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RESEARCH ARTICLE

Experiences and Lessons Learned From DR Resources Participating in the US and UK Capacity Markets: Mechanisms, Status, Dilemmas and Recommendations

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ABSTRACT The role of demand response resources is particularly important under the new-type power system with new energy as the main source. Demand response resources are important for generation adequacy and can provide electricity capacity value for power system. The United States and the UK are the only countries in the world that offer capacity services from demand response resources as generation resources. Their experiences and lessons learned are of great significance to other countries and regions. This paper first analyzes the significance of DR resource participating in the capacity market from two perspectives: the development of demand response resources and system generation capacity. Secondly, a detailed analysis of the mechanism design of demand response resources in the US capacity market is presented and the development status of demand response resources since 2007 is provided, so as to provide meaningful reference for other countries and regions. Thirdly, this study introduces the current situation and dilemma of demand response resources in the capacity market of the UK, and provides corresponding suggestions so that demand response resources in other countries and regions can avoid repeating the pace of the UK in the capacity market. Finally, suggestions for demand response resources to participate in the capacity market are given from four aspects.

INDEX TERMS Demand response, capacity market, market mechanism, status, dilemmas, recommendations.

I. INTRODUCTION

Demand response (DR) refers to the behavior that when the price of power wholesale market rises or the system reliability is threatened, power users change their inherent habitual power consumption mode (reduce or transfer the power load in a certain period of time), so as to ensure the stability of power grid and restrain the rise of electricity price [1]. Since 2010, DR has begun to develop actively in the global electricity market and can compete with power production. In 2016, the global power DR capacity was 39 GW, of which North America accounted for more than half of the total DR capacity, accounting for 28 GW. According to the prediction of market research firm Navigant, the global power DR capacity will reach 144 GW by 2025 [2]. According to Bloomberg New Energy Finance, the global power DR capacity will more than triple to 177 GW by 2030. The flexibility to put more renewable energy into operation in most countries will be crucial [3].

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A. THE ROLE AND CHARACTERISTICS OF DR UNDER THE NEW-TYPE POWER SYSTEM

1) THE ROLE OF DR IN NEW-TYPE POWER SYSTEMS

In the new-type power system, the proportion of traditional units will be significantly reduced, and new energy sources will become the main provider of electricity. Regardless of the form of new energy, its output capacity usually depends on the external environment and is difficult to control artificially, which not only cannot be adjusted with load fluctuations, but also introduces more regulation burden to system operation. Traditional thermal units, which have been the mainstay of power regulation in the past, are a very limited part of the new power system and cannot cope with the fluctuations of new energy and load superimposed on each other. As a result, regardless of the type of new energy source, there will be a large and continuous lack of regulation capacity on the generation side, which is the main challenge for the new power system.

On the other hand, a large number of flexible loads on the demand side can participate in the system operation through many modes, such as participating in DR markets, ancillary service markets, and electricity energy markets. The above-mentioned models differ in terms of user type, implementation purpose, and research basis. Among them, DR has relatively low requirements in terms of policy maturity, user access threshold, etc., and many countries also have research and application bases. With the significant improvement of demand-side digitalization and intelligence level in the new power system, DR will certainly be developed rapidly, making a large number of flexible loads one of the main sources of flexible regulation capacity of the new-type power system.

In a word, the construction of a new type of power system has put forward higher requirements for flexible regulation capability and risk resistance capability. As an important flexible regulation resource, DR resources can realize efficient linkage with new energy consumption, thus playing an important role in enhancing the penetration rate of new energy and alleviating the contradiction between power supply and demand [4].

2) CHARACTERISTICS OF DR IN NEW-TYPE POWER SYSTEM

The new-type power system will continue to face a huge regulation burden, and DR should be promoted and implemented on a large scale and on a normal basis. In this context, the DR mechanism should have new characteristics and development goals [5]. In order to adapt to the new-type power system dominated by new energy, DR mechanism should have the characteristics of scale and normalization.

- **Scale**: A large and diversified group of customers should participate in DR program. Only by significantly increasing the proportion of DR users and forming a scale effect can the implementation effect of DR be sufficiently guaranteed and the regulation capacity of the new-type power system be significantly improved.
- **Normalization**: DR is required to be implemented on an ongoing basis as an important regulation tool for the new power system, rather than only at "extraordinary times". For example, DR can be implemented uninterruptedly throughout the summer to alleviate regulation challenges caused by high loads, full hydro generation, and fluctuations in new energy sources. At the same time, regular operation can significantly increase the utilization and participation of virtual power plants, for example, to ensure their healthy development.

3) CURRENT STATUS OF THEORETICAL RESEARCH AND PRACTICAL APPLICATION OF DR RESOURCES IN THE CAPACITY MARKET

a: THEORETICAL RESEARCH

Many researches have been conducted in the theoretical study of DR resources in capacity markets. One of the most relevant hot-spots is the contribution of DR resources to generation capacity adequacy. The contribution of intermittent resources such as DR resources and renewable energy to the system power supply reliability is usually assessed by the credible capacity. The capacity credibility index can be divided into effective load carrying capacity (ELCC), equivalent firm capacity (EFC) and so on [6]. The larger the value, the greater the contribution to system reliability. The authors in reference [7] concluded that the capacity values of DR resources is comparable to that of wind: (13-23%). Although the capacity values of the tested DR resources vary due to the different testing devices and calculation methods used in these studies to estimate the DR resources. However, it is a well-known fact that DR resources contribute to capacity generation adequacy. The author in reference [8] found that the capacity value of DR resources could be as high as 26% by testing a load shifting device in Ireland. The reference [9] found that DR resources are able to reduce capacity market prices while saving consumers money, and the impact is particularly pronounced when renewable generation is highly variable and initial capacity is insufficient. Capacity values represent the contribution of resources to generation adequacy.

DR resources can be used to address transmission expansion planning issues rather than implementing costly and complex transmission upgrade solutions, in addition to being used as a supply resource to be produced when electricity prices are high or grid reliability is threatened. Many researchers have explored the impact of DR resources on transmission planning [10], [11]. However, none of them consider the impact of quantifying the participation of DR resources in the capacity market on transmission planning. To address the question, the author in the reference [12] proposed a model with an integrated capacity and DR resources, in which DR resources are able to reduce the required transmission capacity. The core of this solution is to replace expensive transmission upgrade solutions through DR. This approach reduces the cost of transmission upgrades and improves social welfare compared to transmission upgrade solutions.

Some research scholars have also focused on the practical application of DR resources in the capacity market. Literature [13] presents the role of DR resources in the PJM capacity market and briefly describes the product types of DR resources in the early PJM capacity market (before 2011). Literature [14] briefly describes the product types of DR resources in PJM and NYISO markets, focusing on the evolution and current status of DR programs in these two markets. In the reference [15], case studies of DR resources in the capacity markets in ISO New England, PJM and Great Britain are provided. The authors focused on the current state of development of DR resources in these markets at the time (2015) and did not analyze the mechanisms of DR resources participating in the capacity market. The authors in the reference [16] show that the six major generation groups and the ''second tier'' in the UK have the ability to manipulate the market, thus leading to a rather small share of the capacity market for UK DR resources in these years.

b: PRACTICAL APPLICATION

In terms of practical applications, currently only in the US and UK DR resources are allowed to participate in the capacity market. DR resources has been participating in the PJM capacity market as a power generation resource since 2007, with a development history of 15 years. In the UK, Dr resources are allowed to participate in the capacity market from 2016 [15]. Although DR and capacity markets have a long history of development in many regions, few countries or regions still allow generation resources to participate in capacity markets. The key reason for this is that in the past, generation-side resources have met the capacity needs of the system. However, with the increasing penetration of renewable energy and the need to continuously tap the flexibility of demand-side regulation, more and more countries (such as China) are exploring the development of DR resources under the new power system, including participating in the electricity energy market, ancillary services market and capacity market, so that demand-side resources can obtain objective revenue and stimulate the development of DR resources [17].

B. PURPOSE OF THE STUDY

As mentioned above, the US and the UK are the pioneers to allow DR resources to provide capacity services as power generation resources in the world, and has relatively mature experience for reference [14]. Thus, the study of their experiences on DR resources participating in the capacity market is of great significance to the development of DR resources in the capacity market for other countries and regions. However, as the analysis in the section I-A3, although there have been many studies related to DR resources in the capacity market, the following research gaps remain:

- Most of the existing studies related to DR resources in the capacity market are the role of DR resources on generation capacity adequacy, such as literature [7]–[9].
- The introduction of existing Dr resources in the capacity market of the US and the UK has insufficient mechanism design analysis, and there is no comprehensive analysis on the specific operation process (such as declaration information, measurement of execution effect, settlement, etc.), which can not bring good reference to other countries or regions.
- The lack of analysis on the auction results of DR resources in the US and UK in the capacity market in the last seven years can not provide a good reference to other countries and regions.

This paper analyzes in detail the mechanism design of DR resources in the capacity market in the US and the UK and the auction results since DR resources participating in the capacity market, and gives some suggestions for the participation of DR resources in the capacity market. Specifically, the contributions of this paper are summarized as follows:

- The importance of DR resources participating in the capacity market is analyzed from the perspectives of both the development of DR resources and the impact on generation capacity adequacy under the new-type power system.
- A detailed description of the mechanism design for DR resources to participate in the US in the capacity market, thus providing a good sense of reference for other countries and regions. The mechanism design mainly includes: Types of DR resources participating in the PJM capacity market, introduction of price responsive demand products and the mechanisms associated with participation in the capacity market, emergency and the mechanisms related to participation of market pre-emergency products (including Information required for DR resources to participate in the capacity market, key parameters for DR resource participating in the capacity market, notification period of DR resources, measurement of the execution effectiveness, and settlement), comparative Analysis of two products participating in the capacity market.
- The auction results of DR resources in the PJM capacity market are introduced in detail, and the development trend of DR resources in the capacity market is analyzed. Two issues of concern for DR resources in the US capacity market are discussed.
- The current situation and dilemma of DR resources in the UK capacity market are analyzed, and corresponding improvement measures are proposed. It can also bring some lessons for other countries and regions to avoid the same problems faced by DR resources in the capacity market in the future.
- General issues and recommendations for DR resources to participate in the capacity market are summarized, including the following four areas: design of diverse capacity products, evaluation of implementation effectiveness, incentivize small users to participate in the market with aggregated resources, and measurement of implementation effectiveness.

This study is structured as follows: Section II analyzes the practical experience associated with mechanisms of DR products participating in the US capacity market, and the overall trend of three aspects in capacity auctions is provided. In Section III, a brief introduction to the UK capacity market, a detailed analysis of the current situation and dilemma of DR resources in the capacity market, and targeted suggestions for improvement are presented. Four recommendations are given for DR resources to participate in the capacity market in the Section IV. The conclusions are drawn in Section V.

II. THE SIGNIFICANCE OF DR RESOURCES PARTICIPATING IN THE CAPACITY MARKET

A. IMPACT ON DR RESOURCE DEVELOPMENT–AN IMPORTANT REVENUE SOURCE

Although DR has been going on for a long time in many countries, it has not been making good progress in many countries [18]. In addition to the imperfect information and communication technology of relevant equipment, the factors affecting the development of DR resources mainly include the following two reasons: (1) the lack of business model for DR development; (2) the lack of reasonable measurement as well as market-oriented guidance objectives in terms of cost-benefit accounting.

1) LACK OF BUSINESS MODEL

The limited maturity of DR technology determines the limited maturity of its market: low participation awareness of user compared to traditional generation resources, immature communication technology, resulting in limited capacity of DR resources, etc. With relatively mature technology level, the development of DR technology needs to meet the existence and development of this industry chain through the introduction of relevant stakeholders and innovative profit models. The main problem brought about by this is the low motivation of customers to participate in DR program [19]. Most electricity consumers do not care about the not generous subsidies that participating in DR programs can bring them, but rather about their comfort. In addition, the cost of conducting DR programs is quite high due to the need to install a variety of expensive equipment, mainly expensive equipment. The total cost of telemetry infrastructure, database system, energy management system, etc. is estimated to be about $750,000. Without a suitable business model, it is difficult to motivate users to carry out DR projects at such high costs. At present, the relevant market-based trading is mainly based on participating in the spot market and auxiliary service market, and is still in the stage of theoretical research design and pilot verification, with only small-scale pilot work in local areas and no large-scale market application for the time being. Therefore, the biggest problem of DR projects at present is that no mature business model has been established, relying mainly on the administrative means of summer peak regulation and power restriction, and the active participation of DR resources in power market dispatch as available resources is still in the exploration stage. With the increase of power trading volume, the improvement of power market mechanism and the increase of the proportion of renewable energy, the system demand for flexible resources will continue to grow, and the profit space of DR resources in the market will be expanded, so the government subsidy can be gradually reduced and a compensation mechanism combining market trading and sharing of beneficiary subjects can be established.

2) LACK OF REASONABLE MEASUREMENT AND MARKET-ORIENTED GUIDANCE OBJECTIVES

In terms of cost-benefit accounting, there is a lack of reasonable measurement as well as market-oriented guidance objectives. If the subsidy standard is too high, it will lead to unnecessary waste of financial funds, while too many users' participation will also cause additional waste of resources. On the contrary, if the subsidy standard is too low, it will not be able to fully dispatch the participation enthusiasm of users, and the network scale required by the market will not be achieved. At present, the existing policy for DR subsidy standards are mostly fixed pricing method, the future DR project indicators subscription should be fully market-oriented, can take a competitive bidding method, according to the high or low offer to determine the amount of each user reduction and reduction period requirements.

Based on the experience of the US electricity market, the capacity market is the most important revenue source for DR resources [20]. Therefore, it is important for DR resources to participate in the capacity market to solve the current problems faced by DR resources in terms of high construction costs and lack of suitable profit models to recover costs.

B. IMPACT ON GENERATION CAPACITY ADEQUACY UNDER NEW-TYPE POWER SYSTEMS

After the grid connection of large scale renewable energy generation, relying solely on generation-side resources cannot fully meet the requirements of reliable, safe and efficient operation of the power system with renewable energy as the main form of power generation in the grid, and new available resources must be tapped from the customer side [21]. DR resources can induce dispatchable, temporary load reductions during system load peaks to ensure system capacity adequacy. Therefore, DR resources can participate in the capacity market as other resources [22]. The participation of relatively low-cost DR resources in the capacity market is of great significance to reduce the peak load of the system, slow down the growth of installed capacity and transmission and distribution capacity, and curb the rise of capacity price [23]. This saves costs for maintaining the adequacy of power generation capacity, improves the efficiency of capacity investment, and balances the system reliability risk caused by the decommissioning of aging units. Currently, studies related to the impact of DR resources on capacity markets have focused on two main aspects: the contribution of DR resources to the capacity market adequacy and the impact of DR resources on transmission planning upgrades [24].

III. PRACTICAL EXAMPLES OF DR RESOURCES PARTICIPATING IN CAPACITY MARKETS: UNITED STATES

A. CHARACTERISTICS OF THE CAPACITY MARKET IN THE US AND THE UK

The capacity market mechanism is used by PJM, MISO, NYISO, and ISO-NE to ensure generation adequacy and reliability during future peak hours. The specific organizational process of the capacity market varies little among regions, so this section takes the PJM capacity market as an example and reviews the market mechanism in the order of its capacity market organizational process.

The capacity market of PJM in the United States was initially the capacity credit market (CCM), which was later replaced by the reliability pricing model (RPM) considering the many shortcomings of the CCM [25]. The RPM market includes a Base residual auction (BRA), three incremental auctions (IA), and one continuous bilateral market.The primary market in the PJM capacity market is the BRA market, which is organized three years ahead of the delivery period. The long-term primary market auction can provide long-term stable financial support for new capacity and guarantee the construction time of units. Due to the inflexibility of capacity trading caused by the long lead time of the primary market auction, PJM has also set up three incremental auction markets, namely the IA market, which makes capacity trading more flexible and allows for timely adjustment of capacity purchases, and there are single or multiple secondary markets in all regions except MISO. The organizational process of the PJM capacity market mainly includes developing capacity demand curve, organizing auctions, and settlement.

In the BRA market, PJM develops a three-stage variable resource requirement (VRR) curve based on the forecasted value of the target capacity requirement (RelReq), the total cost of new peaking units (CONE), and the net cost (Net CONE). Net CONE is the total cost minus the energy & ancillary services market revenue. The diagram of the capacity demand curve is shown in Figure 1, and the calculation method of the horizontal and vertical coordinates of the three inflection points in Figure 1 is referred to the literature [26]. The capacity demand curve in the IA market is then constructed based on the purchase bids submitted by capacity providers as well as PJM. The final capacity demand curve in each auction round is finalized after integrating price-based demand response (PRD) resources. Similar to PJM, ISO-NE and NYISO determine demand curves based on IRM and the total or net cost of new peaking units, but differ in the trend of the curves.

Before the auction begins, each capacity provider is required to submit technical parameters such as installed capacity (ICAP) and Equivalent Demand Forced Outage Rate (EFORd) to determine the unforced capacity (UCAP) and declare the selling price and capacity; PJM will conduct clearing with the optimization objective of minimizing capacity purchase cost, taking into account the location constraint and capacity resource constraint, in order to form the capacity clearing price of each region and the UCAP obligation of each capacity provider.

Capacity Providers are billed at a uniform clearing price for their region, and capacity charges are billed to the load aggregators in that region on a load-proportional basis in the name of the regional reliability charge.

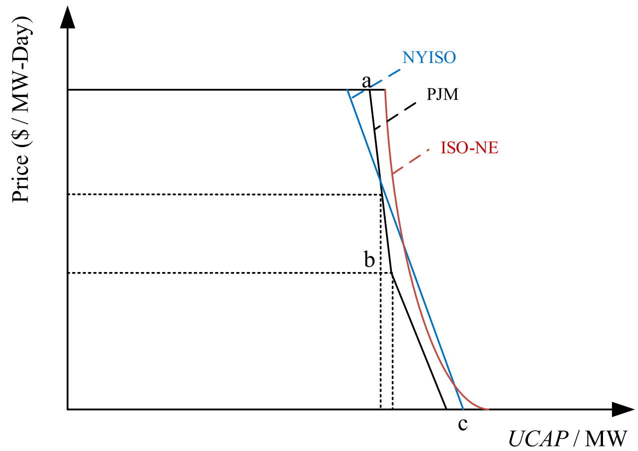

FIGURE 1. Schematic diagram of capacity demand curve in different regions.

B. DR RESOURCES PARTICIPATING IN THE PJM CAPACITY MARKET

1) TYPES OF DR RESOURCES PARTICIPATING IN THE PJM CAPACITY MARKET

The participants of DR resources in the PJM electricity market consists of 4 types:

- Electric distribution company (EDC): Refers to the entity that provides distribution services to users in PJM market by using the distribution equipment owned or leased.
- Load serving entity (LSE): LSE includes load aggregators and other power marketers. Unlike EDC, LSE does not own distribution equipment, but only sells electricity or provides other power services to its contracted end-users.
- Curtailment Service Provider (CSP): It refers to the agents who use their professional technology and service to organize power end-users with the potential of load reduction and willing to participate in DR market transactions. Unlike EDC and LSE, CSP is not responsible for supplying electricity to users, but concentrates users' DR resources from a professional perspective and sells them in the wholesale market to obtain profit [27].
- End Use Customer (EUC): It is the provider of DR resources. It must act as an agent through LSE or CSP to participate in DR market transactions.

In the PJM power market, a small number of DR projects are carried out with LSE as the leading implementer, and most projects are carried out with CSP as the main implementer (CSPs account for about 92% in the 2021/2022 delivery year). In addition, any LSE, EDC or other third-party organization with expertise and service specialties can be as a CSP. Compared with the implementation mode of LSE, CSP is easier to allocate the risk of DR to other market subjects, attract advanced technologies and service to improve the response ability, and make full use of the competition mechanism to

TABLE 1. DR resources participating in the capacity market.

	Scheme	Product type	Capacity Measurement and Verification
Emergency and Pre-Emergency Load Response Program	Emergency capacity only	Limited, Annual, Base, Capacity Performance, Summer Period, Extended Summer	Firm Service Level, Guaranteed Load Drop
	Emergency full (Capacity and Energy)		
PRD Program	Capacity only	-	Firm Service Level

improve the effect of DR resource allocation. However, the form of CSP also increases the complexity of the market and puts forward objective and comprehensive requirements in terms of baseline to measure the reduction effect and settlement mechanism.

In the U.S., DR programs can be divided into time-based programs and incentive-based programs. Emergency and pre-emergency (EP) DR, price responsive demand (PRD), and economic DR, which participate in the PJM capacity market, are incentive-based programs. Emergency demand response (EDR) refers to the behavior of DR resources as a capacity resource to curtail the load according to the instructions of dispatch agency in emergency situations such as when the PJM power market price reaches the specified price ceiling or the system operation reserve is insufficient. PRD is defined as the forecastable load variation in response to changing electricity prices. Of the three DR products, the first two (i.e., EP and PRD) can participate in the capacity market. As shown in the Table 1, EP DR resources participating RPM market can be divided into two schemes: Emergency capacity only and emergency full (capacity and energy). Specifically, EP DR resources include the following product types: Limited, Annual, Base, Capacity Performance, Summer Period, and Extended Summer. The capacity measurement and verification for DR resources includes two types: Firm Service Level and Guaranteed Load Drop. More detailed description about product types and the measurement and verification for DR resources can be seen in Section III-B3.

2) PRD RESOURCES PARTICIPATING IN PJM's CAPACITY MARKET

a: INTRODUCTION OF PRD

In 2008, the Federal Energy Regulation Commission (FERC) issued document No.719, which is intended to improve the participation in DR markets. In addition, the advanced measurement infrastructure (AMI) has been applied in some parts of North America, and some EUCs have the ability to respond to dynamic electricity price or forecast electricity price. Under such policy and technical background, PJM is developing a new demand side resource utilization mode, namely PRD, which is defined as the predictable load change in response to changing wholesale prices. PRD expands the market participation mode of DR resources and is regarded as one of the key research directions of PJM smart grid construction [28]. The original DR program was only for DR resources that could be directly controlled by PJM and required an offer in the wholesale electricity market. Under the PRD mode, residential and small commercial customers that PJM cannot directly control can also participate in the market directly, which increases the regulation potential of DR resources. When PRD resources participate in the market, they can directly respond to the retail electricity price without being directly dispatched by PJM or bidding in the wholesale market.

b: HOW PRD RESOURCES PARTICIPATE IN THE CAPACITY MARKET

Different from traditional DR resources, PRD resources do not participate in the market as a power generation resource, but as a predictable variable load. PRD services are provided by PJM's PRD provider, which on behalf of retail customers who are able to reduce in response to electricity price. Capacity markets in which PRD resources can participate include Base Residual Auction or Third Incremental Auction and promise that the maximum nominated amount of PRD resources can be provided in the delivery year. PRD providers participating in the Base Residual Auction or Third Incremental Auction are required to provide capacity-price information in the Capacity Exchange system, i.e., the PRD Nominal capacity that the PRD provider is willing to provide at different reservation prices. PJM determines the capacity of the PRD resource based on the capacity-price information provided by the PRD provider and the clearing price value. When it is less than or equal to the clearing price, the PRD provider will provide its committed PRD capacity in the delivery year. If a PRD provider cannot deliver the capacity promised in the Base Residual Auction or Third Incremental Auction, the PRD obligation can be transferred to another PRD provider bilaterally to avoid penalty.

In the capacity market, the PRD providers can provide PJM with LMP-anticipated peak load curve of PRD, with an indication of the electrical node to which the resource belongs, prior to the Base Residual Auction (three years in advance) or the incremental auction (three or four months in advance). PRD providers calculate the non-incremental curve by examining the load maximum of PRD resources at different retail electricity prices and considering the relationship between LMP and retail electricity prices. To ensure the reliability of system operation, PJM negotiates with PRD resource providers that the load level of PRD resources shall not be higher than the Maximum emergency load level (MESL) when the LMP is greater than or equal to a certain threshold. In Figure 2, this price threshold is \$2,000/(MWh) for a PRD resource with a MESL of 875 MW. During the operating year, when the LMP reaches \$2,000/(MWh) or more, the PJM has

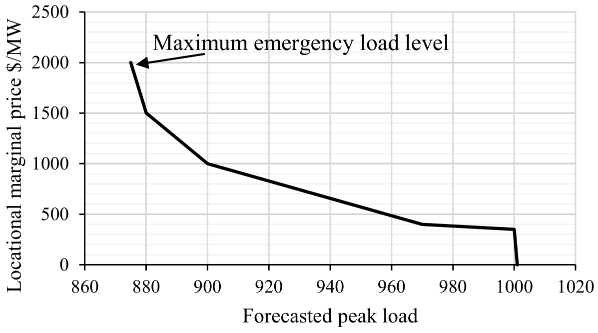

FIGURE 2. Sample of LMP-forecasted peak load curve of PRD.

the authority to issue a load curtailment order to 875 MW if the PRD resource's load level is higher than 875 MW.

As the energy market and capacity market make modification based PRD resources to the original load forecasting curve, the total market clearing capacity is affected, and the demand for power generation capacity is reduced. In this way, the market clearing price is reduced, and the operation cost of power grid is reduced. The impact of PRD on the market price is implicit: as the energy market and capacity market make modification based PRD resources to the original load forecasting curve, the total market clearing capacity is affected, and the demand for power generation capacity is reduced. In this way, the market clearing price is reduced, and the operation cost of power grid is reduced.

The profits obtained by PRD resource providers is also implicit. Unlike DR resources participating in RPM, PRD resources participating in the capacity market do not receive direct financial remuneration, and the profits obtained by PRD resource providers are reflected in the reduction of electricity consumption costs. In addition, in order to encourage PRD resources to participate in the capacity market, PJM appropriately reduced charges of the capacity obligation assessment and reserve obligation assessment of PRD resources.

The development of PRD has formed a win-win situation among power regulatory authorities, power grid operators and users. For the power regulatory authorities, the implementation of PRD is a great opportunity to promote advanced measurement technology and improve demand-side infrastructure automation. For power grid operator, PRD, a form of DR resources, can be used as an effective supplement to the existing form of demand side resource utilization, so that DR resources can participate in the market as power generation resources through aggregation, so as to help PJM modify the load model and reduce operating costs. For power users, the implementation of PRD directly saves power costs and provides a new way to participate in DR program.

3) EP DR RESOURCES PARTICIPATE IN RPM

EP DR resources are subject to mandatory load shedding in the delivery year, and the DR provider receives capacity gains regardless of whether the DR resources is invoked or not. The EP DR resources of the capacity market that have not been invoked must be subject to the mandatory test of PJM to check whether they have the ability to provide the corresponding capacity obligations. If they fail to provide the capacity reduction as required, they will be punished accordingly.

As mentioned in the section III-B1, the capacity measurement and verification for DR resources can be grouped into two types: Firm service level (FSL) and guaranteed load drop (GLD). The customer's load level is maintained within a pre-determined limit when the customer providing FSL service is notified by the CSP Market Operations Center or agency. Determine the capacity reduction. When the user receives the notice from CSP market operation center or institution, the load reduction reaches the predetermined capacity value. Under the GLD mode, load reduction is usually provided by the customer's own generators or shutdown equipment. In the final determination of the response capacity of the EP DR project, the influence of network loss factor and peak load contributions (PLC) must be considered, and the extent of their influence is accounted for by the EDC at the registration stage.

a: INFORMATION REQUIRED FOR DR RESOURCES TO PARTICIPATE IN THE CAPACITY MARKET

DR When participating in RPM auctions, resource providers are required to submit the following information:

- The account information, i.e. EDC account number, Zone, etc.
- Information used to establish the specified EP level, includes PLC, Winter Peak Load (WPL), EDC Loss Factor, notification period (30min, 30-60min, 60-120min), FSL data, and GLD data.
- The name of DR resources
- The types of the EP DR products (including Limited DR, Extended Summer DR, Annual DR, Base Capacity DR, Capacity Performance DR, Summer Period DR), and detailed introduction is shown in Table 2.

b: KEY PARAMETERS FOR DR RESOURCE PARTICIPATING IN CAPACITY

The Installed capacity (ICAP) and the unforced capacity (UCAP) of DR resources are the two key parameters that determine the performance of DR in RPM auction. The ICAP of DR resources is equivalent to the installed capacity of traditional generators, which refers to the maximum load reduction of end users. The determination process of this value is the determination process of users' capacity obligations. UCAP is equivalent to the available capacity of conventional generators, i.e., the remaining available generation capacity at any given time after discounting the generation capacity that is not available due to accidents (e.g., maintenance, etc.). In addition, considering that DR is load shedding on the customer side, its contribution to the system capacity also needs to be discounted to the generation side. Therefore, relevant discounting parameters such as system

TABLE 2. The definitions and features of the EPP DR products.

Items	Delivery period	Interruptible times	Interruption period
Limited DR	During the summer from June to September of theof delivery year	At least 10 times	12:00p.m.- 20:00p.m.
Extended Summer DR	During the extended summer months of June to October and the following May	No limit to the times	10:00a.m.- 22:00p.m.
Summer Period DR	During the extended summer months of June to October and the following May	No limit to the times	10:00a.m.-22:00p.m.
Annual DR	During the delivery year	No limit to the times	June to October, the following May: 10:00a.m.-22:00p.m.; November to April: 6:00a.m.-21:00p.m.
Base Capacity DR	June to September	No limit to the times	10:00am- 22:00pm
Capacity Performance DR	During the delivery year	No limit to the times	June to October, the following May: 10:00am-22:00pm; November to April: 6:00am-21:00pm

loss adjustment factors are established by the DR resource provider in the customer contract based on the customer's geographical location. For FSL product and GLD product, ICAP is calculated by the following expressions respectively:

$$ICAP\_{FSL} = PLC - (FL \times \lambda_{Loss}) \tag{1}$$

$$ICAP\_{GLD} = GLD \times \lambda_{Loss} \tag{2}$$

where, FL refers to the firm service level; λ_{Loss} is the loss factor to account for capacity as determined by the EDC to which the customer belongs; GLD is described as guaranteed load drop; PLC refers to the peak load contribution assigned by the EDC to which the customer belongs, and is expressed as the average of the account's hourly peak load contributions for the five hours designated by PJM as peak capacity hours.

The value UCAP of both FSL product and GLD product are calculated by the following expressions:

$$UCAP_{FSL/GLD} = ICAP \times DRFactor \times FPR \tag{3}$$

where, FPR refers to the forecast pool requirement and $DRFactor$ is expressed as DR factor Starting with the 2018/2019 delivery year, $DRFactor$ is removed from the calculation of the UCAP value.

c: NOTIFICATION PERIOD OF DR RESOURCES

For each type of EP DR program (FSL, GLD), there are three notification periods as follows:

- 30 Minute Lead Time (Quick Lead): Need to be completed within 30 minutes from the time the dispatcher notifies the Market Operations Center of the power restriction.
- 60 Minute Lead Time (Short Lead): Need to be completed within 30 minutes and less than 1 hour from the time the dispatcher notifies the Market Operations Center of the power restriction.
- 120 Minute Lead Time (Long Lead): Need to be completed within 1 minutes and less than 2 hour from the time the dispatcher notifies the Market Operations Center of the power restriction.

Usually, the default lead time is 30 minutes, unless the CSP has physical constraints and other special circumstances that require a 60-minute or 120-minute lead time request to PJM.

d: MEASUREMENT OF THE EXECUTION EFFECTIVENESS OF DR RESOURCE

The effectiveness of the DR program depends on whether or not the customer reduces the contracted capacity of the load during the event time, and is characterized by the difference between the contracted capacity and the average of load reduction during the response period. Next, the measurement approaches of FSL program and GLD program are introduced.

CSPs that choose the FSL program are required to submit 24-hour load data to PJM at the end of the DR event, and the load reduction is calculated as shown below.

$$P_{red\_FSL} = PLC - P_{act\_FSL} \times \alpha \tag{4}$$

where, P_{red_FSL} and P_{act_FSL} refer to the load reduction and the actual load for FSL program respectively; PLC is the peak load contribution.

CSPs that choose the GLD program are required to submit to PJM the 24-h load data and the comparative load capacity curve corresponding to the event after the DR event, and the load reduction is calculated as:

$$P_{red\_GLD} = min\left(\left(P_C - P_{act\_GLD}\right) \times\alpha, PLC - P_{act\_GLD} \times \alpha\right) \tag{5}$$

where, P_{red_GLD} and P_{act_GLD} are defined as the load reduction and the actual load for GLD program respectively; P_C is the value of the comparative load capacity curve submitted by CSP; α refers to the adjustment factor to account for capacity loss.

e: SETTLEMENT FOR DR RESOURCES IN CAPACITY MARKET

The DR resources cleared in RPM will have corresponding incentive compensation, which is equal to the product of capacity clearing price times clearing capacity. In the capacity delivery year, the DR resources invoked by PJM will be punished if they fail to complete the pre-committed capacity, and may be rewarded for exceeding the obligations. For the DR resources that fail to complete the reduction obligations, the penalty will be calculated according to the product of the penalty rate of the LM project in the region times the incomplete reduction. If a time when load reduction is required has not occurred by August 15 of that delivery year, PJM shall organize a test to simulate the issuance of a load reduction signal to test the effectiveness of the response. CSPs that fail to meet capacity reduction requirements during the event or test period will be required to pay a penalty.

4) COMPARATIVE ANALYSIS OF PRD AND EP PRODUCTS PARTICIPATING IN THE CAPACITY MARKET

The participation of PRD resources in the capacity market is completely different from the participation of EP Products in the capacity market. Firstly, EP Products participate in the capacity market as a generation resource, while PRD resources participate in the market as a predictable variable load. Second, in terms of the form of participation in the market, EP Products receive the corresponding remuneration when participating in the capacity market, while PRD resources but are reflected in the reduction of electricity consumption costs and have no direct remuneration. Third, EP Products can participate in the Base residual auction, the three Incremental actions, the Conditional incremental actions, and the Bilateral Market, while PRD resources only participate in the Base residual auction, the third incremental auction and Bilateral Market. Fourth, in terms of scheduling, EP Products are scheduled by PJM, while PRD resources are scheduled by self-scheduling. Finally, in order to encourage PRD resources to participate in the market, PJM appropriately reduces the capacity obligation assessment fee and standby obligation assessment fee for PRD resources.

5) OVERALL TREND IN THE PJM CAPACITY AUCTIONS

a: THE COMMITTED CAPACITY AND EVOLUTION OF DR PRODUCTS

With the great improvement of the DR technology, the application of DR in the PJM power market is becoming more and more widespread. DR occupies an important position in the PJM capacity market. Figure 3 describes the committed capacity of DR providers in the PJM market since the 2007/2008 delivery year [29]. During the initial operation stage of RPM market, namely, 2007 to 2012, DR resources participated in the capacity market in two ways, one by offering emergency DR in the forward market and the other by participating in the incremental auction as interruptible load for reliability (ILR) closer to the delivery year [30]. In addition, as can be seen from the Figure 3, the share of Limited-ILR was much larger than that of Limited-DR in that period. However, as Limited-ILR grew from below 2 GW in 2007/2008 delivery year to nearly 9 GW in 2011/2012 delivery year, concerns began to emerge about its impact on the integrity of forward capacity auctions. Therefore, PJM ended the Limited-ILR, and from 2012 to 2013, all DR resources were required to participate in the forward auction. This is the reason why Limited-ILR skyrocketed from just 2,425 MW in the 2011/2012 delivery year to 7,361 MW in the 2012/2013 delivery year [31]. It can be seen from the figure that since then, the committed capacity of Limited DR has remained almost unchanged until the 2016/2017 delivery year.

As mentioned above, the mechanism by which customers offer Limited-DR products agree to interrupt power supply only 10 times in a year for a maximum of 6h each time exposes a flaw in the market design. As the capacity cleared by Limited-DR providers at RPM auctions increases, the probability that paid capacity users will need that capacity also increases. In this case, the capacity that Limited-DR can provide is actually insufficient, and such a shortfall means that such demand resources sold in the RPM market are less expensive in terms of meeting market demand. The cost of providing such resources is also lower compared to annual DR or generation capacity. And if Limited-DR resources that are required to provide the same level of benefit obligation as generation or Annual-DR products will again be offered at a higher price than they are currently. In addition, the limited dispatchability of the Limited-DR resources led to the reliability of the system cannot be guaranteed.

To address this question, PJM had significantly reduced the procurement cap for Limited-DR and the lead time had been reduced from 2 hours to 30 minutes. In this way, since the 2017/2018 delivery year, the committed capacity of Limited-DR began to to drop dramatically. It decreased by 68.9% and 79.8% year-over-year in the 2017/2018 and 2018/2019 delivery year, respectively. There was another reason for this result, namely, the low clearing price of the auction market in 2016/2017 played an important role [32].

In the 2016/2017 delivery year, the Capacity Performance (CP) DR is defined by PJM [33]. This is a measure based on avoiding generation resources that are unable to provide service under extreme conditions and improving the stability of emergency resources throughout the year. During the extreme cold weather in January 2014, approximately 22% of generation resources in the PJM electricity market was unavailable to serve customers. This indicates that the power system needs stronger incentives to guarantee year-round performance stability of emergency capacity resources. As a result, PJM designed CP to improve system reliability by guaranteeing that resources are always available when needed. However, in the 2018/2019 and 2019/2020 delivery year, most of the DR products cleared in the auction market are Base Capacity DR [34]. CP resources with higher scheduling requirements in the 2018/2019 and 2019/2020 delivery years accounted for only 10.5% and 6.5%, respectively. As can be seen in the Figure 3, the Base capacity and CP products, respectively, is nearly that of the sum of the extended summer and Limited-DR, and that of the amount of Annual DR in the 2017/2018, 2018/2019 and 2019/2020 delivery years. It may imply that there still existed some challenges for DR providers to offer the resources with high performance required at that time. To encourage the the DR providers to offer more resources with high performance and improve the stability of emergency resources, in June 1, 2020, capacity performance would be the only offer for PJM's Emergency Capacity program. Just as shown in the figure,

TABLE 3. Comparative analysis of PRD and EPP products participating in the capacity market.

Items	PRD resources	EP Products
Characteristics of DR Resource Providers	Mainly includes small end-users without great communication devices	with great communication devices
Nature of resources	As the predictable variable load	As the generation resources
Types of participating in the capacity market	Base residual auction, the third, the incremental auction, and Bilateral Market	Base residual auction, three Incremental actions, Conditional incremental action, and Bilateral Market
Scheduling method	Self-scheduled	Scheduled by PJM
Remuneration	No direct financial reward, but rather a reduction in electricity costs	Direct economic remuneration

there is no committed capacity since the 2020/2021 delivery year.

b: THE PENALTIES OF DR PRODUCTS

As previously mentioned, in the delivery years, emergency DR resources called by PJM that do not meet their committed capacity are subject to penalties. For DR resources that do not complete reductions, the penalty will be calculated as the product of the load management program penalty rate for the region in which they are located and the amount of reductions not completed.

When DR resources are not scheduled during the mandatory scheduling period, in addition to receiving a penalty, the CSP must test their portfolio to meet capacity commitment levels. the CSP chooses a weekday as the test day to conduct the one-hour test. Of course, test compliance is not an accurate representation of the resources' ability to cope with actual conditions. The ability of resources to respond to actual PJM dispatches. Given that the demand resource is now an annual product, multiple tests are required to ensure responsiveness throughout the year.

The committed Shortfall of DR resources is determined by many factors, such as the load shedding capability of DR resources, clearing capacity, etc. Some DR resources with large clearing capacity may have a relatively large Shortfall. In addition to the amount that DR resources are willing to provide, the clearing capacity is also related to the capacity cap specified by PJM. In other words, there is a great uncertainty in the amount of shortfall of DR resources. Therefore, the Shortfall of DR resources will not be analyzed in detail here.

Table 4 gives the average penalty rate paid per MW in 2016/2017, 2017/2018, 2018/2019/, and 2019/2020 delivery years [35]. As can be seen from the table, the value of CP in delivery year 2020/2021 decreased significantly compared to delivery year 2017/2018, by about 33%. This is due to an incentive proposed by PJM to encourage DR resources to provide more CP resources with higher capacity performance. For Limited-DR, it can be seen that the average penalty rate paid per MW fluctuated widely in 2016/2017, 2017/2018, 2018/2019/ delivery years. As shown in the table, the penalty rate has increased significantly from 124.08 in the 2017/2018 delivery year to 179.8 [34]. This would greatly reduce the incentive for DR resource providers to actively bid in the next auction, so it is speculated that this may also be a measure to phase out limited DR.

TABLE 4. The average penalty rate paid ($/MW).

Product Type	16/17	17/18	18/19	19/20	20/21
Limited DR	166.41	124.08	179.8		
Extended Summer-DR	138.14	142.86			
Annual-DR	137.45	144			
Base DR			186.8	154.69	
CP	160.72	137.54	187.03	154.69	125.3

c: THE ORGANIZATION OF DR RESOURCES PROVIDING REDUCTION CAPACITY

DR resources in the PJM market mainly consist of on-site generation, heating, ventilation and air conditioning (HVAC), refrigeration, lighting, manufacturing, water heating, and other (batteries or plug load). Figure 4 describes the percent of DR resources providing reduction capacity [36]. It can be seen that manufacturing has always been the main composition of DR resources, accounting for nearly half of the total, and the overall trend to maintain a small increase. It implies that the development of the manufacturing industry has certain improvement. The other major composition of DR resources is HVAC. However, as shown in the Figure 4, the share of HVAC has decreased by about 10 percentage points in the last 2 years. Overall, both manufacturing and HVAC have a combined share of over 70%. Refrigeration, water heating and other have always had a smaller share of no more than 5%. As mentioned above, The PRD mechanism allows some small end-users with poor communication devices to participate in the RPM market since 2020. However, it can be found that there is no increasing for lighting. Perhaps this is due to the low level of PRD resources participating in the market, as shown in the Figure 3. Overall, there has been essentially no wide change in the composition of DR resources since the 2016/2017 delivery year to now.

As mentioned above, DR resources have 2 options when participating in the capacity market: emergency capacity only and emergency full (capacity and energy). However, most DR resource providers will choose the second option. In the delivery year 2021/2022, 98.1% of DR resource providers choose the second model, and 1.9% choose emergency capacity only [38]. DR resources that choose the emergency full model can participate in the energy market, reserve market, capacity market, regulation market to obtain revenue. Figure 5 gives the revenue earned by DR resources participating in each electricity market from January to September 2008 since the establishment of the RPM mechanism for the

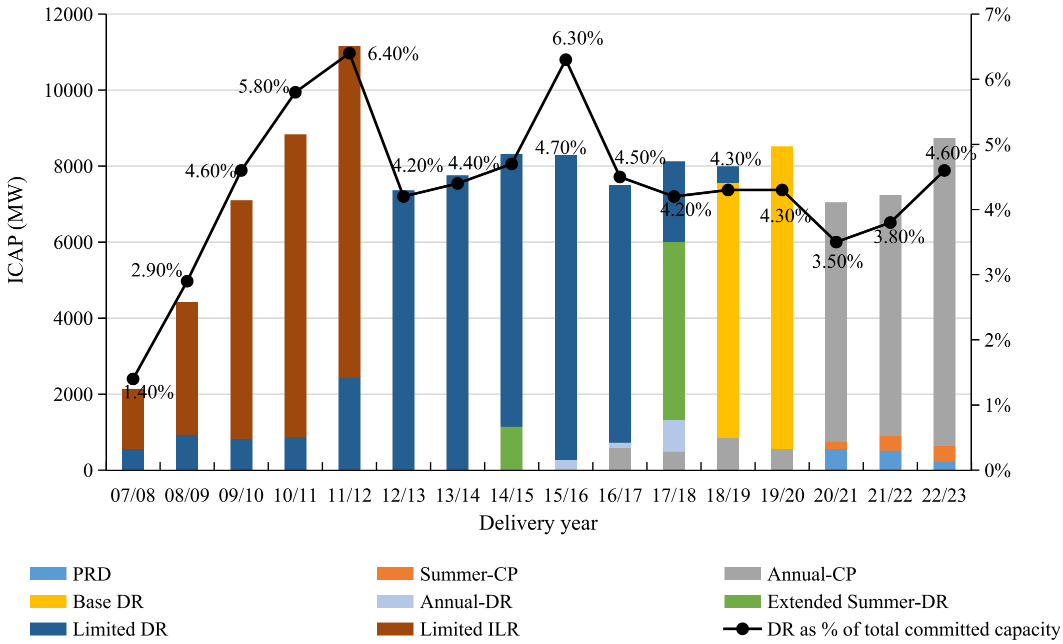

FIGURE 3. The committed capacity of DR providers in the PJM's capacity market since the 2007/2008 delivery year.

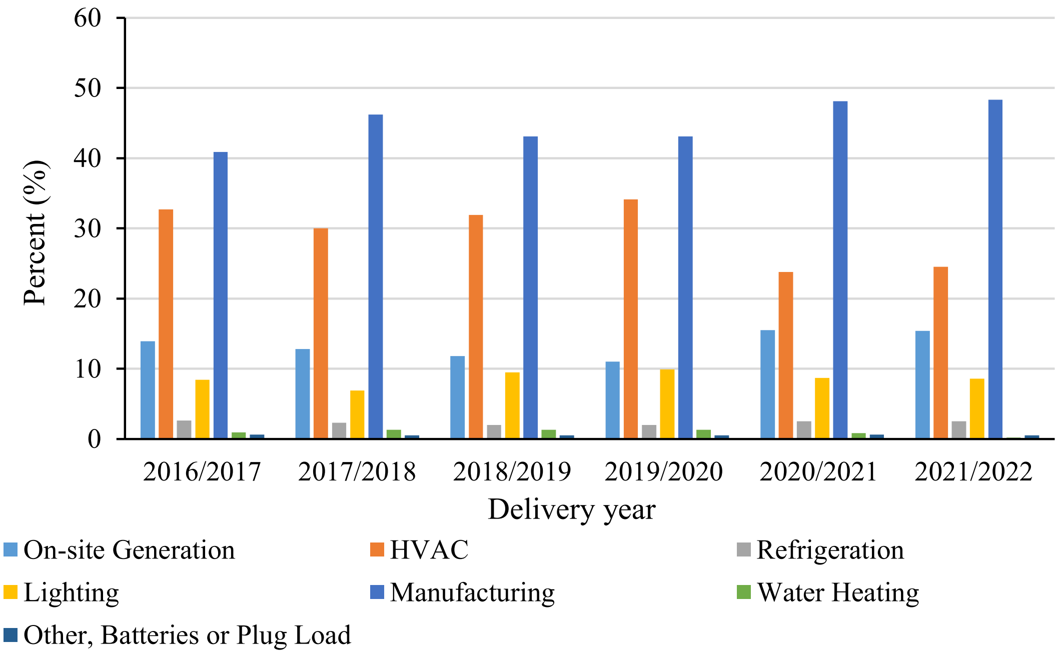

FIGURE 4. The percent of DR resources providing reduction capacity [37].

years 2018 to 2021. As can be seen from the figure, although the emergency full model is chosen by most DR resources, the capacity market is the main source of revenue for DR resources. Since 2008, DR resources providers' revenue from the capacity market has exceeded 75% of total revenue, with a maximum of over 99%, such as in 2016, 2017, 2019, and 2020. It is clear that the capacity market is the most significant source of revenue for DR resources to participate in many markets.

The application value in power systems of DR is now widely recognized, and all parties in the industry have a positive attitude toward the prospect of DR [39]. However, from the situation of DR project development in China, the enthusiasm of DR project development is still not high. The main reason is that DR projects require a large amount of capital investment, and the current DR projects in China mainly rely on government subsidies to compensate DR providers, and the compensation amount is far from covering the investment cost. Based on the experience of the PJM power market, the development of DR in the capacity market should be actively explored in the future.

C. DISCUSSIONS

Although the capacity market is a key development direction for DR resources in the future, it must be mentioned that DR resources participating in the capacity market also faces uncertainties and certain revenue risks. On the one hand, looking at auction results over the last decade or so, PJM's DR revenues have fluctuated significantly, declining nearly 40% from 2010 ($500 million) to 2012 ($320 million), and growing to $800 million in 2015. This issue could lead to a significant reduction in the incentive for DR resource providers to participate in the capacity market and affect the development of DR resources. At the same time, it is not conducive to the optimal allocation of resources. This may be an important issue that PJM or other countries or regions need to focus on when DR resources participate in the capacity market.

On the other hand, the strategy of forward planning prior to several delivery years is another challenge. For DR resources, this means risks in terms of resource development and capacity performance. Capacity cost is calculated by subtracting the expected net benefits in all PJM markets from the total cost of new incoming capacity. Net revenue compensation is the key link between the electric energy market and the capacity market. The capacity market rules make the expected net benefits equal to the 3-year average net benefits of individual units or, in the case of new capacity, the 3-year average net benefits of reference units of the same technology. 3-year historical average price always deviates from actual. If the state of the energy market can be remained relatively stable, then it can provide a reasonable approximate estimated revenue for the actual price of the capacity implementation year. However, the energy market is unstable. Taking the capacity auction as the point in time, the net revenue compensation is referenced to the price of the first 3 years and the price of the estimated next 3 years, and the time difference between them is undoubtedly huge. If in one of the last 3 years the net revenue is very high, then it will result in this 3-year average exceeding the reasonable expectation of the net revenue at the time of the auction now, or exceeding the net revenue actually incurred in the capacity execution year, with the result that the capacity market price is too conservative. The converse is also true. One solution to this problem is to develop a new forecasting tool that allows the forecasted energy market and ancillary services market revenues to match more closely with the expectations of investors during the capacity auction period.

IV. DR RESOURCES PARTICIPATING IN THE UK CAPACITY MARKET

A. INTRODUCTION TO THE UK CAPACITY MARKET

In 2014, as part of a new round of electricity market reform measures, the UK government established the capacity market to ensure the security of electricity supply [40]. The UK capacity market consists of a primary market four years in advance (T-4) and a fine-tuned market one year in advance (T-1). Starting in 2020, the primary auction market is changed to three years in advance (T-3). All types of resources, including power plants, DR resources, and energy storage, are eligible to participate in the capacity market. Participants are penalized if they do not deliver the agreed power when the market requires it.

The UK capacity market is operated and organized by National Grid. After assessing the load demand on the system, National Grid organizes the auction of capacity and purchases the corresponding capacity. The capacity market can be classified into six operational stages as follows [41]:

- **Determination of target capacity**. The target capacity is the traded capacity determined by the system operator based on a reliability index of 3 hours/year load forecast losses.
- **Pre-qualification**. The UK capacity market is "technology neutral" and capacity eligible for market application includes both supply-side resources and demand-side resources. Supply-side resources are divided into stock and new-build units.
- **Auctions**. Auctions are organized four years in advance of the delivery year to determine capacity prices and units to be cleared. Fine adjustments can be made in the auction one year prior to delivery.
- **Private Trading**. Capacity suppliers can trade in the private market during the period after the end of T-4 and before the start of T-1.
- **Deliveries**. Suppliers commit to deliver power from October 1 of the delivery year to September 30 of the following year. Oversupply and undersupply will be subject to incentives and penalties accordingly.
- **Settlement**. Capacity settlement costs are borne by the power sales company and are based on its share of the electricity market in the delivery year.

B. ANALYSIS OF AUCTION RESULTS FOR DR RESOURCES

As the penetration of renewable energy increases, the high intermittency of renewable energy units and the poor scheduling flexibility put higher requirements on peak shaving and maintaining smooth grid operation. Therefore DR resources are expected to play a key role in improving system flexibility and reducing system costs [42]. However, DR resources in the UK have been at a disadvantage in terms of auction results in the capacity market. The auction results are in stark contrast to the early expectations of the UK capacity market executives for DR resources to play a major role.

6 presents the auction results for DR resources in the capacity market from 2014 to 2020. As the figure shows, the

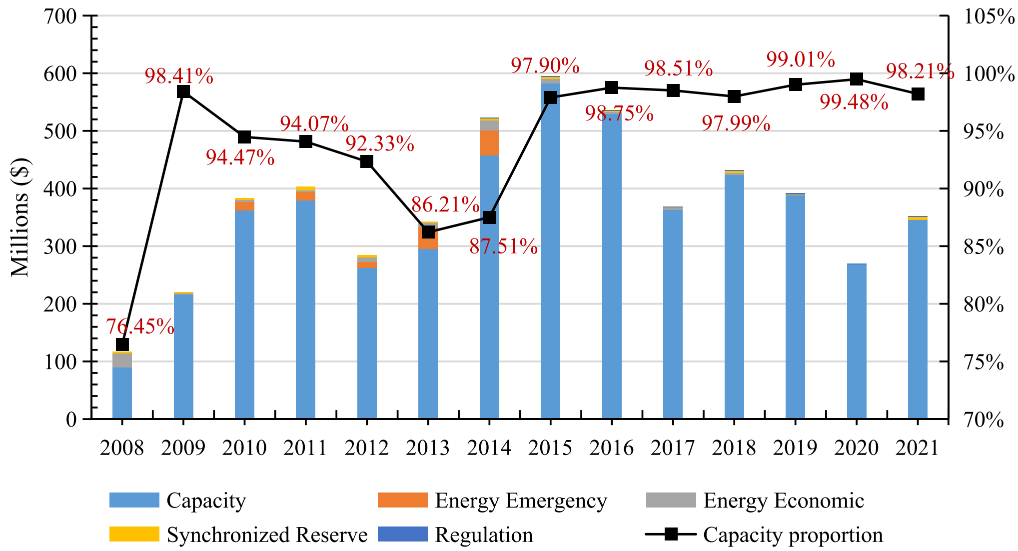

FIGURE 5. DR revenue by market from 2008 to 2021 [37].

share of contracts signed by DR resources in the capacity market is quite small. As shown in the figure, the share of DR resources in the capacity market in the primary auction market from 2014 to 2020 is 0.35%, 1.3%, 2.69%, 0.39%, 2.39%, and 1.19%, respectively [16].

From 7, it can be seen that the UK capacity market in 2024/2025 delivery year DR resources clear capacity of about 1066 MW, accounting for 2.61% of the total clear capacity, of which 0.23% and 2.38% are verified and unverified DR resources, respectively [43]. It is worth noting that the capacity of DR resources auction is much higher than that of wind power, because most wind power in the UK is subsidized, and subsidized wind turbines are not allowed to participate in the capacity market.

C. REASONS FOR THE UNSATISFACTORY AUCTION RESULTS OF DR RESOURCES IN THE UK CAPACITY MARKET

There are many perspectives on the reasons for the unsatisfactory auction results of DR resources in the UK capacity market. Specifically, they can be summarized in the following three aspects.

- The first is the high bid bond mechanism. In terms of bid bond, it is not designed to be applied to small resources such as DR resources. The high bid bond amount discourages many DR resources from participating in the capacity market based on their investment strategy.
- The second is the cumbersome pre-qualification process and the inadequate DR testing arrangements. Many DR resources are excluded because the pre-qualification process is too stringent and DR resources are not able to complete testing in a short period of time.
- The third is the problem caused by the Dutch-style price reduction auction method [44]. The Dutch-style reduced-price auction method has the feature of high efficiency. However, the need to provide information to the market during the auction process gives generators the ability to manipulate market prices when a few larger generators monopolize the market (the top six UK generators and the second tier owned 96% of the UK's generation capacity as of 2012). As a result, many DR resources are forced out of the capacity market because they cannot compete with them.

In November 2018, the UK capacity market was suspended from the capacity auction scheme by the European Court of Justice, requiring a revision of the capacity market rules, but the EU found no evidence of a bias in the capacity market in favour of generators [45]. In May 2020, the relevant regulators revised the rules with the aim of removing barriers to the deployment of DR projects [46]. The rule amendments mainly include the possibility for DR resources to bid for agreements of all durations in the capacity market, provided they can be pre-qualified and provide the corresponding proof of capital expenditure, in addition to lowering the minimum capacity threshold for bidding (Drop from 2 MW to 1 MW).

D. SUGGESTED IMPROVEMENTS FOR DR RESOURCES TO PARTICIPATE IN THE UK CAPACITY MARKET

DR resources will certainly occupy an important position in the future under the new-type power system [47]. The current design of market mechanism is extremely unfavorable to the development of DR resources. Therefore, in order to stimulate the development of DR resources so that they can provide sufficient flexible services in the new-type power system in the future, it is necessary to take some measures to change the current situation.

On the one hand, the design of the market mechanism is tilted toward DR resources. It is important to design

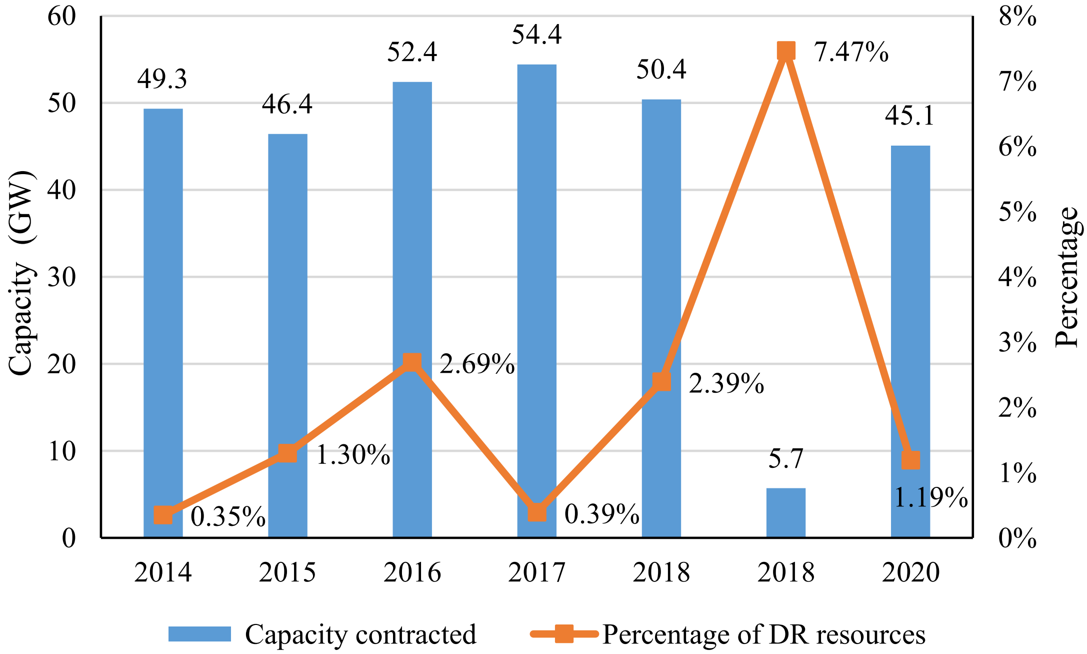

FIGURE 6. Auction Results of DR resources in the UK Capacity Market from 2014 to 2020. Note: (1) The second data for 2018 and the data for 2017 in the chart above is different from the others. They are the auction result for T-1, while the other data are the primary market auction results for T-4. (2) The capacity market is suspended for 2019.

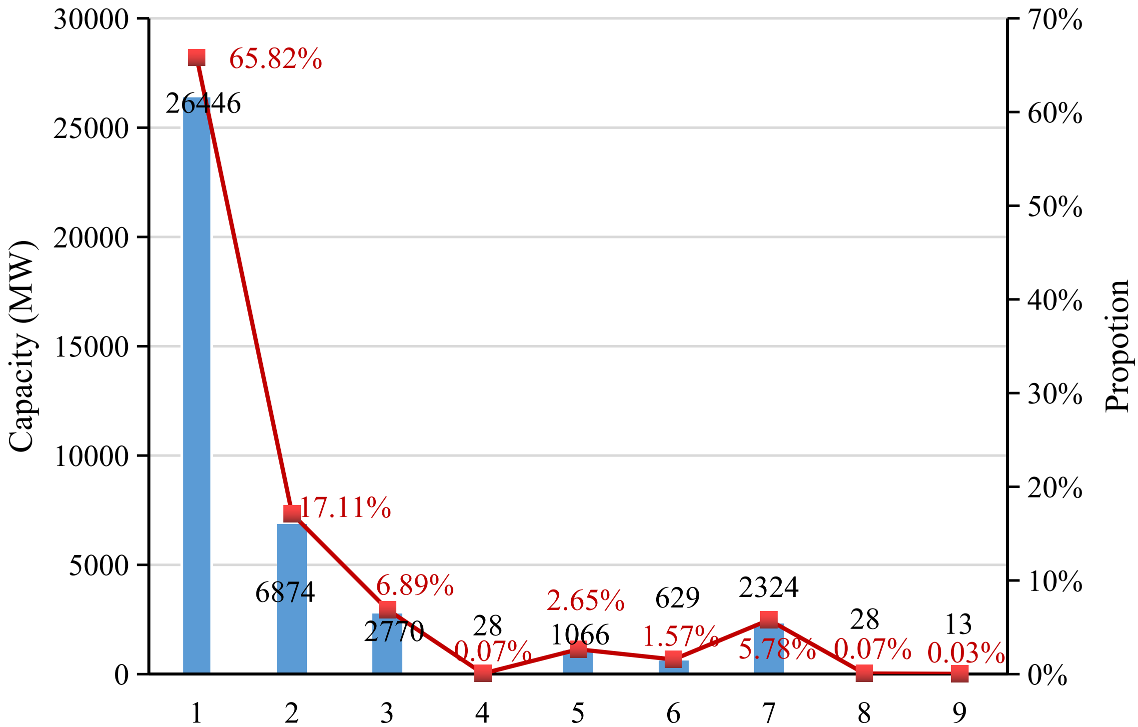

FIGURE 7. Auction results for the UK Capacity Market in 2024/2025 Delivery Years.

mechanisms that are different from other generation resources based on the characteristics of DR resources. For example, the bid bond system should be modified to lower the amount of the bond so that DR resources can afford the cost.

In addition, appropriate modifications should be made in the pre-qualification process and testing arrangements [48].The specific method of DR testing is to analyze the current load adjustable amount compared with the average load during the reference period. There is a division into verified and unverified based on participating in the test. unverified DRs can also participate in the capacity market, but need to pass the test before capacity delivery. Failure to pass the test and validation before the delivery date is subject to a penalty. This measure ensures the performance of DR resources while allowing more resources to participate in the capacity market.

On the other hand, two measures can be taken to address the problem of market price manipulation by the six major generators and the second tier. One is to establish a third-party regulator to oversee the development of capacity market policies. Examples include the Committee on Climate Change (CCC) and the National Infrastructure Commission (NIC). These two bodies have roles primarily in high-level decarbonization and infrastructure planning, respectively. Although neither the CCC nor the NIC has specific authority or capacity to provide detailed advice on energy policy, the state needs to consider the views and recommendations of both bodies when making relevant decisions. Second, it is important to gather the various types of participants in the capacity market to discuss and develop rules to ensure the interests of each party. In market-based power system management, there is a structural dependence of the government on the energy industry. Since only a small number of market players outside of generation resources are involved in making decisions, non-interested parties can be appropriately introduced into the decision making to ensure the fairness of the decisions.

V. SUGGESTIONS FOR DR RESOURCES PARTICIPATING IN CAPACITY MARKET

Although DR resources can participate in the capacity market as capacity resources to provide electricity capacity value. However, the response characteristics of DR resources are complex, and they cannot provide fixed capacity at all times like generating units [49]. Therefore, the mechanism for DR resources to participate in the capacity market is also more complex. This section will analyze several key issues for DR resources participating in the capacity market.

A. DESIGN OF DIVERSE CAPACITY PRODUCTS

In addition to capacity performance products, there are also basic products (2018/2019 and 2019/2020 delivery years) and summer-period products (2020/2021 delivery years) in the PJM capacity market. Compared with the stringent requirements of capacity performance products, basic products and summer period products are only valid for part of the time, which can fully utilize the seasonal characteristics of DR resources. In addition, a single DR capacity product is prone to power shortages due to lack of flexibility from an operational point of view, which is not conducive to long-term stable grid operation. Diversified DR capacity products can compensate when one of them is unable to provide capacity services. Therefore, in the mature stage of capacity market development, the capacity products should be designed with reference to the PJM market, so that the flexibility and responsiveness of each resource can be fully utilized to maintain the stable operation of the system from different dimensions. On the other hand, the standardized design of capacity products will also facilitate the overall management of the market.

B. EVALUATION OF IMPLEMENTATION EFFECTIVENESS

The investigation and evaluation of DR resources is a fundamental task that should be taken seriously, and the project supervision department should strengthen the audit of DR resources. Unlike traditional power resources, DR resources have greater uncertainty, so it is necessary to analyze and evaluate the effect of implemented DR resources and, on this basis, to strictly review the load reduction capacity of DR resources. In PJM capacity market, registered CSPs are strictly reviewed by PJM for load shedding capacity based on historical usage data and relevant factors provided by LSEs and EDCs when participating in the electricity market. It is necessary for government management departments as well as power dispatching agencies and market operators to have a detailed understanding of the total amount of DR resources and the characteristics of resources by type. On the one hand, it is necessary to investigate and evaluate the resource potential by sector, and include the scattered load resources that have not been considered in the past into the scope of investigation and evaluation. On the other hand, it is necessary to judge the technical feasibility of each type of load to participate in DR market. Finally, the technical characteristics of each type of DR should be evaluated and the value should be assessed in the context of the proposed market. On the basis of the above resource evaluation, a DR resource pool should be established by province (district, city) region, and the available DR resources should be included in the power development planning and annual power balance program.

C. INCENTIVIZE SMALL USERS TO PARTICIPATE IN THE MARKET WITH AGGREGATED RESOURCES

From the user's point of view, small DR resources participate in the market as aggregated resources, which can allow more market members to participate in the market and enable users to gain considerable benefits. On the other hand, the participation of small DR resources in the market in the form of aggregated resources can reduce the calculation and settlement pressure of market operators. In 2001, PJM established a mechanism to participate in DR market in the form of CSP, which greatly facilitated the development of DR. Since individual users lack specialized knowledge in DR and different users may show different levels of response at different times, the effectiveness of DR execution by individual users fluctuates greatly [50]. Through the aggregation of different users by CSP, the users who have over-completed the reduction plan and those who have not completed the reduction plan can offset each other, and the execution effect of DR is more stable, which is conducive to the unified scheduling of resources and can greatly improve the efficiency of the process of subscription, response, and settlement in the execution of DR projects. Almost 85% of the DR types in PJM in recent years have been in the form of CSP every year. This situation cannot be separated from the support of the U.S. government. The U.S. has been cultivating load aggregators for many years, with more policy support, making it a more mature profit model even in the early years, such as allowing load aggregators to gain revenue by providing various services. In order to cultivate more load aggregators and incentivize small resources to participate in the capacity market in the form of aggregated resources, it is necessary to improve the cultivation mechanism and financing mechanism of load aggregators by introducing corresponding policies and giving full play to the role of market management of third-party service companies.

D. MEASUREMENT OF IMPLEMENTATION EFFECTIVENESS

As an important evaluation basis for DR projects, the baseline load of users is an important guideline for the development of reasonable subsidy settlement criteria [51]. At present, there are a lot of international research results in baseline load analysis. The Association of Edison Illuminating Companies Load Research Committee has proposed a load baseline analysis method based on DR dynamic measurement data, expecting to evaluate the curtailed power and electricity through data interaction.The difference between the customer's load baseline and the actual electric load curve is the customer's load reduction [52]. However, in the actual system measurement, the estimation of load baseline is often inaccurate. If the customer's load baseline is overestimated, the utility or aggregator will have to pay extra for it. On the contrary, if the customer baseline is underestimated, the customers participating in the market will not be able to obtain the due benefits [53]. In the long run, this will seriously attack the enthusiasm of customers to participate in the power grid interaction, and is not conducive to the cultivation and healthy development of the market [54]. At present, for small residential customers, metering and settlement is more difficult, there are also relevant research in considering through blockchain and other new information communications technology to solve the problem [55]. In the future, it is also necessary to fully integrate the electricity market environment and the development of relevant policies to further study the baseline load calculation strategy, and develop a variety of baseline load calculation methods according to the nature of the user, such as reference to year-on-year data, to ensure that DR users can obtain reasonable benefits.

VI. CONCLUSION

As the only two countries in the world where DR resources participating in the capacity market, the experience and lessons learned from the US and the UK are of great reference significance to other countries and regions in the subsequent development and construction of DR resources and capacity markets. This study first analyzes the importance of DR resources participating in the capacity market from two perspectives: the development of DR resources and system generation capacity adequacy. Secondly, the mechanism design of DR resources in the US capacity market is analyzed in detail, and the auction situation of DR resources since their participation in the capacity market is introduced. Then, the development status and dilemma of DR resources in the UK capacity market are analyzed in detail, and the corresponding suggestions for improvement measures are given. Finally, suggestions are given for common problems in the participation of DR resources in the capacity market.

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