The Values of Market-Based Demand Response on Improving Power System Reliability under Extreme Circumstances

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Abstract

Power system reliability faces serious challenges when supply shortage occurs because of unexpected generation or transmission line outages especially during extreme weather conditions. Alternative to conventional approaches that solicit aids from the generation side, operators can now leverage the demand-side resources through a variety of electricity market mechanisms to balance the active power and enhance system reliability. The benefits of the demand response (DR) have long been recognized in many works and empirical cases. Systematic analyses, however, have never been addressed to assess the values of the market-based DR for supporting system reliability. In this paper, a case study on the performance of DR in PJM Interconnections during the 2014 North American Polar Vortex is provided to highlight the significant contributions to improving system reliability and maintaining grid stability from DR programs. The unique merits in technical, economic and environmental aspects exhibited by DR during this extreme event verse conventional system-reliability-improving approaches are also demonstrated accordingly. Furthermore, we reveal the difference of DR programs driven by various existing market mechanisms after describing the fundamental DR functions. Values of various DR programs are also highlighted. At last, challenges and opportunities facing China on the design and implementation of DR programs during the transform from the monopoly scheme to an open electricity market during the power industry restructuring in recent years are also discussed.

Keywords: demand response; electricity markets; power system reliability; polar vortex

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1. Introduction

The reliability has long been the primary concern in all operational and planning activities of electric power systems[1]. Conventionally, system operators and planners solicit solutions mainly from the generation side to maintain a desired reliability level, which is typically characterized by the reserve margin in short-term operations and by the loss of load expectation in the long-term planning. This approach has proved to function effectively for decades. However, in recent years, reliability threats increase drastically due to the deepening penetration of various energy resources (VERs). The uncertain and sometimes fast-changing VER outputs require more flexibility in power systems to respond to expected or unexpected changes in order to maintain reliability. Moreover, the frequent occurrences of extreme weather such as 2014 North America Polar Vortex [2] and recent heat waves in major cities in China also pose substantial threats to the system. Under such urgent conditions, the load may jump up in a short time yet the availability of conventional generators as well as the available transfer capability of the transmission network may deteriorate significantly, further resulting in deficiencies in reserves or even worse, shortages in power supply. Undoubtedly, the ability of a power system to ensure reliable operations, particularly during system emergencies, become increasingly critical.

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There have been many works addressing power system reliability from the conventional supply and transmission sides. A long-term reliability-constrained tri-level robust power system expansion planning framework is proposed in [3] while considering multi-fold uncertainty from generation, transmission and demand sides. Reports [4] and [5] suggest the construction of new generation and transmission assets to maintain system reliability since New England region is increasingly reliant on the natural gas. Strategic operations of generations, storage devices and other conventional facilities are also addressed to improve the system reliability. However, with the increasing complexity of the power grid, power system planning with focuses on conventional facilities becomes extremely challenging from both technical and politic aspects, in particular for transmission line expansion [6]. Several major factors delay the developing pace of transmission network: lack of effective coordinated planning efforts to prioritize transmission projects to be built; lack of an efficient cost allocation mechanism to incentive transmission developers; and impediments to siting new transmission facilities from both state government and local residents.

The advent of massive demand-side resources brings new opportunities for system operators to leverage the flexibility and to maintain system reliability from the other side [7, 8, 9, 10, 11, 12]. The concept of the demand response (DR), which evolved from a precedent concept called *demand side management* (DSM), has emerged as a new vehicle to help maintain power system reliability. Federal Energy Regulatory Commission (FERC) defines the *demand response* (DR) as "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [13]. The issuing of FERC Order 745 legitimized the eligibility of DR to be paid at same locational marginal price (LMP) in the wholesale markets [14].

Location-dependent impacts of demand responses are addressed in [15, 16]. Meanwhile, paper [16] assess the benefits of residential DR programs in real-time energy market from the distribution level. Some preliminary works [17, 18, 19] discuss functionalities of the demand-side management from the perspective of electricity markets. Papers [20, 21, 22] propose several approaches or mechanism that encourages end users to sign up for the right contract and make use of the true value of their flexible demand activities. Reports [23, 24, 25] explore major industrial incentives for the development of DR under the smart grid paradigm and summarize the evolving/existing DR programs at different independent system operators (ISOs) or regional transmission operators (RTOs). In 2007, Southwest Power Pool established *Demand Response Task Force* and started to integrate DR programs into its market framework [26]. Florida Power & Light Company has sought out and implemented cost-effective DSM programs since 1978 and the efforts through 2015 have resulted in a cumulative summer peak reduction of 4,845 MW and an estimated cumulative energy savings of 74,717 GWh at the generator [27]. Midcontinent ISO (MISO) market provides multiple opportunities [28] for DR participants: 1) Demand Response can offer into the energy market or spinning/supplemental reserve markets; 2) Demand Response can offer into the energy market and regulation/spinning/supplemental reserve markets and is treated identically to a generation resource; 3) Emergency Demand Response. MISO also describes in [29] the compensation for demand response in wholesale markets to comply with FERC Order 745. Both reliability-based and economic-based DR programs are adopted by New York ISO for different application purposes [30]. Recently, California ISO establishes a new policy to encourage the development of viable wholesale demand response products with direct market participation capability [31]. Upon completion, demand response services can be traded as market products by non-generation resources and used for maintaining power system reliability. In PJM, DR is a voluntary program that allows electricity customers to curtail their electricity usage during periods of high electricity prices [32]. In exchange, customers are compensated for decreasing their electricity use when requested by PJM.

Demand Side Management Methods released by National Development and Reform Commission of China formally initialized demand-side management efforts in China [33, 34]. Last year, a new regulation policy entitled "Decree No. 9: Several Guiding Principles of Furthering the Reform of the Electricity Market" issued by China's government urged the transform from monopoly structure to open electricity market under the background of great reform of the entire electricity sector [35]. Several provincial and municipal governments become demonstration sites for electricity reform, including Shenzhen, Guizhou Province, Hubei Province, Yunnan Province and so on. This big step towards market reform builds a solid background for China to develop DR [36, 37]. In April 2015, following the No. 9 [2015] of State Council, National Development and Reform Commission released Notice on *Improving Demand Side Management Pilots through Emergency Power Mechanisms* to further strengthen the development of demand-side management and, thus, DR. Research work [38] discusses the potential role of DR in China as an efficient tool to alleviate energy shortfall. However, lack of appropriate incentive to implement DR programs by grid operators and lack of one competitive electricity market are both barriers for China to further develop DR programs [39, 40]. We will briefly talk about opportunities and challenges to implement DR in China.

A comprehensive and deep understanding of the values that market-based DR can bring to power systems will surely benefit the development of future DR programs in China as well as the improvement of existing DR programs in US. To this end, we first present some statistics and facts from the 2014 North America Polar Vortex event to highlight the significant contribution that DR can make to maintain system reliability. With this special case in mind, we proceed to present a systematic analysis on the market-based DR programs using PJM as a representative example – from the fundamental physical functions to the various existing market programs, and from the retail market level to the wholesale market level – to reveal the values of the market-based DR in supporting system reliability. We note that the fundamental physical functions constitute the basis for the implementation of various retail DR programs, which further constitute the basis for the provision of DR products in the wholesale markets. In addition to relating the commodity properties of the DR to its physical properties, we also link the advantages of DR as a market product to its reliable and flexible physical nature.

The rest of this paper is organized as follows. In Section 2, we describe the 2014 North American Polar Vortex event and analyze the contribution of DR in PJM in maintaining system reliability during this event. Fundamental functions of DR, as well as its advantages, are summarized in Section 3, followed by a detailed discussion in Section 4 on the existing market programs that incentivize the participation of DR in various markets and recognizes its reliability and economic values. We analyze the challenges facing the DR implementation in China in Section 5 and make some concluding remarks in Section 6.

2. DR's contribution in PJM during The 2014 Polar Vortex

During January 2014, the North America, the Eastern Interconnection[1] in particular, was swept by extremely cold weather with record or near-record low temperatures [2]. While the temperature was low throughout the entire January, it reached its lowest levels during the Polar Vortex from January 6 to 8 and the Winter Storms during January 16 to 29.

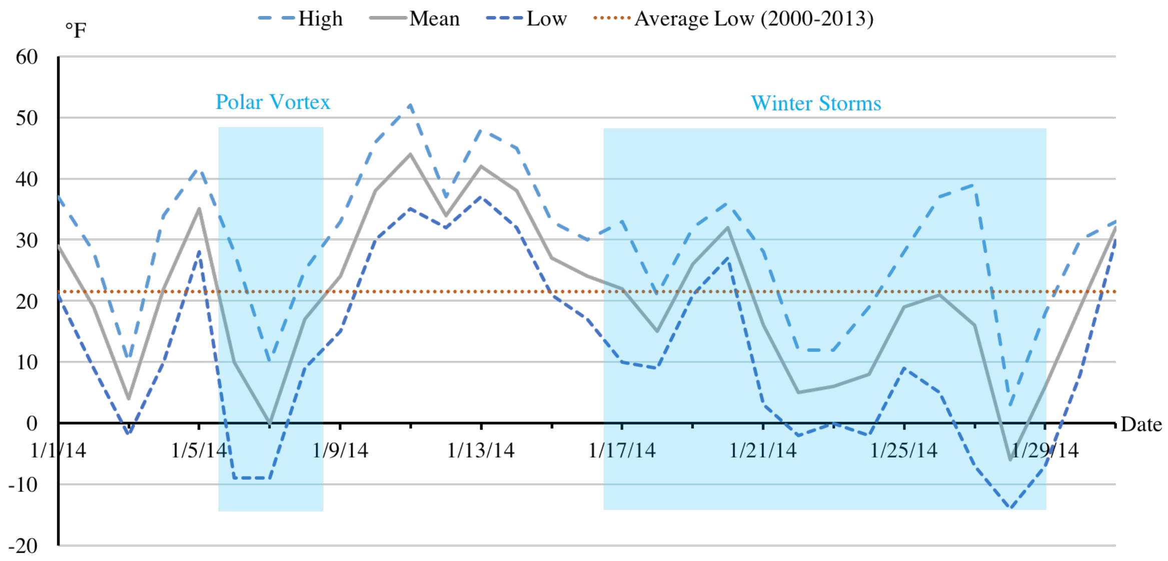

Figure 1: Temperatures of Columbus, Ohio in January 2014.

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[1] The Eastern Interconnection is the interconnected ac transmission network in the eastern part of the continental U.S.

Fig. 1 shows the daily high, mean and low temperatures recorded at Columbus, Ohio during January, 2014 [41]. The daily low temperatures deviated for a considerable amount, especially during the Polar Vortex and the Winter Storms, from the average low temperatures in January from 2000 to 2013. Driven by the extremely cold weather, the energy consumption soared to a high level, hitting the previous record winter peak load constantly across North America [2]. Taking PJM as an example, the previous record winter peak load, which is 136675 MW, was replaced by a new record of 137,998 MW at 7:00 on January 7 and later replaced by a peak load of 140,510 MW at 18:00 on the same day. The demand curves of the entire PJM region during the Polar Vortex are shown in Fig. 2 [42].

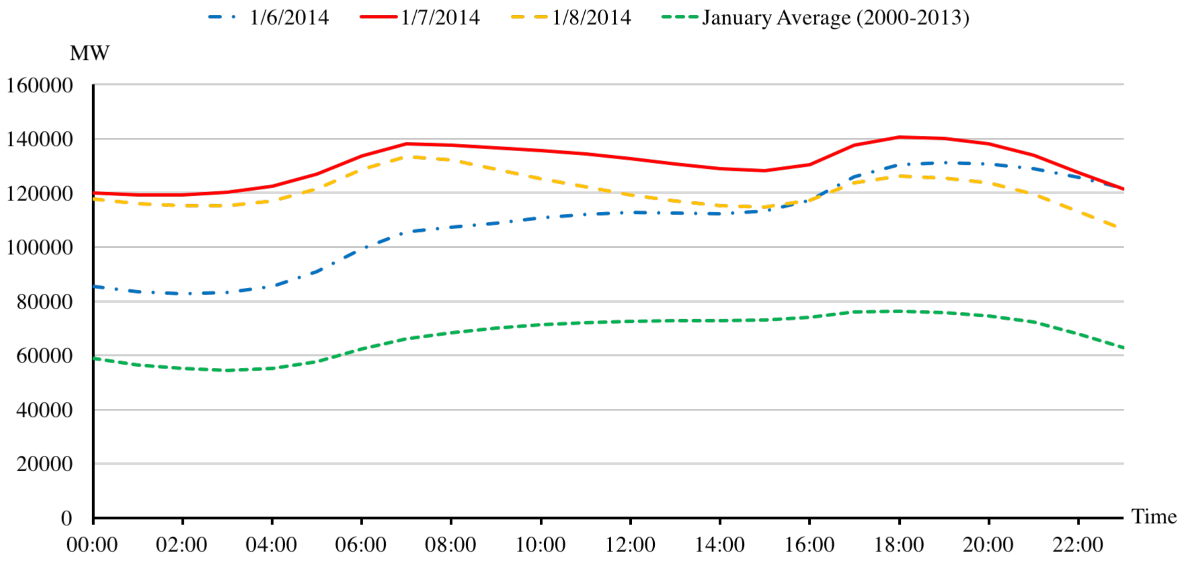
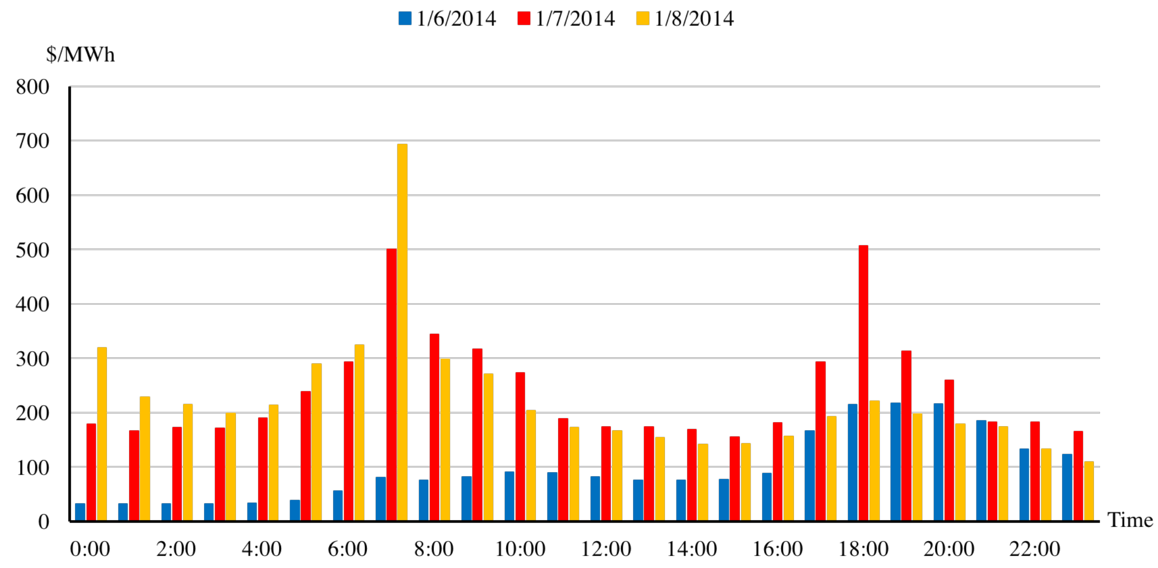


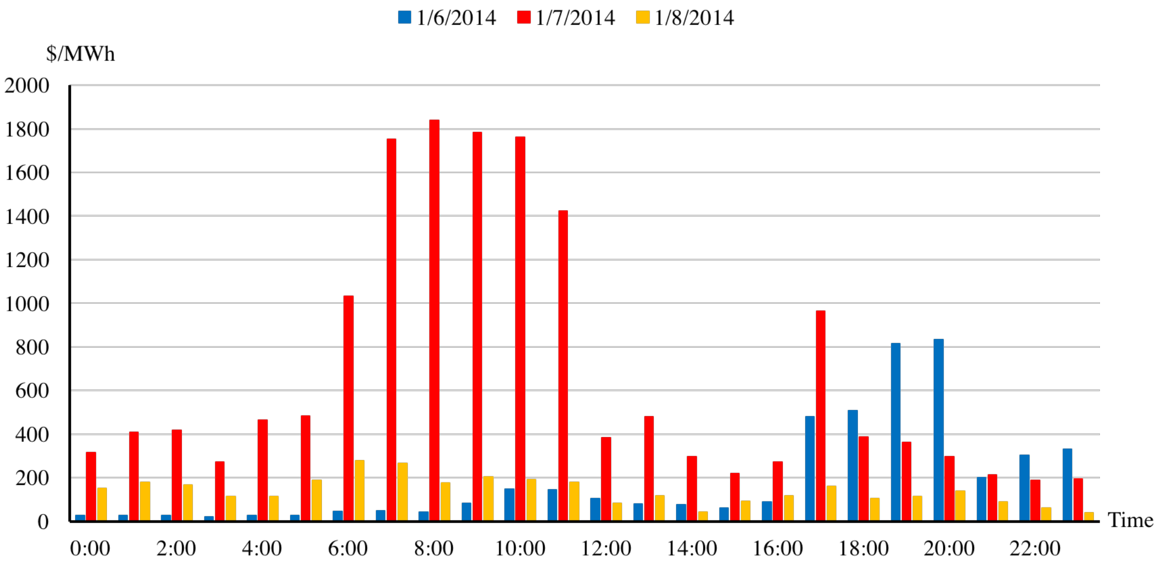
Figure 2: PJM load curves during 2014 Polar Vortex.

The situation was deteriorated by the unprecedented low availability of the conventional generators. The forced outage rate of generators reached 22% on January 7 in contrast to the historical average value of 7% [43]. The gas-fired and coal-fired generators, which are the two major types of generators that accounted for approximately 70% of the total installed capacities in PJM, contributed to 81% of the unavailable megawatts. The low availability was caused by a variety of reasons, two most noticeable ones among which are the gas interruptions and weather related factors. It was expected that the thermal generators would become harder to start up during cold weather and the chances they encounter outages due to either mechanical or electrical reasons would also escalate. Yet, the problem of fuel availability, particularly the availability of gas to gas-fired generators, was relatively less expected and had not had such a sizable impacts on the power system operations any time before. In fact, the high gas prices and the limited deliverability of gas to gas-fire generators significantly impaired the flexibility of these generation plants, which usually plays a critical role in maintaining system reliability.

During the prolonged periods of freezing weather, the co-occurrence of the record-high demand and unprecedented low availability of the conventional generators drastically increased the pressure on system operations, continuously pushing the system to its operating limit. In spite of the fact that the system did not encounter any serious reliability issues, a direct consequence of the Polar Vortex is the price spikes in both the day-ahead markets (DAMs) and the real-time markets (RTMs). The hourly average energy prices in the DAMs and RTMs in PJM during the 2014 Polar Vortex are shown in Fig. 3 [42]. Compared to the average energy prices in previous Januaries in PJM which usually are tens of dollars per megawatt, the price spikes during the 2014 Polar Vortex are one or two magnitudes higher. Particularly, the prices are extremely high around the two peak time period both in the morning and evening from January 6 to January 8, 2014. In consequence of this, the cost of electricity supply becomes remarkably high, so is the cost to maintain the reliability of the power system.



(a) Day-ahead energy prices



(b) Real-time energy prices

Figure 3: Hourly energy prices in PJM during 2014 Polar Vortex.

Notwithstanding the challenges from multiple sources, PJM successfully maintained the reliable operation of the power system without having any electricity shortage. This was due largely to its organized market and operation activities which provide a systematic way to address potential reliability concerns. Fig. 4 outlines the sequence of market and operation activities related to a specific operating day in PJM [43]. One week before the operating day, PJM starts the load forecasting process which is updated continuously to take advantage of more accurate information that gradually becomes available when approaching the operating day. Three days prior to the operating day, PJM conducts an outage analysis and reliability analysis to determine a set of system operation conditions, which are used to establish DAM conditions in the following day. All offers are required to be submitted before noon on the day before the operating day and the

DAM will be cleared between noon and 16:00. Uncommitted generators are allowed to re-submit their offers during 16:00 to 18:00 to reflect any changes in their fuel cost. During the reliability assessment commitment following the rebidding, additional resources may be called on to meet the demand and reserve requirements that has not yet been met in the DAM. During the operating day, RTMs are cleared and cleared resources are dispatched to meet the demand. By constantly monitoring the incoming system conditions and preparing potential solutions to deal with reliability challenges, operators become more aware of the situation and can have take the most out of the existing resources to ensure reliability.

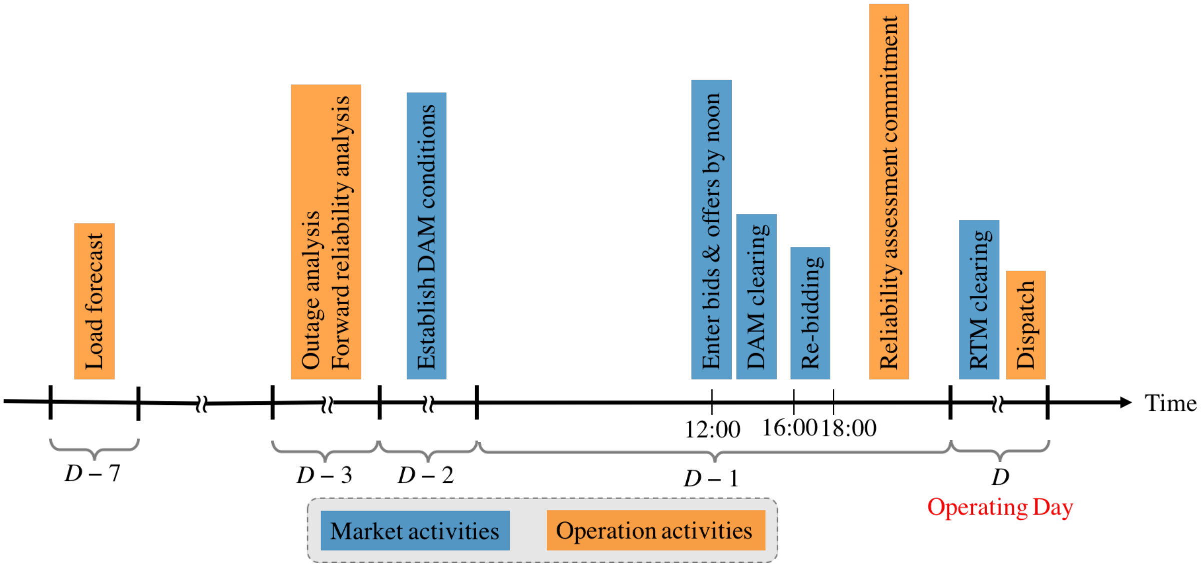


Figure 4: Market and operation timeline in PJM.

Among all the actions that PJM took to ensure the power system reliability, one important factor that made non-negligible contribution is the DR. During the emergency conditions, PJM solicited help from DR resources to relieve the burden on the generation side to meet the demand. Although the DR resources were not obligated to respond anytime other than a specified period in the summer, the DR resources did respond actively. During the entire Polar Vortex, the DR was deployed three times. The timeline of first two deployments is sketched in Fig. 5 [43].

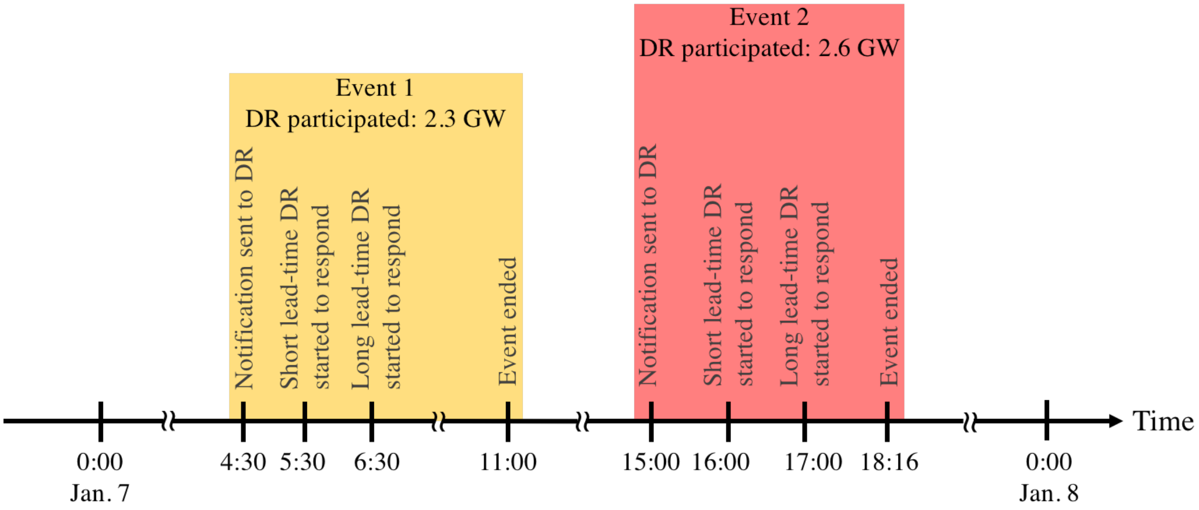


Figure 5: DR events during 2014 Polar Vortex.

On January 7, 2314.6 MW (30.7%) and 2604.04 MW (34.6%) out of 7535.7 MW committed DR capacity, participated in the load reduction in the two events, respectively [44]. The first deployment lasted 4.5 hours and the second about 3 hours. The DR resources were the marginal resources during some of the hours in the morning on January 7 and set the energy high prices around 1800 $/MWh. The DR, together with other procedures, helped maintaining the reliability of the power system operated by PJM throughout the extreme weather[2].

3. Fundamental Functions and Advantages of DR

By definition, DR is the changes in electric usage by demand-side resources from their normal consumption patterns. The two fundamental changes in the consumption patterns are the *demand decrease* and the *demand increase*, which we refer to as the fundamental functions of the DR. The demand decrease can be realized either by a reduction in the power use or by the start-up of on-site generators which is commonly seen in institutional customers. This function is valuable, for example, during the peak load periods, to relieve the burden on the power supply. Symmetrically, the demand increase can be achieved by an increase in the power use or by turning off the on-site generators. This function may be beneficial to the system, for instance, when the system is experiencing a low load condition but some of the generators are unable to be turned off due to physical, economic or reliability considerations.

The important role of the DR in maintaining power system reliability is demonstrated during the Polar Vortex. Typically, the demand decrease function is more valued than the demand increase function due to the mere fact that peak load conditions are more challenging than low load conditions. Nevertheless, the demand increase function should not be underestimated since it may also make significant contributions to increasing the flexibility of a power system, which is becoming increasingly necessary as the penetration of VERs deepens. Undoubtedly, the capability to maintain the supply-demand balance from the demand side when the supply-side resources are inadequate can significantly reduce the risk of electricity shortage.

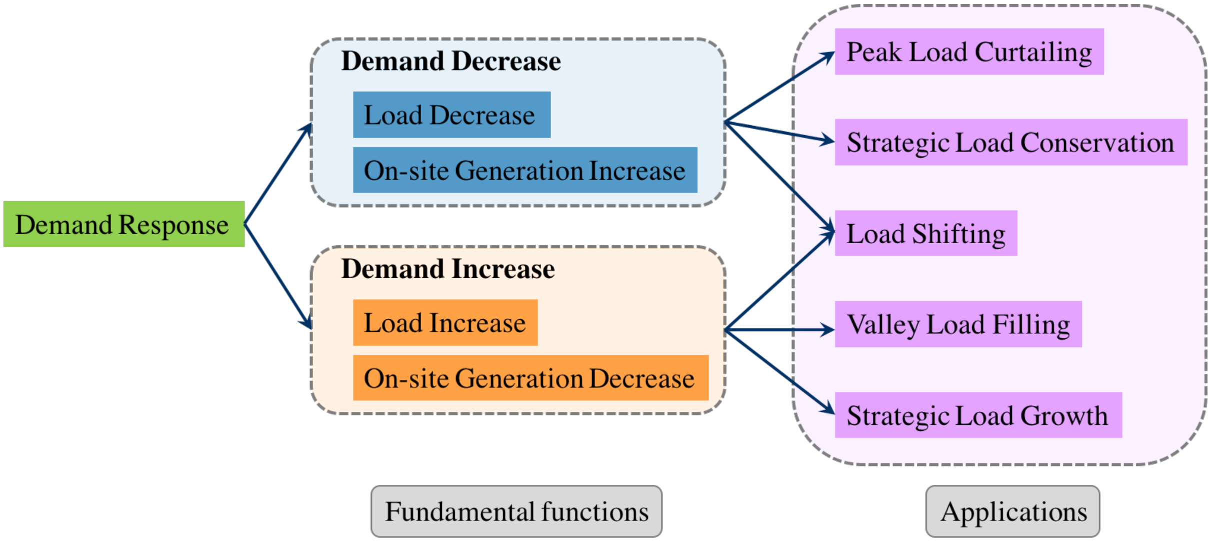


Figure 6: DR Fundamental functions and applications of DR.

Derived from the two fundamental functions, the DR can be utilized in a variety of applications shown in Fig. 6. The most common one is the *peak load curtailing*, which is used by system operators to economically and reliably maintain the supply-demand balance during peak load conditions. Especially in system emergencies such as those occurred in the Polar Vortex, a sizable portion of load was “met”[3] by the DR. The

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[2] More statistics about DR in the Polar Vortex can be found in reports such as [43] and [44].

[3] To be more accurate, the portion of load is curtailed rather than met. Yet, we still use the word ”meet” to emphasize the fact the DR is treated as a *resource*.

peak load, albeit relatively small in percentage of the total load, poses major threats to system reliability from the demand side. Equipping the system operators with the capability to deal with the peak load also from demand side gives them more flexibility to help system survive from emergencies. In addition to the the peak load curtailing, the DR can also be dispatched to achieve the *strategic load conservation*, where the demand is decreased throughout the day. The load conservation becomes essential during the time of supply deficiency. In terms of the demand increase function, it can be applied to *valley load filling* and *strategic load growth*. These two applications are valuable when the system has over-generation issues, i.e., when the generation exceeds the load. By increasing the demand through the DR, those generators that are not able to shutdown, that prefer not to shutdown due to economical concerns or that must be online out of considerations for system reliability in the following hours, can stay operational during low load conditions. Different from the applications mentioned above, *load shifting* application requires demand decrease in peak load hours and demand increase in low load hours, or shift energy consumption from high-demand hours to low-demand hours.

The DR has two distinguishable advantages compared to conventional generation resources, i.e., its flexibility and high availability. The DR is flexible in two senses. From an operational perspective, the DR can be treated either as a generation resource to reduce load or simply as a load that can follow dispatch signals to increase its consumption. From a planning perspective, the DR is flexible also in terms of locations since it can be located anywhere in the system, while the locations of the generation facilities are more constrained due to various reasons from environmental concerns to economic considerations. Such flexibility makes DR a favorable alternative to the convention generation resources for the purpose of maintaining power system reliability both in the short-term and in the long-term. Another distinguishable advantage of the DR is its high availability demonstrated during the 2014 North America Polar Vortex and the Winter Storms. Due to the technological nature of the DR, its forced outage rate is lower than those of generators, whose forced outage state may be caused by a variety of factors including failure of mechanical and electrical components, which could further be caused by lots of factors such as weather conditions. Additionally, unlike conventional generators, DR resources (excluding on-site generation) do not need fuel to be functional. As such, the availability of the DR is not subject to the fuel supply or fuel deliverability which, during the extreme weather conditions in January 2014, largely limited the normal operations of gas-fired generators. The nature of the DR makes it a valuable resource to the reliable operation of power systems.

4. DR Programs in Electricity Markets

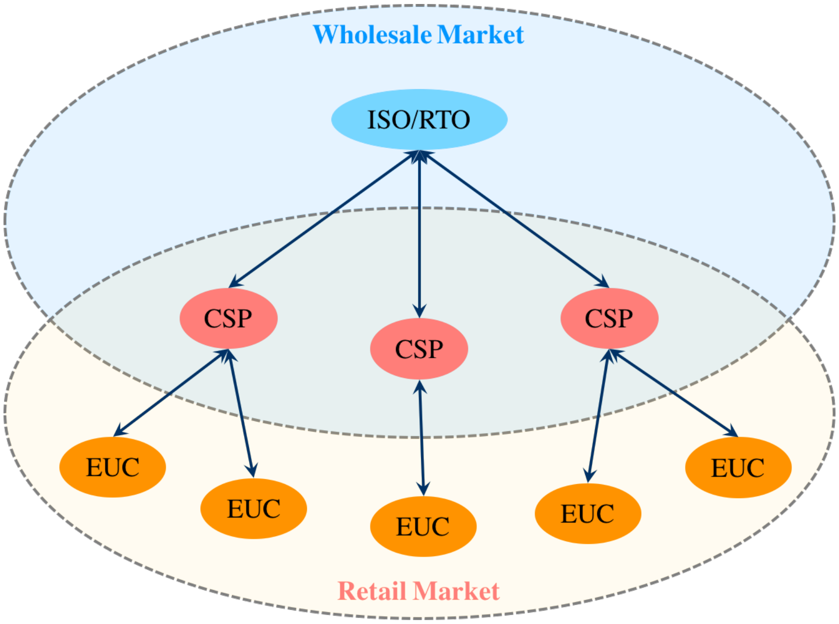

Figure 7: Illustration of the market structure for DR.

While technologically the DR is an effective means to ensure the reliability of power systems, the utilization of its full potential still requires appropriate market mechanisms to send proper economic signals to incentivize owners of existing DR resources as well as investors interested in DR. The power industry in the U.S. has laid out an excellent market structure that encourages the provision of DR in the short-term operations and the investment in DR in the long-term planning. An illustration of the existing market structure for DR is presented in Fig. 7. The DR can participate in two levels of electricity markets, the wholesale market and the retail market. End-user customers (EUCs) can participate individually in the retail markets operated by load-serving entities (LSEs) or electric distribution companies (EDCs). The LSEs or EDCs, which register in the wholesale market as curtailment service providers (CSPs), act on behalf of EUCs to participate in the wholesale-level DR programs. The wholesale market is operated by an ISO or a RTO. Corresponding to the structure of the market, there are DR programs specifically designed for each level of markets. Major DR programs[4] in the electricity markets are listed in Fig. 8 [44, 45]. We note that the retail DR programs do not exist in the wholesale markets – they are rather the means the participants use to realize the DR products they provide in the wholesale markets.

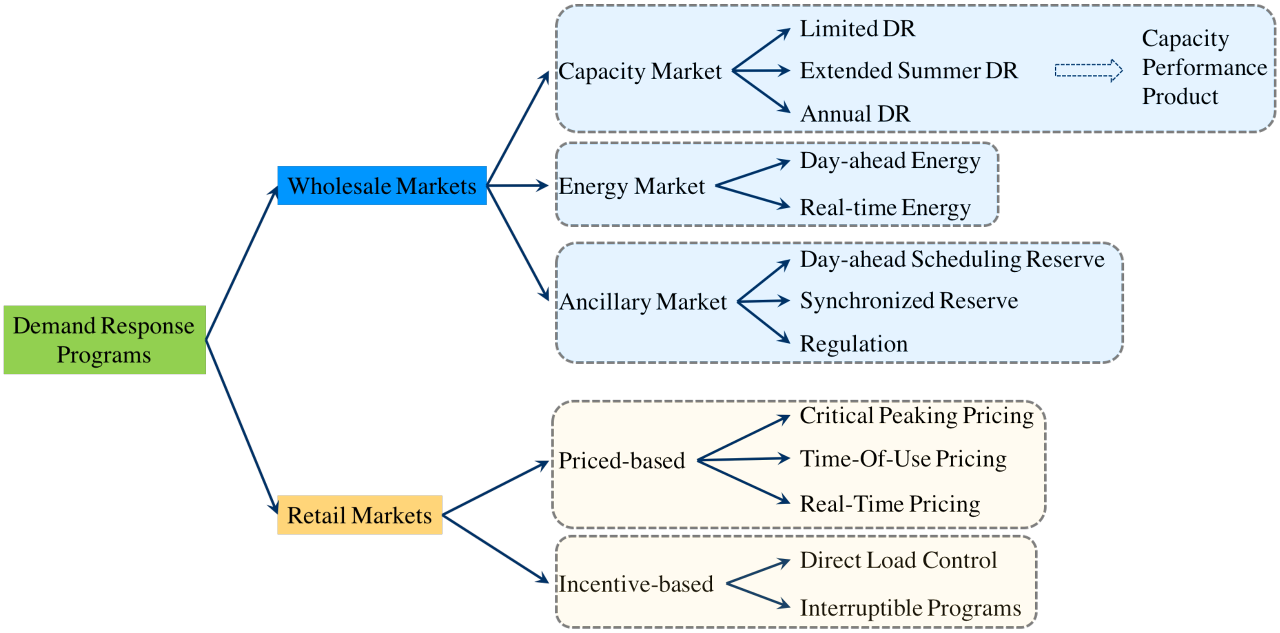

Figure 8: DR programs in wholesale and retail markets.

On the retail level, there are two categories of DR programs – *price-based program* and *incentive-based program* [45]. In price-based programs, dynamic prices are used to signal the DR to make expected changes that can lead to more reliable and economic operations of the power system. Typical price-based DR programs include critical peaking pricing (CPP), time-of-use pricing (TOUP), and real-time pricing (RTP) [45]. In the CPP, real-time prices are used during critical system peaks. This is expected to relieve burdens on supply using the peak load curtailing application of the DR by discouraging EUCs from consuming energy since real-time prices under peak load conditions are much higher than normal conditions. In the TOUP, energy costs for EUCs are determined based on both the amount of energy consumption and the time when the energy is consumed. This helps smoother the load curve by incentivizing DR resources to implement the load shifting application, i.e., encourages them to shift their electricity usage from times of high prices – usually coincide with the peak loads – to times of low prices. Different from the CPP, the prices in the TOUP are generally predetermined. The RTP fully takes advantage of the price signals in the wholesale markets and relates the retail rates for electricity directly with the wholesale prices. Under RTP, the behavior of DR

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[4] We use market program for DR from PJM as a representative example of the wholesale market. While the names of DR programs in the retail market varies, we use the most terminologies defined by Department of Energy.

is expected to align with the real-time reliability needs of the system – to reduce load during the peak load hours when prices are high and possibly increase load during low load hours when prices are low. Another category is the incentive-based programs, DR resource owners receive fixed payments that are rewarded for their participation. The benefits of participating in these programs are precisely known in advance. A feature of such programs is that DR resources give out their control for a specified number of times yet at uncertain time periods. Typical programs include direct load control and interruptible program. The CSPs aggregate the capabilities of DR resources that spread over a certain region through these diverse retail DR programs and participate in the wholesale market.

On the wholesale level, the DR is eligible to participate in the capacity markets, energy markets, and ancillary markets. The capacity market, specifically the reliability pricing model (RPM) in PJM[5], holds a series of auctions to procure adequate capacity based on certain reliability requirements priori to a delivery year (DY) covering June in the first calendar year to May in the second calendar year. The timeline of the RPM is outlined in Fig. 9.

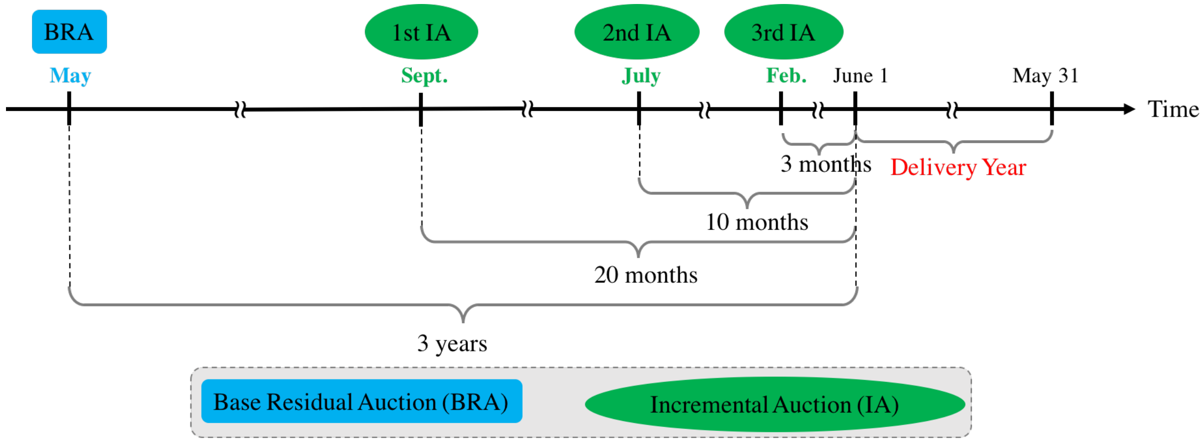

Figure 9: RPM timeline.

Table 1: Comparison of different DR products in the RPM.

Requirement	Limited DR	Extended Summer DR	Annual DR	CP
Availability	Non-NERC holiday weekdays, June–Sept.	Any day during June–Oct., May	Any day	Any day
Maximum Interruption Number	10	Unlimited	Unlimited	Unlimited
Maximum Interruption Duration	6 hours	10 hours	10 hours	June to Oct., May: 12 hours, Nov. to Apr.: 15 hours
Response Hours	12:00–20:00	10:00–22:00	June–Oct., May: 10:00–22:00, Nov. to Apr.: 6:00–21:00	June–Oct., May: 10:00–22:00, Nov.–Apr.: 6:00–21:00

A base residual auction (BRA) is first held 3 years priori to each DY to procure the majority of capacity required to maintain a specified level of reliability for that DY. Three incremental auctions (IAs) will be

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[5] We note that terminologies used in this paper regarding the wholesale market part are all established by PJM. The detailed definitions of these terminologies can be found in [46].

held sequentially following the BRA. The IAs are organized to adjust the procurement of capacities based on the updated reliability requirements that takes into consideration the most update-to-date system and resource conditions.During 2014 when the extreme weather occurred, the DR resources offered into the RPM as limited DR, extended summer DR, or annual DR, which are to be replaced by a single product called capacity performance (CP). Each of the capacity product that DR resources can offer is defined by certain characteristics detailed in Table 1 [42, 44]. DR products in the RPM mainly differ in the required availability, number and duration of maximum interruption, and the hours during which the DR resources are expected to respond. Once the DR resources are cleared in the RPM, they will receive capacity payments for the provision of capacity in the specified DY, regardless of whether they are dispatched or not. This mechanism provides investors some revenue guarantee to mitigate the potential risks they may encounter in the short-term markets. It can be seen from the development of long-term capacity product that the year-around reliability value of the DR is recognized and being increasingly valued. The RPM has attracted investment in DR resources and the provision of capacity from DR ever since its creation. The total capacity addition procured in the RPM from DR and energy efficiency (EE)[6] has reached about 12.8 GWs, amounting to 20% of total capacity additions from DY 2007/2008 to DY 2019/2020, as shown in Fig.10 [44].

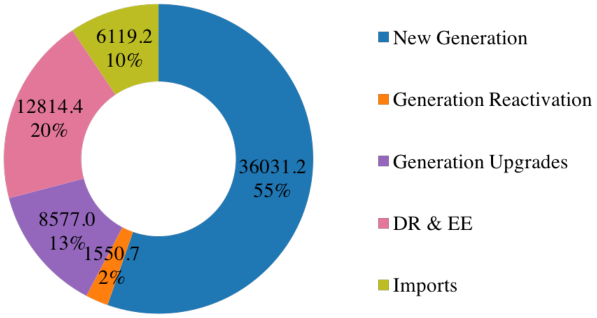

Figure 10: Capacity additions (MW) from DYs 2007/2008 to 2019/2020 in RPM.

The goal of the capacity market is to ensure power system reliability can be maintained in the long-term from a planning perspective by procuring adequate megawatts for the future. In the short-term operations, what comes into play are the energy market and ancillary market, which are developed to economically maintain operational reliability of power systems. The DR resources can offer into both the day-ahead energy market and the real-time energy market. Once they are cleared in the markets, they will be dispatched by the system operators to meet the demand and in the same time receive full LMPs. Similarly, the DR resources can offer into both day-ahead market as the day-ahead scheduling reserve and real-time ancillary market as synchronized reserve or regulation. The DR resources will be paid at the LMP for each ancillary service.

The DR programs in the wholesale market can be also classified into reliability program and economic program. Specifically, the DR products in the capacity market concerns about the capacity adequacy of the power system, which is critical to maintaining a desired level of reliability. As such, these products belong to the reliability program. On the contrary, the DR products in energy markets mainly aim to provide more economic ways to meet the demand, and consequently belongs to the economic program. While both the reliability program and the economic program are beneficial to the power system, the former contributes the majority of revenues to the DR. Fig. 11 shows the monthly revenue of DR in 2014 [44]. Except the cold winter months, where DR resources were frequently dispatched to satisfy the demand due to a severe lack of conventional supply resource especially gas-fired generators, the revenue from economic program is negligible compared to that from emergency program, which further demonstrate the reliability value of DR.

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[6] EE is a program to reduce the amount of energy required to provide products and services permanently by means such as device upgrade.

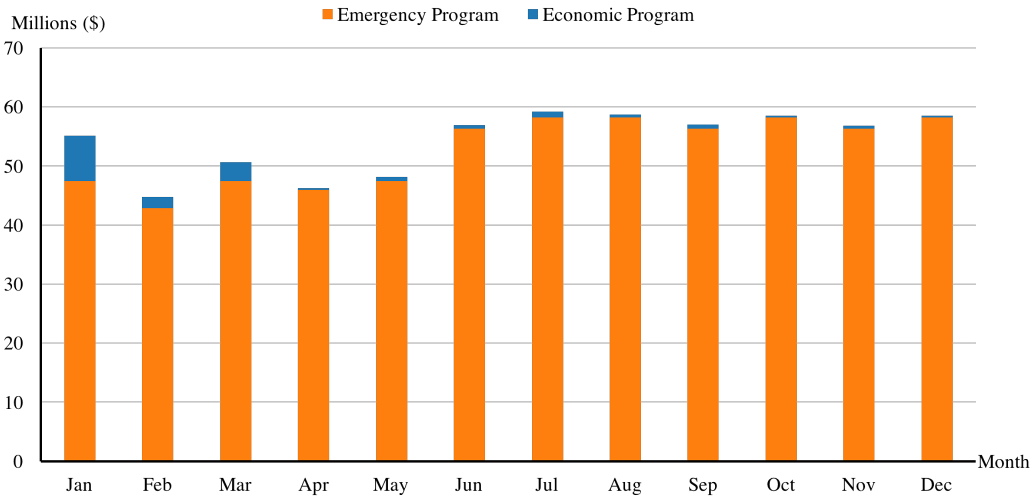

Figure 11: DR revenues in PJM, 2014.

5. Challenges of DR Implementation

The rapid development and standardization of advanced metering infrastructure have enabled State Grid Corporation of China (SGCC) and China Southern Power Grid Company (CSG) for building DR programs over the nation [47]. The effective utilization of DR programs will assist the Chinese government to achieve a low-carbon electricity sector and reduce renewable energy curtailment. The implementation data of DR programs of SGCC and CSG in 2015 including Target of Saving Electricity (TSE), Actual Saving Electricity (ASE), Target of Saving Power (TSP) and Actual Saving Power (ASP) are shown in Table 2 and Table 3 [48]. However, the traditional centralized unit commitment and economic dispatch procedures have limited the potential applications of flexible demand-side resources. Without a well-designed market mechanism suitable for demand-side resources, DR programs could not be taken full advantage of under various market operations. Developing such a market mechanism suitable for demand-side resources faces at two major challenges.

From the policy perspective of view, the DR program participants sell their DR capacities in the wholesale electricity markets, which is simply not applicable in China due to the lack of such a market in China. The DR market mechanism has also not been established and integrated into its current electricity market framework. Particularly, China has 30 provincial power grids distributing over very large scale geographical region with huge different system conditions including the supply mix, the energy structure, the presence or absence of supply and transmission constrains, the demand growth rate, the resource plans for meeting demand growth, etc. The potential benefits are tied directly to local electric power system involving with the specific regional electricity market in terms of market structure, operation and resources balance. Therefore, the basic purposes and main concerns described as following should be always highlighted during the whole establishment process of each regional electricity market framework in China. Report [49] by the U.S. Department of Energy encourages states to coordinate, on a regional basis, energy policies to provide reliable and affordable demand response services since implementing DR resources in the wholesale electricity market can provide: 1) participant financial benefits – bill savings and incentive payments earned by customers; 2) social welfare – lower wholesale market costs; and 3) reliability benefits – improvement in operational security and stability ; 4) Market performance benefits - mitigating suppliers' ability to exercise market power. In addition, the effective utilization of DR programs necessitates the revenue distribution analysis, market incentive design, appropriate work assignment with associated responsibility among different market participants from generation, transmission, distribution and demand sides. As such, a complete wholesale electricity market should be established for the aggregated DR participants to trade in. Given that market background, to design an effective DR market mechanism, relatively fast responding capability and high operational flexibility of DR programs must be taken into consideration in electricity market framework.

A comprehensive comparison between the contributions by DR programs to power system operations from market and regulation perspectives of view is also of acute need.

Table 2: The implementation data of DR programs of SGCC in 2015.

Region (Province)	**TSE (Billion kWh)**	**ASE (Billion kWh)**	**TSP (MW)**	**ASP (MW)**
Beijing	2.52	2.59	52.3	68.0
Tianjing	1.96	2.23	39.3	43.8
Hebei	8.48	8.73	154	162.3
Jibei	4.05	4.48	63.2	78.6
Jinan	4.42	4.25	90.8	83.8
Shanxi	4.11	5.12	73.2	10.93
Inner Mongolia	2.82	3.08	40.1	64.4
East Inner Mongolia	0.42	0.54	14.1	33.1
West Inner Mongolia	2.40	2.54	26	31.3
Shandong	9.08	17.34	171.2	400.1
Liaoning	4.75	5.69	76.7	138.4
Jilin	1.11	1.33	26.6	36.0
Heilongjiang	14.4	14.4	35.7	36.4
Shanghai	3.37	4.03	8.04	9.54
Jiangsu	12.79	13.08	235.9	241.2
Zhejiang	5.76	6.00	173.2	298.9
Anhui	3.65	3.76	81.5	84.5
Fujian	4.45	6.23	76.2	124.7
Hubei	3.94	4.06	79.4	85.5
Hunan	3.02	3.64	64.1	94.7
Henan	4.95	6.20	150.2	150.4
Jiangxi	2.49	2.52	46.0	59.6
Sichuan	4.86	4.94	83.0	108.1
Chongqing	1.81	2.02	43.8	46.3
Xizang	0.08	0.10	2.0	2.5
Shanxi	2.08	2.34	52.4	53.8
Gansu	2.48	3.01	41.5	90.0
Qinghai	1.94	2.08	27.0	30.1
Ningxia	3.57	4.00	21.5	21.8
Xinjiang	2.31	3.18	36.4	41.8
SGCC	**99.81**	**118.75**	**1963.6**	**2688.0**

Table 3: The implementation data of DR programs of CSG in 2015.

Region (Province)	**TSE (Billion kWh)**	**ASE (Billion kWh)**	**TSP (MW)**	**ASP (MW)**
Guangdong	14.02	14.80	292.8	348.4
Guangxi	2.34	2.42	41.0	53.7
Guizhou	2.52	2.55	51.3	54.6
Yunnan	3.16	3.59	45.9	114.7
Hainan	0.58	0.62	10.3	13.1
CSG	**22.62**	**23.98**	**44.13**	**58.45**

From the technological perspective of view, the centralized market clearing mechanism implemented by dispatch center determines the operations of generation resources, substations and transmission lines. This control is single-direction and has not considered DR resources as a fast-responding, effective load regulation method, which may hinder system optimization, collaboration and overall efficiency. Furthermore, the standardization and modernization of energy consuming devices in residential side differs in China and U.S. Such differences make it difficult to develop DR programs in China. The current DR mechanism [50] adopted in Beijing, China, consists of six steps:

1) End-use customers or LSEs submit application for installation of DR programs;
2) National Development and Reform Commission reviews the collected applications;
3) Once the application for installing DR programs is approved, end-use customers or LSEs sign contracts with Beijing Energy Conservation Center;
4) DR programs respond to the control signal from the system operator for implementation;
5) A third-party utility verifies the implementation of each registered DR program;
6) National Development and Reform Commission deposits subsidiaries to each implemented DR program.

In 2015, the peak load of Beijing power grid reached 18,566MW at 13:42 on August 13 exceeded the previous maximum load 18,437 MW occurred just one day ago, which was the 3rd time to update the historical maximum records of peak load in that summer. In order to reduce the peak load and mitigate the operation risk of Beijing power grid, the first subsidiary based DR program in Beijing was triggered at this moment. The distribution of participants and the reduction capacity of the DR programs in Beijing from August 12 to 13 are shown in Table 4 [51].

Table 4: The distribution of participants and reduction capacity of the DR programs in Beijing.

Time, Date	**Reduction Capacity (MW)**	**Aggregator**	**Large Consumer**	**Industrial Enterprise**
11:00-12:00, August 12	7.0	17	74	29
12:00-13:00, August 12	3.0	17	36	29
11:00-13:00, August 13	6.6	15	73	29

There are three different compensation standards as 80/kW, 100/kW, 120/kW for the DR participants that correspond to three different response time of DR as 24h, 4h and 0.5h [51]. These predetermined compensation standards are fixed and not related to the real-time situation of the active power balance of electricity grid. Even so, the DR program wasn't conducted as well as 2015 in 2016. However, during 2016 summer peak load period in Beijing, the delay in subsidy depositing to DR program participants caused failure in the implementation of more DR resources afterwards. Such delays can be avoided if DR program aggregators behave dynamically according to the locational market clearing price as an active market participants, but not to the signal sent by the system operators. Additionally, the current mechanism could not fully take advantage of all available resources. Imperfect DR market mechanism cannot reveal the potential benefits of many demand-side resources. The lack in information, such as capacities, types, characteristics and locations, of resources qualified for installing DR programs also holds back the development of DR programs and corresponding market mechanism. Currently, the DR program participants are industrial factories, hotels, schools and so on. Distributed resources, like residential houses, have not been effectively considered to implement DR programs due to insufficient market incentives [52]. Current mechanism is not also able to fully utilize the existing DR program participants since the implementation of DR programs is not driven by the price signal. Actually, the current demand-side resources in China [53] are purely under the unidirectional control from system operators but not been driven by the effective price or incentive signals through market mechanism based DR programs. Namely, it means there are still lot efforts need to be made to implement and develop the great potential capability of DR coming from the active participation and response of demand-side resources itself to contribute to system reliability. If China could move forwards to implement DR programs, further achievement can be realized in cost reduction, renewable energy curtailment reduction, emission reductions and social welfare improvements [38], [39], [40].

6. Conclusions

As a summary, we note DR programs have several advantages over conventional generation units. First, DR programs have a higher availability on average. Secondly, conventional generation units are heavily dependent on fuels, of which shortage may result in severe power grid contingencies, especially during extreme conditions as mentioned in previous sections. Furthermore, compared to those of conventional generation units, the responding capability of DR programs is faster and more flexible, which enables system operators to better maintain the system stability. As such, in extreme operating conditions, rather than conventional generators, DR is a more effective tool to improve the power system reliability.

DR programs are also essential to enhance system reliability and overall cost-efficiency. However, the effective implementation of DR programs requires systematic and scientific design, and a healthily operating electricity market. An appropriate and reasonable price signal during electricity market clearing process is the key to provide correct direction for all the market participants. Such a signal can take full advantage of the collaboration among ISOs/RTOs, generation companies, LSE and EDCs to make the system more capable of surviving extreme contingencies. Nowadays, structural reforming of electrical system probably could provide a solid platform for China to develop DR programs for effectively improving system reliability and social welfare.

We will undertake the work on this topic more specifically not only in North America RTO like PJM but also internationally in future work. For instance, future study about this research will focus on discerning the applicability of electricity market mechanisms based DR for regional power grid in China with high penetration of renewable energy generation including solar PV plants, wind farms and hydro power.

Abbreviations

BRA	Base Residual Auction
CP	Capacity Performance
CPP	Critical Peaking Pricing
CSP	Curtailment Service Provider
DAM	Day-Ahead Market
DR	Demand Response
DSM	Demand Side Management
DY	Delivery Year
EDC	Electric Distribution Company
EE	Energy Efficiency
EUC	End-User Customer
FERC	Federal Energy Regulatory Commission
IA	Incremental Auction
ISO	Independent System Operator
LMP	Locational Marginal Price
LSE	Load-serving Entity
NERC	North American Electric Reliability Corporation
PJM	Pennsylvania-Jersey-Maryland
RPM	Reliability Pricing Model
RTM	Real-Time Market
RTO	Regional System Operator
RTP	Real-Time Pricing
TOUP	Time-Of-Use Pricing
VER	Variable Energy Resource

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