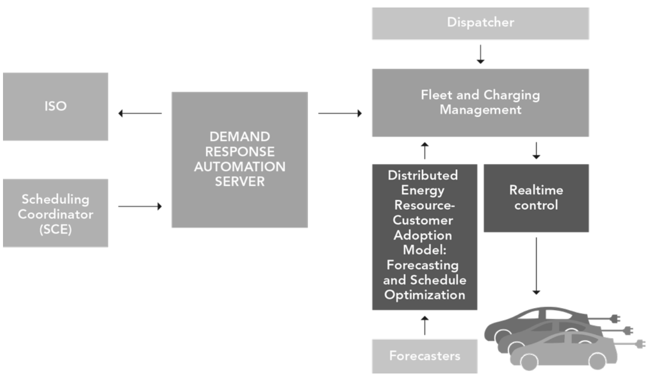

Fig. 3. Electric Vehicle Integration for Smart Charging and Grid Services (*Source: Lawrence Berkeley National Laboratory, DRRC Annual Report*)

D. U.S. Smart Grid Interoperability Standards

Demand response provides multivariate benefits or values for utilities or ISOs and different vendors to develop and sell products for customer sectors and the grid. Technologies-based interoperability standards allow different vendors to easily participate in grid transactions [22]. A Smart Grid can be viewed from different domains that are operated by disparate entities, and can provide benefits such as efficiency in electricity delivery, consumption, and de-carbonizing the grid using renewable generation. While this study focuses on interfaces between the distribution and customer-side systems, there is an underlying and critical need to develop standards for a secure and interoperable Smart Grid, and to improve cyber-security of the critical infrastructure [23]. The U.S. efforts also provide cyber-security guidelines [24] and have led to acceptance and use of DR technologies to harmonize Smart Grid standards and a global architectural framework.

Summary: Technologies can improve electricity reliability and energy security by managing the demand to reduce peak power without additional capacity, and better integration of variable generation. The priorities of both U.S. and India are well aligned in the areas of distributed and renewable generation, demand-side transactions, and development of technologies and power systems for the next-generation electric grid. These priorities represent key market opportunities for grid-integration technologies and energy efficiency in India.

III. TECHNOLOGY CHARACTERIZATION IN INDIAN MARKETS

This section characterizes technologies to increase reliability and readiness of customers for an AutoDR project by a distribution utility in India, Tata Power Delhi Distribution Limited (TPDDL). This first-of-its-kind project includes smart meters and a DR system for automated dispatch and load reduction during power deficit periods. Major U.S. vendors in this market provided the advanced technologies and services to modernize the distribution system and improve electricity reliability. These technologies are similar to those deployed in the U.S. for customer transactions with the electric grid and markets, and for interoperability standards.

A. Advanced Technologies for Distribution System Reliabilty

TPDDL technology solutions include an AutoDR system and DR controller, provided by a U.S. vendor. The automated metering infrastructure and Smart Meters provide 15-minute interval energy use data. Figure 4 shows the interconnection between TPDDL and the customer. While the meter data management systems use energy data for billing and to provide customers access to energy data, the AutoDR system uses the data for measurement and verification (M&V) or DR settlement. The AutoDR system uses interoperable communication standards to send the operation modes to the DR controller. Customers use the online portal to commission the DR controller, view DR event status, and configure operation modes. DR controller "polls" for these operations modes from TPDDL, and the direct digital control (DDC) outputs, as opposed to the analog controls, activates the customer's pre-programmed DR strategies.

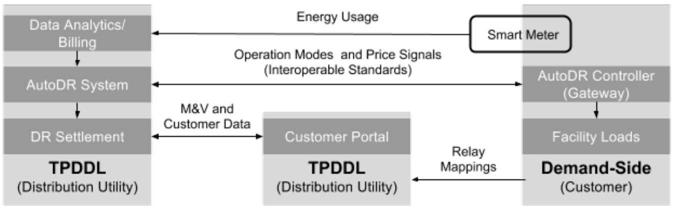

Fig. 4. Automated Demand Response System Architecture by TPDDL

B. Technical Specifications

The U.S. vendors worked with TPDDL for technology transfer and for the applications of AutoDR technologies in the Indian markets. The deployments identified new requirements to lower technology costs and to harmonize Smart Grid interoperability standards. For example, using the development lessons, the AutoDR controller solution costs 45% less than the traditional controller used in the U.S. Providing a minimum necessary number of DDC inputs/outputs, memory, processor units, control system protocol interfaces, pulse inputs, and Ethernet and cellular communications reduced the cost. Use of open and industry-supported standards reduced the deployment and installation costs. Since most of the facility controls did not have connectivity (e.g., Internet) to the external network, GSM cellular modems provided DR communications.

All 173 customers who participated used simple DR strategies to turn the equipment ON/OFF, which involves the curtailment of non-critical loads with customer's consent. TPDDL programs defined the signals, which included operation modes such as NORMAL, MODERATE, HIGH, etc. These modes are used to indicate load- or price-change levels. The AutoDR system also provides other DR programs such as electricity/energy prices and load changes (e.g., kilowatts/kilowatt-hours, percent). The participating loads from the customers included three-phase pumps, motors, compressors, cooling systems, etc. where the AutoDR controller monitored the status (ON/OFF) and changed the status of loads in the ON state upon the receipt of DR signals.

Summary: The TPDDL project characterizes technology for field tests. While technology costs were lower, vendors are considering improvements to further reduce the costs. The lack of network connectivity required the use of cellular data networks, which increased the operation costs. Solutions such as mesh networks; low-data transfer, etc. can be considered in future. The lack of intelligent controls in facilities led to the use of simple DR strategies. The use of advanced strategies and dynamic optimization may be necessary to temporarily reduce the service levels as opposed to complete lack of service (e.g., dimming lights) without impacting the building operations.

IV. Technolgy Effectiveness In Indian Markets

This section describes the customer sectors and their performance results. The reliability of AutoDR performance can be a proxy for the effectiveness of automation technologies. Considering there were no preset load-reduction estimates, *reliability* refers to the automated execution of DR.

A. Analysis of Customer Performance Results

The customers included offices, educational institutions, retail stores, industrial facilities, water and sewage pumping, flour mills, and cold storage. Of the 173 customers, meter data were provided for 144 customers, which was used in our analyses. The resulting total coincident peak was 25 MW.

The baseline models are key for measurement and verification (M&V) of DR performance. The baselines provide an estimate of what the facility load would have been on the day of the DR event without any DR actions. While TPDDL used the 5/10 (pronounced *5-in-10*) baseline for M&V, our study also used the 5/10 with a Morning Adjustment (MA) factor. Earlier studies have reviewed different baseline models used in the U.S. and concluded that the MA factor significantly reduces the bias and improves the accuracy [25]. Table II shows the taxonomy for each of the nine customer sectors, total peak demand, and total demand reduction percentage when measured against the whole-building power (WBP) and 5/10 baseline. Our analyses show a total coincident peak demand of 25 MW with average reduction of 10%, or 2.3 MW, for the 75th percentile. According to the TPPDL, the total connected customer load is 67 MW, the maximum DR from all the customers was 7 MW, and the total DR achieved from 17 events was 0.063 million units (or million kWh). Customers defined the control strategies and end use types for AutoDR. These control strategies were based on day-ahead notifications.

TABLE II. Customer Sector Peak Demand Reduction (kW and %)

Sectors	Peak Demand kW (# cust.)	% WBP (75_{th} percentile)
Cold Storage	1,131 (6)	34
Commercial	4,646 (11)	8
Education	1,936 (3)	3
Flour Mill	7,265 (25)	19
Hospital	1,434 (2)	18
Industrial	10,044 (77)	10
Others	1,889 (14)	26
Pumping	556 (3)	62
Retail	62 (3)	50
Total	**25,259 (144)**	**10**

To evaluate the grid impacts of these results, we have to understand the electricity supply and demand conditions in the DR region. Figure 5 shows the allocation and actual energy drawl imbalance in TPDDL territory. The imbalance is calculated from the scheduled drawl (allocation) versus actual demand data, which can be a proxy for drawl (*Imbalance = Allocation – Drawl*). Of the 4,000+ imbalance hours from April to September 2013 shown in Figure 5, 25% of the hours represent over-drawl conditions for TPDDL. The over-drawl potentially could be reduced from 324 megawatt-hours (MWh) to 147 MWh if TPDDL had dispatchable demand for the top 40 hours of the highest over-drawl power (~1% of the total).

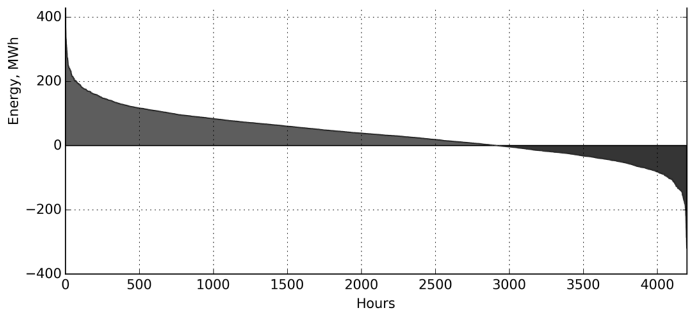

Fig. 5. Over- and Under-Drawl Imbalance Conditions for TPDDL (Apr. to Sep. 2013); Top: Under-drawal, Bottom: Over-drawal

Figure 6 shows an aggregated DR performance, and for each of the sectors for all 17 events using a 5/10 baseline. The industrial and flour mill sectors were the majority customers with a 75th percentile DR of 10% and 19%, respectively. The aggregated DR from all customers is 10%, and the cumulative coincident peak demand is 25 MW. The 75th percentile is considered because it represents a conservative estimate, reflecting the lack of financial incentives offered to customers that encourage persistent DR performance. The financial incentives have the potential to improve the performance.

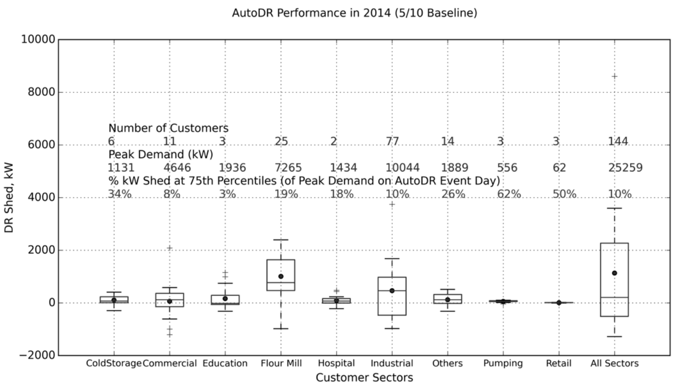

Fig. 6. Individual and Aggregated Customer Sectors' AutoDR Performance

Note that these results indicate the reliability of technology performance and automated execution of DR strategies. The minority of customer sectors, other than flour mills and industrial, that did not perform well need further investigation for performance of load effectiveness. However, this must not be interpreted as lack of technology effectiveness. The detailed customer analysis, baseline models, and load effectiveness are described in our complementary study [7].

B. Technology Costs and Market Potential in India

One of the key metrics to evaluate AutoDR cost-effectiveness is to look at the customer technology enablement costs and how much DR they can provide. For example, if it cost $10,000 to enable a DR of 100 kW, then the customer technology enablement cost is $100/kW. These costs typically include hardware and software, controls programming for DR strategies, and integration of AutoDR signals with these pre-programmed strategies for end-to-end automation. Similar to energy savings, these DR savings accumulate every year, which leads to larger technology adoption benefits over time. From the U.S. experiences, the average AutoDR technology enablement costs in existing buildings are about $215/kW [13]. While this cost is high, it still costs 10% to 15% of current grid-scale battery storage costs [6]. Deployment and operational costs of AutoDR and grid-scale batteries continue to decrease as a result of technology improvements and scaling. According to TPDDL, the DR technology enablement costs per customer are expected to be less than INR 80,000 (~$1,300). Based on these preliminary data, the estimated technology enablement costs for 2.3 MW of DR from 144 customers is $80/kW. This cost is about 63% lower than similar technology deployments in the U.S. This study did not review all the reasons for these lower costs due to insufficient information.

For TPDDL and similar Indian utilities, peak load reduction can result in savings, either through reduction in unscheduled interchange over-drawl penalties, reducing the need for short-term power purchase through the day-ahead market, or by avoiding generation from expensive marginal generation units. For customers, potential benefits come from avoiding higher prices during peak hours and through improved grid reliability. Cost savings can vary, based on whether the reduction in peak demand is a shed or a shift to non-peak hours. Customers can also receive financial incentives, a compensation for costs incurred to enable DR automation, and their "opportunity costs" from DR. The incentives that the utility will need to provide will depend on the costs and savings of both consumers and the utility. These incentives, in turn, will dictate the participation and response rates of the customers. The detailed valuation of DR through the TPDDL pilot study and the market potential for DR in the state of Delhi are described in our complementary study [8]. Previous studies describe the technology market potential in the context for efficient, responsive, and resilient buildings [10].

Summary: AutoDR has the potential to lower a utility's over- and under-drawl imbalance band significantly by providing slow and fast dispatchable demand. The customers were not paid any incentives or performance-based credits to participate in the demonstration. The TPDDL-paid AutoDR technologies and Smart Meter were key motivations for customer recruitment and participation in the field tests. Customers also benefited from online access to energy use data, which can be used for energy efficiency improvements. Customers responded to the day-ahead signals, which can be scaled to shorter notification times as needed. The technologies used by TPDDL provide additional benefits. Customers can be better aware of their load profiles and facility operations, which can drive to energy efficiency goals. According to TPDDL, the key technologies benefits include: customers' empowerment, better feeder management and customer loading, optimization of grid investments, and peak power purchase savings. TPDDL anticipates expanding the AutoDR project to 800 more customers, resulting in a three-fold increase in DR potential of 20 MW.

V. Discussions, Conclusions, and Future Work

In this paper we reviewed and characterized the grid integration technologies necessary to enable customer-side loads and DER to participate in utility's electricity markets. The study has engaged public and private sector stakeholders from the two countries, as well as regulators, utilities, and customers in India. The preliminary findings and results reported here suggest that DR is a promising area for continued support from the U.S. and India, and public and private sectors. India's Smart Grid initiatives are at a nascent stage. The U.S. knowledge and technology transfer in this area through bilateral collaboration can leapfrog India's quest for technology and accelerate their adoption. Initiatives such as NSGM and R-APDRP provide an excellent platform for technology development and adoption in the Indian markets. We reviewed an advanced demonstration project by India's TPDDL to verify the effectiveness of AutoDR technologies. The TPDDL project provides insights on customers, demand, and DR benefits. The lessons will help TPDDL, other utilities, and regulatory agencies develop market mechanisms to improve the distribution system. The project is a testament to India's accelerated technology adoption, which drives improved reliability of the U.S. electric grid.

A. Discussions

The TPDDL project provides early insights for demand flexibility. The small dataset show the need for more empirical studies to identify benefits at various levels (e.g., customers, utility, system) and evaluate the role of technologies and regulations for electricity reliability and security imperatives.

AutoDR and Demand-Side Flexibility Benefits: Customer's load flexibility and AutoDR can improve electricity reliability and mange peak loads within the distribution system. Utilities can use AutoDR as a resource to adjust corresponding over- or under-drawl conditions to reduce price risks and the unscheduled interchange penalty, and to improve reliability. To scale technologies within larger areas, India must consider the value stream at different Smart Grid domains, and also the impacts of AutoDR notifications of shorter duration (hour, minutes).

Electricity Reliability and Energy Security Imperative: India's grid reliability and energy security objectives are drivers to review the TPDDL project for scalable applications of technologies. These objectives and ever-increasing demand charge the public bodies, government, commissions, and utilities to develop grid codes and dynamic-pricing electricity markets to encourage AutoDR programs and technologies.

B. Conclusions

From the characterization and performance analyses, the technologies were effective in average load reduction of 10%, or 2.3 MW. Two major customer sectors, flour mills and industrial, had a load reduction of 10% and 19%, respectively. Albeit a minority, other customer sectors, cold storage, commercial, education, pumping, and retail show promising results. These results are indicative of technology potential for large impacts where T&D losses amount to 25% and average peak power deficit is 9%. Technologies can lower utility's over- and under-drawl imbalance band by providing slow and fast dispatchable demand. The technologies used by TPDDL can also be used in large commercial and industrial facilities for resilient and responsive cities. The following factors can affect the success of DR automation technologies in India.

- Electricity market design to establish technology value.
- Financial incentives for persistency in DR performance.

Flexible and responsive demand will help India mitigate investment costs for expensive generation, improve system efficiency, and help integrate renewable energy into the grid. By the same token, the U.S. will gain critical technical and market knowledge by adapting their technology to the Indian environment. The implementation of DR systems and technologies is highly dependent on the local context; market conditions, policy and consumer behavior, and the international collaborative nature of this project will help accelerate knowledge transfer with tangible results.

Through the NSGM, R-APDRP, Smart Cities, and relevant initiatives, India should conduct technology research and development while deploying mature and tested technologies to support both energy efficiency and grid integration. National policies, model projects, and education and training must encourage customer participation, harmonize standards, and facilitate system- and component-level interoperability for grid connectivity. We believe that cost reductions from hardware and software development and plug-and-play features will advance Smart Grid objectives in India, which also benefits the U.S. by lowering the deployment costs. Initial results show that AutoDR can improve customer responsiveness and utility arbitrage for electricity shortfalls and the high cost of peak power. Without a formal DR program and financial motivation, the performance may not be persistent. A well-designed program accelerates technology use and customer participation and potential new value streams. Innovative technology solutions can enhance the grid reliability by minimizing the instances of outages and improve energy security by enabling integration of renewable generation to scale.

C. Future Work

Future technology development in India must focus on two key aspects: cost reduction and performance scaling. The technology enablement costs considered simple DR strategies such as switching equipment ON/OFF. Advanced strategies involve controls programming and integration of DR signals, which costs more. The key questions to focus are: **What are the technical considerations to reduce the technology costs by an additional 50%? How to develop scalable demand-responsive controls systems for a persistent AutoDR load reduction of 10% or greater? What market-based incentive type and levels are appropriate for DR to be reliable?**

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