Review of Market Power Assessment and Mitigation in Reshaping of Power Systems

Nan Shang, Yi Ding, and Wenqi Cui

***Abstract*—The deregulation of the power industry requires avoiding market power abuse to maintain the market competitiveness. To this end, a sequence of assessment measurements or mitigation mechanisms is required. Meanwhile, the increasing renewable energy resources (RESs) and flexible demand response resources (DRSs) are changing the behaviors of market participants and creating new cases of market power abuse. Such new circumstances bring the new evaluation and control methods of market power to the forefront. This paper provides a comprehensive review of market power in the reshaping of power systems due to the increasing RES and the development of DRS. The market power at the supply side, demand side, and in the multi-energy system is categorized and reviewed. In addition, the applications of market power supervision measures in the US, the Nordics, UK, and China are summarized. Furthermore, the unsolved issues, possible key technologies, and potential research topics on market power are discussed.**

***Index Terms*—Market power, renewable energy source (RES), flexible demand response source (DRS), assessment, mitigation.**

I. Introduction

WITH the restructuring and deregulation of the power system, its basic structure has transformed from centralized command dispatch to deregulated transaction [1], [2]. However, market power has become one of the major impediments to the deregulated electricity market. As a fundamental concept in economics, market power is defined as the phenomenon in which market participants can alter prices and thus pose a threat to the normally competitive levels of the market [3], [4]. In addition, the Federal Energy Regulatory Commission (FERC) also defines market power as the ability of participants to withhold capacity or services, to foreclose input markets, or to raise rival companies' costs to increase prices of consumers on a sustained basis without related increases in cost or value [5].

Market power is derived from various causes, including network constraint, market-control strategy, and explicit collusion behaviors [4]. With the abuse of market power, some benefits of market participants could flow to the market dominators, the market price signal may be distorted, and social welfare may be reduced [6].

Nowadays, market power is changing along with the development of the electricity market. In particular, the increasing penetration of renewable energy resources (RESs) in recent years [7], [8], emerging market participants (such as electric vehicle (EV), storage, etc.) [9], [10] and flexible demand response sources (DRSs) have brought variability and uncertainty to power systems, reshaping the way in which electricity markets operate [11] - [13]. Another significant change is the reconstitution of the electricity market during the transition to a low-carbon power system, which has raised new requirements for market design and regulations [14].

The development of the electricity market exerts a subtle influence on not only the assessment but also the restraint of market power. Previous studies have attempted to account for this influence from different perspectives such as in terms of generation units and reactive power suppliers [15], [16]. However, these previous studies focus less on the impact of emerging market participants, including RESs, DRSs, prosumers, etc. [17]. Meanwhile, few studies have categorized the various evaluation technologies from the viewpoint of both the supply and demand sides.

This paper reviews the sources, motivation, assessment, and mitigation of market power. This paper contributes to expanding the scope of market power analysis and enriches the content of market power assessment, which is more in line with the emerging trends of power systems and electricity markets. By providing an extensive overview of market power under these new circumstances, we aim to provide a reference for the policies and research on the construction of an efficient electricity market mechanism.

The remainder of this paper is organized as follows. Firstly, the sources and empirical evidence of market power are identified in Section II. Then, the method of market power assessment, including the structural indices/modeling methodology at the supply side, the evaluation technologies at the demand side, and multi-energy systems are detailed in Section III. In addition, the overviews of the market power mitigation measurements made worldwide (e.g., the US, the Nordics, UK, China, etc.) are stated in Section IV. Unsolved is-

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sues and potential research topics are discussed in Section V, and Section VI gives the conclusion of this paper.

II. Sources and Empirical Evidence of Market Power

A. Sources of Market Power

1) Second-by-second Balancing of Supply and Demand

Compared with other industries (e. g., production retail, equipment manufacturing, etc.), the power system is required to maintain the balance between the supply and demand at all times. Considering the lack of cheap storage for power, market participants may take advantage of their large-capacity or quick-response resources to achieve large profits by forcing the related players to accept unreasonable prices under some circumstances (e.g., extreme weather, random failures, etc.). Specifically, [18] investigates the minimum must-run capacity of a generator to supply a given load at a node, which represents the capability of generation units that force the market operation institutions to dispatch them. In addition, [19] and [20] focus on the demand side, specifically the market power of the flexible DRSs at the demand side. Under some extreme circumstances, flexible DRSs must be dispatched to maintain the balance between the supply and demand. At this time, the flexible DRSs possessing market power can be harnessed to control the prices or request higher incentives temporarily, since the market operators have to accept.

2) Power Industry Monopoly

For a long time, the electricity industry has a large economy and is considered as a natural monopoly [21]. The market power in the electricity industry stems primarily from industry concentration. Specifically, the monopoly is the result of high entry barriers, high investment cost, transmission network externalities, etc. The power generation providers with high market share may control the market by eliminating other small competitors or colluding with others [22], [23]. Recently, the market power at the demand side has also been raised as a realistic concern [19]. Similar to the market power at the supply side, the dominators at the demand side can use resource advantages (e.g., information, technology, etc.) to exclude other small retailers, distort the signal of clearing prices, and obtain unreasonable profits.

3) Network Congestion

Network congestion may result in local and system market power, which can be reflected in the separation of markets or the strategic actions [24], [25]. Specifically, given the network topology, generation units can intentionally affect the power flow to reach the transmission constraint through increasing or decreasing production [26]. As a result of network congestion, they are capable of exercising market power and earn extra profit. Moreover, the separation of markets may lead to the formation of a local monopoly.

B. Empirical Evidence

There are abundant empirical evidences revealing the abuse of market power, including the increasement in market prices above competitive levels, the unreasonably high operation costs, and the market failure. For example, the actual electricity price was 22% above the competitive level in the California wholesale electricity market during June-November, 1998 [27]. Such sharp price spikes during some periods can be regarded as the result of market power. In addition, the excess monetary loss caused by the aforementioned crisis reached \$40 billion and led to the bankruptcy of Pacific Gas and Electric [28], [29], which is also the result of market failure caused by market power.

Moreover, if one participant with a high market share can control or affect the market clearance result, it may have an incentive to choose malicious strategies such as economic or physical withholding. For example, the two dominant generation suppliers, i. e., National Power and PowerGen in the England and Wales pool (E&W) market, may exercise market power by withdrawing power during some time periods [30]. In France, the Electricite de France (EDF) is the absolute leader at the demand side with a market share of over 80% [31]. In China, the State Grid Corporation of China (SGCC) owns more than 90% of the power users [32]. These participants may subject consumers and other participants to the risk of having a high cost.

III. Market Power Assessment

It is never an easy task to detect market power and determine how much market power is excessive in electricity markets. The studies on market power assessment demonstrate that the judgment of market power abuse varies with different regulations, market designs, and market rules. Depending on the market operation model, the methods of evaluating market power can be classified as: ① the structural indices; and ② the others based on the market clearance results. From the application domain, there are distinctions at the supply and demand sides.

A. Structural Indices of Market Power at Supply Side

The structural indices are commonly defined according to the static characteristics of electricity markets. In this paper, such indices can be divided into the following two categories.

Structural indices of type I (SIT-I): the indices of this category can be obtained without modeling any power flow, cost-efficient market operation, or game behaviors among participants. Most of these indices can be determined from their intrinsic properties. However, the relevance of these indices to realistic market operation is relatively weak.

Structural indices of type II (SIT-II): such structural indices are calculated without remodeling or solving new optimization problems. They can be calculated only by utilizing the existing electricity market mechanism, the economic dispatch/unit commitment process, the current power system topology, or public information (e.g., market price, unit marginal cost, etc.). Correspondingly, these indices have higher requirements for information disclosure.

1) SIT-I

1) Herfindahl-Hirschman index (HHI)

HHI is defined as the sum of the squares of market shares of all participants [33]:

$$HHI=\sum_{i=1}^{N}S_i^2 \tag{1}$$

where N is the number of participants; and S_i is the market share for the i^{th} participant.

HHI has played an important role in the FERC judgments with respect to the market structure type (e.g., competitive, monopoly, competitive monopoly, etc.), which is as shown in Fig. 1. However, the function of HHI is to reflect the industry concentration ratio, which is static and weakly correlated with system networks.

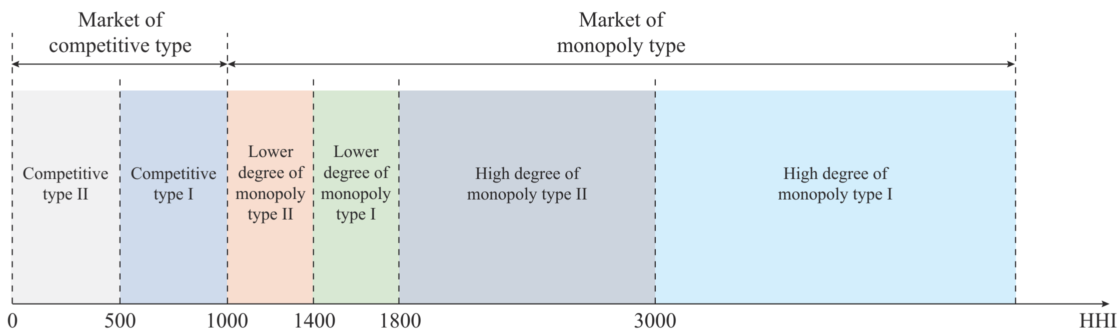

Fig. 1. Market structure types based on HHI.

2) Must-run ratio (MRR)

MRR is utilized to analyze zonal market power [34]. Considering the transmission constraints, the MRR for a generation company A (Genco A) in zone i is defined as:

$$MRR=\frac{P_d-P_l-\left(\sum_{j=1}^{N_g}P_{gj,\max}-\sum_{j=1}^{N_{gA}}P_{gj,\max}\right)}{\sum_{j=1}^{N_{gA}}P_{gj,\max}} \tag{2}$$

where P_d and P_l are the total load and the import limit of the zone, respectively; $P_{gj,\max}$ is the output limit (capacity) of generator j; N_g is the number of generators; and N_{gA} is the number of generators owned by Genco A in the zone. The MRR shows the capacity of one Genco to supply a given load through a congestion zone.

3) Contribution congestion factor (CCF) matrix

CCF matrix $\boldsymbol{M}_{\text{ccf}}$ is used to evaluate the impact of each individual generator output P_{gi} on the transmission-constrained line L_j [35]:

$$\boldsymbol{M}_{\text{ccf}}=[P_{gi},L_j] \tag{3}$$

The positive value of CCF indicates that the generated power will aggravate transmission congestion. Correspondingly, a negative value reveals that the increased electricity generation can reduce the power flow in the transmission-constrained line.

2) SIT-II

1) Lerner index (LI)

The ideal competitive equilibrium price is the benchmark from which the degree of market power abuse can be evaluated [28]. Therefore, the LI or price-cost margin index (PCMI) is used to measure the proportional deviation of the price of generation units from the marginal cost at the profit-maximizing output [36]. The LI for generation unit i is defined as:

$$LI_i=\frac{\rho_i-MC_i}{\rho_i} \tag{4}$$

where ρ_i and MC_i are the price and marginal cost of unit i at profit-maximizing output, respectively. The value of LI greater than zero indicates that Genco possesses the market power. However, the LI cannot reflect the price response on demand and also fails to address the impact of transmission line constraints on the market price.

2) Location privilege (LP)

LP represents the influence on the producer surplus according to their locations of power system [37], which is defined as:

$$\eta_i=\frac{S_{i,P}(F_l)-S_{i,Pu}}{S_{i,Pu}} \tag{5}$$

where η_i is the LP index for the power producer i; $S_{i,P}$ is the producer surplus with network constraints; F_l is the transmission flow limit; and $S_{i,Pu}$ is the producer surplus under unconstrained perfect competition.

3) Market price controllable (MPC)

MPC represents the ability of market participants to affect the market price [38], which includes the index for a certain generation unit $I_{MPC,i}$ and that for the whole electricity market I_{MPC}.

$$I_{MPC,i}=\frac{p_{e,\max}-p_{e,\min}}{p_{e,\max}} \tag{6}$$

$$I_{MPC}=\sum_{i=1}^{N_g}I_{MPC,i}\gamma_i \tag{7}$$

where $p_{e,\max}$ and $p_{e,\min}$ are the maximum and minimum prices controlled by the generation unit, respectively; and γ_i is the percentage for the capacity of generation unit i of the total installed capacity.

4) Residual supply index (RSI)

From the perspective of supply and demand, the RSI refers to the ratio of the available capacity of one generator to the total demand [39], which is defined as:

$$RSI_i(h)=\frac{\sum_{k=1}^{N_g}P_k(h)-P_i(h)}{D(h)} \tag{8}$$

where $\sum_{k=1}^{N_g}P_k(h)$ is the total available market generation capacity; $P_i(h)$ is the production capacity of the firm i; and $D(h)$ is the total market demand.

According to the California Independent System Operator (CAISO), when the RSI_i is between 120% and 150%, the market can be considered to be in a competitive state. When the RSI_i is less than 100%, it can be concluded that the generation unit i can control the price.

The structure evaluation indices mentioned above have been summarized in Table I.

TABLE I
SUMMARY OF SIT-I AND SIT-II ASSESSMENT INDICES

Type	Index	Concept	Prior information	Reference
SIT-I	HHI	Sum of the squares of market shares of all participants	Market share ratio	[40]-[42]
	MRR	Ratio of the power generation unit to supply a zone load	Generation capacity and load	[15], [34]
	CCF matrix	Impact of power generation output on the transmission line	Network topology, generation/load location, and operation parameters	[35], [43], [44]
SIT-II	LI	Proportional deviation of price at the profit-maximizing output of generation unit from the marginal cost	Market operation result (clearing price) and marginal cost	[41], [45], [46]
	LP	Proportional deviation of the producer surplus with or without constraints	Network topology, market operation result, and transmission line constraints	[37], [47]
	MPC	Proportional deviation of the maximum and minimum prices that the generation unit can control	Market operation result (clearing price)	[38], [48]
	RSI	Ratio of the capacity except for one particular generation unit and the total load	System generation capacity and load	[49]-[51]

B. Methodology of Market Power Evaluation at Supply Side

Market power evaluation is closely associated with the operation of the electricity market and the power system. The cost-efficient market operation, which includes the economic dispatch, unit commitment, and the stochastic renewable resources, forms the fundamental basis in modeling market power. Therefore, in addition to the structural indices mentioned above, there are many methodologies of market power evaluation related to specific cost-efficient market operation circumstances. Correspondingly, these indices vary with the supply/demand situations, market mechanisms [52], [53], component states, network constraints [54], strategic bidding behaviors [55], etc.

Although the existing market power indices have been applied in many new scenarios, including transmission-constrained operation and fuzzy system formulation [56], [57], new indices and measures have been proposed to adapt to new developments in power system operation [58]-[60]. In particular, stochastic renewable energies [61] and the transition to a low-carbon power system bring continuously changing circumstances of market power abuse (see [62]-[64] for hydropower, [65], [66] for wind, and [67] for combined heat and power (CHP)).

These models generally evolve from traditional economic dispatch or unit commitment problems and differ in their specific formulation such as the supply/demand situations, market operation states, and the strategic behaviors among participants. Because of the dependency of these new indices on the specific model, it is generally difficult to identify which indices can be adapted to new scenarios in future problems. Therefore, we form a more complete framework for market power assessment in Section III-B, and the model-dependent indices can be better classified and distinguished. We have classified the indices derived from the economic dispatch or unit commitment problem formulation as follows.

1) Must-run Generation (MRG)

Based on the economic market dispatch, generation units may possess must-run power, in which malicious strategies can be utilized (e.g., the bidding price uplift). Therefore, the MRG index is defined as the minimum generation output considering the load and transmission constraints [18]:

$$\begin{cases} \min P_{gk} \\ \text{s.t. } \boldsymbol{e}^{\mathrm{T}}(\boldsymbol{P}_g-\boldsymbol{P}_d)=0 \\ \qquad \boldsymbol{0}\le \boldsymbol{P}_g \le \boldsymbol{P}_{g,\max} \\ \qquad -\boldsymbol{P}_{l,\max}\le \boldsymbol{F}(\boldsymbol{P}_g-\boldsymbol{P}_d)\le \boldsymbol{P}_{l,\max} \end{cases} \tag{9}$$

where $\boldsymbol{e}^{\mathrm{T}}$ is the vector containing all ones; $\boldsymbol{P}_g$ and $\boldsymbol{P}_d$ are the power dispatch and demand vectors, respectively; $\boldsymbol{P}_{l,\max}$ is the line limit; and $\boldsymbol{F}$ is the distribution factors matrix [68]. Based on MRG, more extended indices, such as must-run share (MRS) [69], [70], nodal must-run share (NMRS) [18], [71], and expected nodal must-run share (ENMRS) [72], [73] are proposed to evaluate nodal market power, as shown in Table II, where p_r is the availability probability of component r; and N_c is the number of scenarios. As for the ENMRS, we assume that there are m failed system components in a power system with n independent components at the state s.

Moreover, [74] also proposes the nodal market power (NMP) assessment index and utilizes it for visualizing market power with a color contour map. Reference [75] quantifies the market power of distributed pumped storage units with the must-dispatch power (MDP) index.

TABLE II
SUMMARY OF CORRESPONDING EXTENDED INDICES OF MRG

Index	Formula	Concept	Prior information	Reference
MRS	$MRS_k = P_{gk}^{must}/P_d$	Ratio of MRG P_{gk}^{must} to total load P_d	MRG and load	[69], [70]
NMRS	$NMRS_{k,i} = P_{gk,i}^{must}/P_{di} \quad i = 1, 2, \ldots, N_g$	Ratio of MRG $P_{gk,i}^{must}$ to load at bus i P_{di}	MRG and topology	[18], [71]
ENMRS	$\begin{cases} p_s = \prod_{r=1}^{m}(1-p_r)\prod_{r=m+1}^{n} p_r \\ ENMRS_{A,i} = \sum_{s=1}^{N_c} p_s NMRS_{A,i}^s \end{cases}$	Expected value of MRG $NMRS_{A,i}^s$ with the multi-state system possibility p_s	MRG, system state, and stochastic system states	[72], [73]

2) System Interchange Capacity (SIC)

The SIC indicates the maximum power that one market participant must sell under the constraints of the network topology and system states (e. g., generation, load, node voltage, etc.). Based on the principle of cost-efficient market operation, the SIC can be obtained through solving the following optimization problems [76]:

$$\begin{cases} EXP = \max \sum_{k=1, k\neq m}^{N_g} \Delta P_{gk} \\ \text{s.t.} \ \sum_{k=1}^{N_g} \Delta P_{gk} = 0 \\ \quad -(S_{\max} + S_{hl}) \leq \sum_{k=1, k\neq m}^{N_g} PTDF(h,l,i,j) \leq S_{\max} - S_{hl} \\ \quad \Delta P_{gk} \geq 0 \quad \forall k \end{cases} \tag{10}$$

where $S_{\max}$ is the maximum transmission power; S_{hl} is the power flow of the transmission line from h to l; m is the agent, to which the market ability of selling is considered. The parameter $PTDF(h,l,i,j)$ is the power transfer distribution factor for the transmission line from i to j associated with the power trades between the sale point h and purchase point l. This index also reveals the information about the strategic coalition of two agents for obtaining market power under transmission congestion [15].

3) Structure-conduct-performance (SCP) Framework

In micro-economics, there is a causal link between the market structure (S), the conduct of market participants (C), and the market performance (P). According to the operation process of the electricity market and the criteria for quantifying market competition, the SCP paradigm can be utilized in market power assessment [77]. The SCP framework for market power assessment includes the following steps.

Step 1: construct a set of market power assessment factors and confirm the subsets.

Step 2: determine the target of market power evaluation using the analytic hierarchy process (AHP) for each level and the weights for the indicators.

Step 3: calculate the membership of the indicator for a single factor.

Step 4: carry out the single-level fuzzy evaluation for market structure, market conduct, and market performance.

Step 5: evaluate the market power for the generation suppliers and the whole market.

Step 6: determine the uniform fuzzy factor and compare the final evaluation indices.

4) Transmission-constrained Network Flow (TCNF)

The TCNF unifies the transmission-constrained structural market power indices based on the residual supply, network flow, and minimal generation [78] and can be defined as:

$$\begin{cases} TCNF_s(\rho) = \max \left\{ \sum D \right\} \\ \text{s.t.} \ P_{gs} \leq \rho \\ \quad \text{Other network constraints} \end{cases} \tag{11}$$

The TCNF can be interpreted as the optimal power flow (OPF) problem in which the objective is to satisfy the demand $\sum D$, and the production level of the generator P_{gs} is bounded above by the parameter ρ [79]. The TCNF is utilized to measure the relative importance of each generator in order to meet the additional demand at different levels of ρ by bidding considering the network constraints.

5) Stochastic Indices to Account for Renewable Energy

To account for the impact of stochastic RES on the market power [80], the market power assessment index based on the market revenue share $MRS_{MP}(A_i)$ is expressed as:

$$MRS_{MP}(A_i) \in [MRS_{\min}(A_i), MRS_{\max}(A_i)] \tag{12}$$

$$MRS_{\max}(A_i) = \max\left\{\left\{MRS(A_i)|_{E_1}\right\}, \left\{MRS(A_i)|_{E_2}\right\}, \ldots, \left\{MRS(A_i)|_{E_n}\right\}\right\} \tag{13}$$

$$MRS_{\min}(A_i) = \min\left\{\left\{MRS(A_i)|_{E_1}\right\}, \left\{MRS(A_i)|_{E_2}\right\}, \ldots, \left\{MRS(A_i)|_{E_n}\right\}\right\} \tag{14}$$

$$MRS(A_i)|_{E_j} = \frac{R_{A_i}}{\sum_{i=1}^{m} R_i} \times 100\% \tag{15}$$

where $\sum_{i=1}^{m} R_i$ is the revenue of the whole power industry; and $\left\{MRS(A_i)|_{E_j}\right\}$ is the market power of the generation company A_i based on the results of the following optimal process.

$$\begin{cases} E_j\text{: } \max \sum_{j\in A_j} U(Q_j) = \boldsymbol{XQ} \\ \text{s.t.} \ \boldsymbol{e}^{\mathrm{T}}\boldsymbol{Q} = Q_L \\ \quad \boldsymbol{0} \leq \boldsymbol{Q} \leq \bar{\boldsymbol{Q}} \\ \quad \boldsymbol{0} \leq \boldsymbol{X} \leq \bar{\boldsymbol{X}} \end{cases} \tag{16}$$

where $U(Q_j)$ is the revenue function of the generator j; Q_L is the system load; and $\boldsymbol{X}$ and $\boldsymbol{Q}$ are the price and power matrices, respectively.

6) Other Related Evaluation Indices

In several specific market trade models, many other indices are also utilized or proposed for market power assessment. Most of these indices are derived from the comparisons between the sufficient competition market scenarios and market power scenarios.

1) Price deviation: the abuse of market power often results in the change of market clearing price [81]. In [82], the variation congestion index (VCI) is proposed as:

$$VCI=\frac{\sum_i P_i \sum_j CP_{i,j}^2}{\sum_i P_i} \quad i\in\{\Omega_{\mathrm{G}},\Omega_{\mathrm{L}}\} \tag{17}$$

where $CP_{i,j}$ is the congestion contribution from the j^{th} congestion for a generator (or load) i; P_i is the generation from the i^{th} generator or the cleared load quantity from the i^{th} load; and Ω_{G} and Ω_{L} are the sets of generation and load, respectively.

In addition, [83] decomposes the locational marginal price (LMP) into three components for monitoring market power at the supply side:

$$LMP_n=A_{0,n}+\sum_i A_{i,n}a_i+\sum_j A'_{j,n}P_j^{\max} \tag{18}$$

where the first component $A_{0,n}$ is a constant value; the second component $\sum_i A_{i,n}a_i$ includes the weighted summation of the strategies of the generation companies without generation caps; and the third component $\sum_j A'_{j,n}P_j^{\max}$ is composed of the weighted summation of generation units with generation caps.

2) Social-welfare deviation: based on welfare economic theory and welfare-maximization philosophy, [84] and [85] propose the social welfare loss rate (SWLR), which is formulated as (19) and illustrated in Fig. 2.

$$R_i=\frac{S(\Delta CFK)}{S(\Delta AFP_{MC(i)})-S(\square EFP_{MC(i)}L)} \tag{19}$$

where ΔCFK, $\Delta AFP_{MC(i)}$, and $\square EFP_{MC(i)}L$ denote the graphic areas of the triangles CFK and $AFP_{MC(i)}$, and the rectangle $EFP_{MC(i)}L$, respectively; and $S(\cdot)$ is the area function.

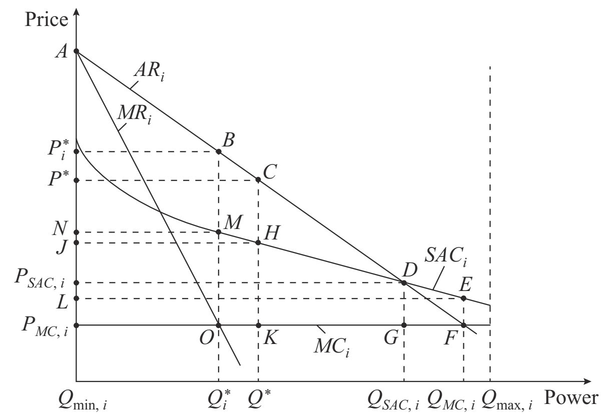

Fig. 2. Market power assessment based on social welfare.

In Fig. 2, Q and P represent the corresponding power and price, respectively; and AR_i, MR_i, SAC_i, and MC_i are the demand curve, marginal income curve, average cost curve, and marginal cost curve, respectively.

The indices from evaluation methodology at supply side in Section III-B are summarized in Table III.

TABLE III
SUMMARY OF INDICES FROM EVALUATION METHODOLOGY AT SUPPLY SIDE

Index	Concept	Prior information	Reference
MRG	The minimum output provided by one particular generator	Network topology and generation/load-related parameters	[86]-[88]
SIC	The maximum power that a specific market participant must sell	Network topology and generation/load-related parameters	[89]
SCP	Evaluation of market structure, conduct, and performance	Market operation result and market shares	[90]-[92]
TCNF	Generator output bounded by demand requirement	Network topology, generation/load location, and operation parameters	[78], [79]
$MRS_{MP}(A_i)$	Revenue share of one generation company considering RES	Market operation result and generation-unit-related bidding parameters	[80]
VCI	Congestion contribution from a generator (or load)	Network topology, generation/load location, and operation parameters	[82]
SWLR	Proportion of the loss of social welfare in total social welfare	Supply/demand curve	[84], [85], [93]

C. Game Model and Market Equilibrium

Among the mainstream theoretical game methods used to predict the strategies or market participants for market power assessment [94], the Cournot model and Bertrand model are most commonly studied in the literature.

The Cournot model (also known as the Cournot duopoly model and the duopoly model) was proposed by French economist Auguste Cournot in 1838 [95]. In the Cournot model, the suppliers decide how much they produce and assume their rivals will not alter their outputs [30]. Reference [36] provides the Cournot equilibrium point of two, three, and infinite suppliers and concludes that as the number of suppliers tends to infinity, the market price moves toward the marginal cost. The Cournot model has been utilized extensively in [27], [96] - [98] to analyze the market power abuse in California. However, the Cournot model is normally limited to a single-period interaction of supply and demand and is also sensitive to the demand elasticity, which may be difficult to estimate.

The Bertrand model proposed in 1883 is a type of price competition model [4]. In the Bertrand model, there are two suppliers that produce identical products and have identical marginal cost curves. Bertrand model represents the competition behaviors between the suppliers that cannot collude. If no less than two suppliers exist in markets, the price of the the market will equal the marginal price [36]. Importantly, the Bertrand model assumes that any supplier can capture the market by pricing below others and can expand output to meet the demand. Therefore, the Bertrand model may not be applicable to electricity market because the outputs of generation resources are always constrained [30].

D. Discussion on Relevance of Power Market Indices

Section II-A to Section II-C have presented a preliminary overview of various market power indices. The relevance of the indices discussed can be summarized as follows.

This paper classifies the evaluation indices at the supply side into three categories: SIT-I, SIT-II, and market power evaluation methodology. Indicators in the same category often have similar application conditions, premises, or assumptions. This provides a guidance for the selection of indices in different problem formulations. Although the concepts, effects, advantages, and shortcomings of the indices in different categories differ from one to another, these indices do not conflict with each other. The combination of different indices can be utilized according to the specific problem formulation (e.g., the existence of economic dispatch, system topology details, and consideration of the stochastic components). This may achieve a better evaluation or mitigation effect of market power.

E. Market Power Manifestation at Demand Side

Unlike the market power at the supply side, the market power at the demand side is aggravated with the advancement of electricity markets and has been considered as a realistic concern [99]. Specifically, as the buyers in the wholesale market, the large consumers at the demand side can force related market participants to accept unreasonable prices or payments. As the sellers in the retail market, the retailers may also utilize strategic behaviors such as forecasting errors to influence market results.

1) Classical Evaluation Indices

Based on the classical evaluation indices at the supply side from the perspective of microeconomics (e.g., LI, HHI, etc.), similar indices in evaluating market power at the demand side have been discussed in many works. Specifically, several indices (e.g., the buying concentration rate) are proposed to evaluate market power at the demand side [100], [101]. Reference [102] indicated that the purchasers could lower the prices below the competitive level, and the buying power index (BPI) is proposed to quantify the deviation of prices from ideal competition.

However, these classical indices have their limitations. For instance, most of them cannot fully consider network topological characteristics or transmission constraints. In addition, these indices may ignore other instances of market power abuse at the demand side such as the exclusion of other market participants [103].

2) Retail Monopsony Power in Wholesale Market

In the wholesale electricity market, the potential monopsony power of retailers may appear in highly concentrated markets such as the EDF mentioned above. Specifically, in the pool-type day-ahead (DA) and real-time (RT) markets, the strategic behaviors of profit-driven retailers can be divided into three categories, as shown in Fig. 3, and further constitute four typical trade scenarios, as shown in Fig. 4 [104].

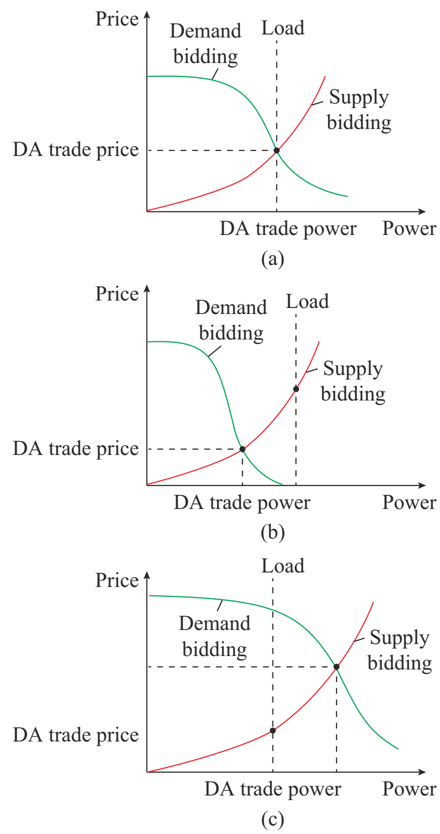

Fig. 3. Three strategic behaviors of profit-driven retailers. (a) Behavior mode 1: perfect competitive bidding curve. (b) Behavior mode 2: withholding bidding curve. (c) Behavior mode 3: upraising bidding curve.

Three behaviors and four typical scenarios are summarized in Table IV. It is evident from the data that the withholding bidding strategies are more likely to be carried out by retail dominators rather than upraising bidding declaration.

As for the evaluation indices, the price deviation rate of DA market ρ_r, the power trade deviation rate of DA market q_r, the power market revenue deviation E_P^r, and the average purchase power cost deviation W_r can be utilized to quantify the influence of market power abuse, which are shown in Table V.

3) Market Power Assessment of Load-serving Entities (LSEs)

The increasing DRSs improve the flexibility of power systems [105], [106]. The profit-driven LSEs, on behalf of DRS, can exercise market power when the supply and demand are unbalanced. Reference [19] discusses such a problem and proposes a novel nodal market power analysis framework with indices to evaluate it. Figure 5 shows two cases (case 1 and case 2) to explain how the flexible DRSs exercise nodal market power in a power system with two buses and three generators, where λ is the state transition rate. The flexible DRSs are located at bus 2.

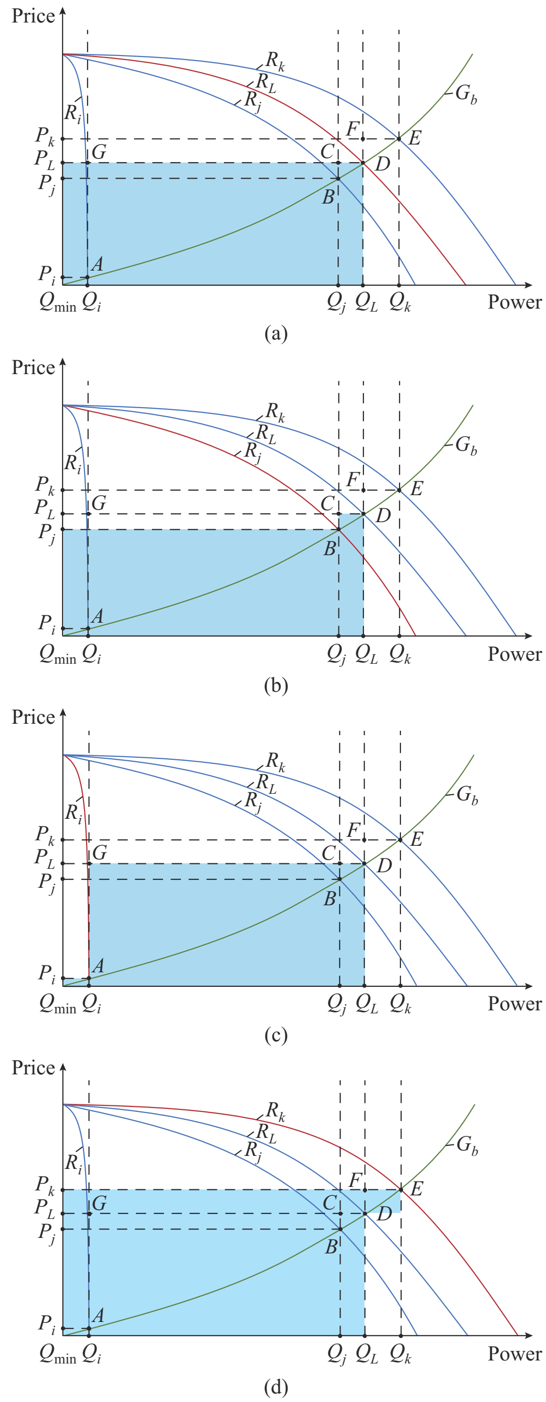

Fig. 4. Four typical trade scenarios for profit-driven retailers. (a) Scenario 1: with perfect competitive bidding curve R_L. (b) Scenario 2: with withholding bidding curve R_j. (c) Scenario 3: with withholding bidding curve R_i. (d) Scenario 4: with upraising bidding curve R_k.

TABLE IV
SUMMARY OF THREE CONDUCTS AND FOUR TYPICAL SCENARIOS

Behavior mode	Trade scenario	Intersection	Power clearing fee (PCF)
Perfect competitive bidding	Scenario 1	Point D	$PCF_L = S(Q_{\min} Q_L D P_L)$
Withholding bidding	Scenario 2	Point B	$PCF_j \leq PCF_L$
	Scenario 3	Point A	$PCF_j \leq PCF_L$
Upraising bidding	Scenario 4	Point E	$PCF_k \geq PCF_L$

TABLE V
RELATED EVALUATION INDICES AT DEMAND SIDE

Index	Formula	Concept
Price deviation rate of DA market	$\rho_r = \dfrac{\rho_{DA}(S_1) - \rho_{DA}(S_0)}{\rho_{DA}(S_0)}$	Difference of DA market price ρ_{DA} between perfect competition scenario S_1 and market abuse scenario S_0
Power deviation rate of DA market	$q_r = \dfrac{Q_{DA}(S_1) - Q_{DA}(S_0)}{Q_{DA}(S_0)}$	Difference of DA trade power Q_{DA} between S_1 and S_0
Market revenue deviation	$E_P^r = E_P(S_0) - E_P(S_1)$	Loss of total purchase cost value of retail dominators E_P between S_1 and S_0
Average purchase power cost deviation	$W_r = W(S_0) - W(S_1)$	Loss of end-users W between S_1 and S_0

Specifically, in peak load periods, the power supply shortage may appear. In this example, the load of bus 2 is 350 MW. The maximum power supply of bus 2 from the transmission line is 100 MW, while the maximum power supply of bus 2 from generator C is 200 MW. Therefore, there will be 50 MW load that cannot be supplied. The flexible DRS at bus 2 must be reduced at the demand side to maintain the system balance.

However, if the flexible DRS at bus 2 is reluctant to be cut, extra peaking generation units will be dispatched or the rigid load will be cut. Correspondingly, there will be a price spike at bus 2, as shown in Fig. 5. Therefore, the flexible DRS nodes possessing must-cut quantity have the market power to control nodal prices and obtain excess profits.

Based on the circumstances mentioned above, the market power of DRS can be evaluated by assessment indices such as NMUQ, NMCQ, ENMUQ, and ENMCQ. The four proposed indices are summarized in Table VI.

F. Market Power Abuse in Multi-energy Systems

The integration of CHP units and regional heat and electricity integrated energy system (RHE-IES) is promoting the coordination of multiple energies in market trades [107], [108]. The integrated multi-energy system projects in Germany, called "E-energy", have been operating in Cuxhaven, Harz, Ruhrgebiet, Aachen, Rhein-Neckar, and Baden since 2008 [109]. The multi-energy market has also been operating on Bornholm Island in Denmark [110]. The urban integrated-multi-energy pilot constructed in Jiaxing, China has achieved 100% consumption of RES [111]. Under such circumstances, the multi-energy trading agents (META) can also exercise market power [112]. For instance, [99] discusses possible market power abuse of the hydrothermal system. In this section, the market power in the multi-energy system can be reflected on multi-type generation resources collusion or multi-type system network coupling, which are classified into the following two types.

1) Type I: Collusion Among Multi-type Generation Resources

With a higher proportion of RES, more peaking generation resources are required to cover the gap caused by the variation of RES. This circumstance provides the chance for collusion among generation units with different operation flexibilities [113].

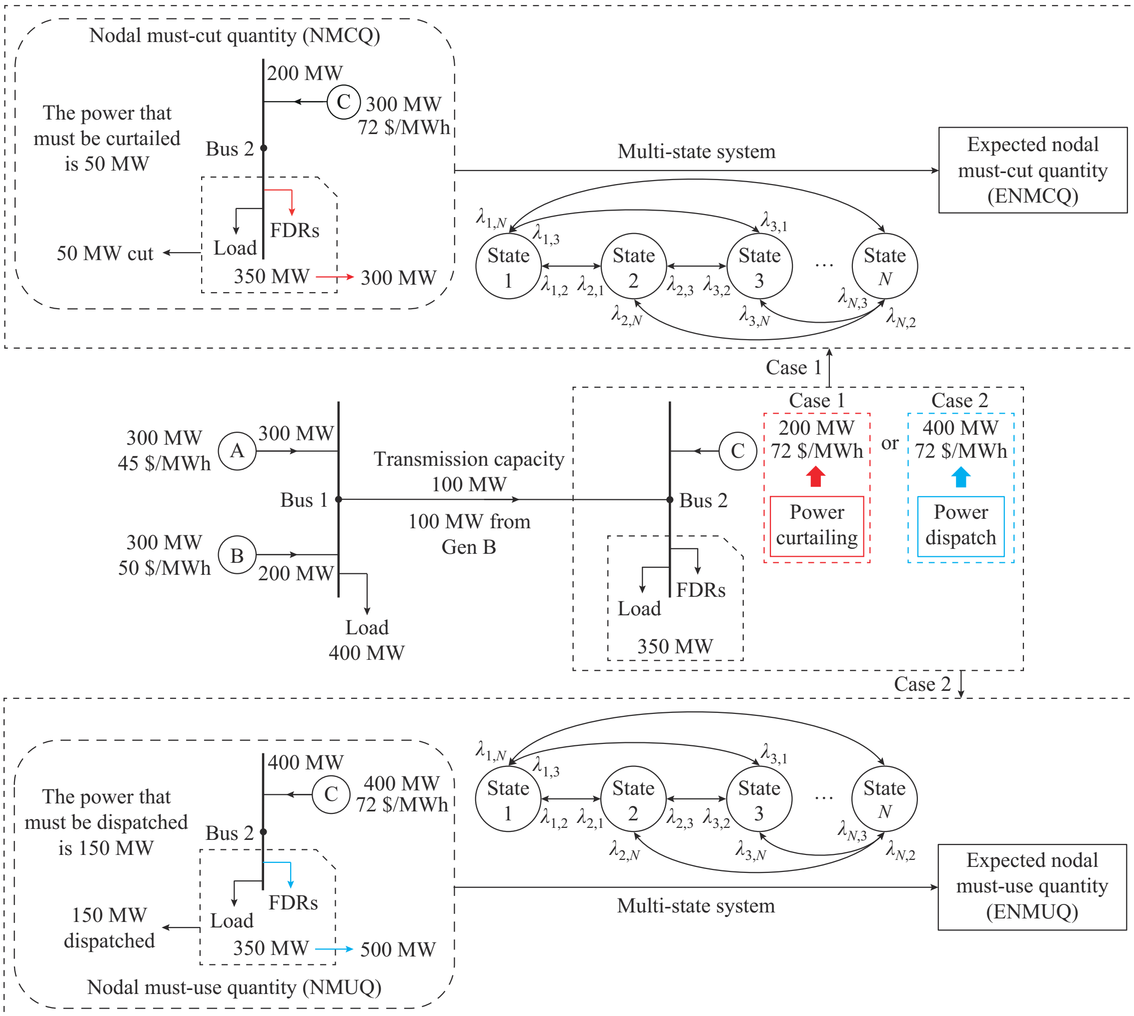

Fig. 5. Scenarios of market power abuse of DRS.

TABLE VI
SUMMARY OF FOUR PROPOSED INDICES FOR DRS MARKET POWER ASSESSMENT

Index	Concept	Application	Meaning
NMUQ	The minimum power that must be consumed	Low load, transmission line break, or unresponsiveness of DRS	Capability of DRS to obtain excess profits by providing must-use/must-cut service
NMCQ	The minimum power that must be reduced	Peak load, transmission line break, generators tripping, or unresponsiveness of DRS	
ENMUQ	Expected value of NMUQ considering multiple system states	Identical to NMUQ	Capability of DRS to obtain excess profits considering stochastic system states
ENMCQ	Expected value of NMCQ considering multiple system states	Identical to NMCQ	

Specifically, extra profit can be earned from the collusions among the generation units by combining their advantages (e.g., high ramp rate, fast starting or stopping, etc.). For example, base-load generation units such as nuclear or coal-fired units (units A and B in Fig. 6) can collude with fast-ramping units such as gas-fired or pumped-storage units (unit C in Fig. 6) by withholding the dispatch of power needed to promote the peaking units.

Such situations can be formulated as a more general problem of optimizing the capacity portfolio of the units with various operation characteristics (e. g., generation output, ramping rate, etc.).

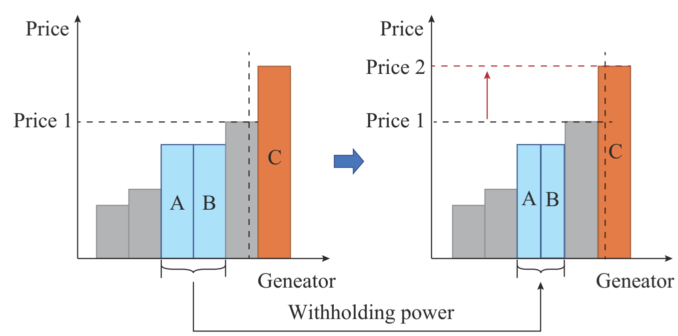

Fig. 6. Collusions among generation resources with various flexibilities.

2) Type II: Multi-energy Coupling Network System

The increasing number of multi-energy participants will strengthen the connections among the components, including power systems, natural gas systems, transportation systems, communication systems, heating systems, etc. Specifically, Fig. 7 shows an example of the gas-power integrated market. For the META possessing both natural gas resources and gas generator capacity, the revenues are the sum of power and gas market incomes, which is determined by the price or quantity from both electricity and gas markets. Therefore, it can increase the price of the gas market by withholding the amount of gas. Meanwhile, the price of the electricity market may increase because of the higher gas price, therefore yielding extra income for gas-fired units.

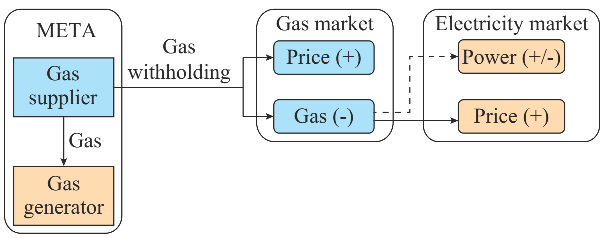

Fig. 7. Collusions among generation resources with various flexibilities.

Moreover, in order to ensure the consumption of gas and minimize the construction cost of gas pipelines, several monopolistic government-run liquefied natural gas (LNG) enterprises such as Petro China may widely invest and construct the gas-fired generation units in neighborhoods. In addition, the peak load of gas and electricity often occurs simultaneously, which increases the chances of exerting market power through a multi-energy network.

IV. Market Power Mitigation in Practice

The mitigation measures of market power are important for market regulators. From the perspective of the regulation theory in microeconomics, there are already plenty of traditional mitigation measures of market power in the electricity market [27], which are shown in Table VII.

TABLE VII
Traditional Mitigation Measurements of Market Power

Measurement	Specific practice
Ease of entry	Encourage more market participants to enter the market
Division	Reduce or limit market share of market dominators
Financial contract	Contract for difference (CFD)
Price cap	The upper limit to submitted price

Concerning the market power, a controversial issue for a long time is how to coordinate the regulation and competition. Most market power monitoring measures in electricity markets are performed by the national/regional electricity market regulatory authorities, such as the Gas and Electricity Markets Authority of Great Britain, the Nord Pool ASA, the Nord Pool Spot AS of the European electricity market, etc. Many screens, triggers, or measures for market power mitigation have been formed and utilized. This section specifically emphasizes the methods available for the analysis and mitigation of market power. Both the traditional mitigation measures of market power and the specific supervision practices used in the US, the Nordics, UK, and China are introduced.

A. Electricity Market of US

In the US, FERC has used various procedural and institutional measures for market power monitoring, such as the market-based rate authorization, approval of merger or acquisitions, and so on. The regional transmission organizations (RTOs) such as ERCOT, MISO, PJM, NYISO, and ISO-NE have also employed the corresponding mitigation rules to control market power. Among them, the well-known mitigation measures include the three jointly pivotal supplier (3JPS) test utilized by PJM, the constraint competitiveness test (CCT) used by ERCOT, and the conduct and impact test (CIT) employed by MISO.

1) 3JPS Test

In PJM, the 3JPS test is performed under toggle conditions when the local market concentration (valued by HHI) is over 2500 or the sensitivity of one generation unit to relieve transmission constraints is greater than 3%, etc. Following PJM tariff 3.2.2A.1, the 3JPS test of PJM is performed after the bids are submitted in the DA and RT markets. The relevant equation is expressed as [114]:

$$R_j=\left(\sum_{i=1}^{N_g}Q_s^i-\sum_{i=1}^{N_{gM}}Q_s^i-Q_s^j\right)\Big/Q_L \tag{20}$$

where R_j is the evaluation index in 3JPS test; N_{gM} represents the two largest units; Q_L is the total demand for easing the congestion; and Q_j is the corresponding available capacity of the j^{th} generation units that will be tested. If $R_j<1$, the generation units dispatched for congestion relief fails in the 3JPS test [115], that is, the remaining capacity cannot meet the dispatch demand for easing the congestion after removing the three members tested [116].

The test process proceeds as follows. Firstly, each power generation unit is sorted according to the size of capacity. Then, beginning with the three largest suppliers, the test is performed. As the test occurs throughout the cycle, the first two largest suppliers remain unchanged, and the third one is replaced according to the sorting order. The 3JPS test is performed in an order of time, and the corresponding stockholder will be regulated if it fails the test.

2) CCT

ERCOT believes that the bidding prices can be mitigated if the local transmission congestion is relieved. Hence, the CCT is employed, which will form a list of competitive constraints before the auction. ERCOT attempts to identify the changing of bidding behaviors of market participants due to the real scarcity in the electricity market. In CCT, the "competitive constraints" are identified for which congestion can be relieved through a competitive bidding process among various competitors [117]. The process of CCT may include the following steps.

Step 1: when congestion occurs, the congested transmission lines will be elected.

Step 2: if the congestion exists, the impact of the output of market participants on each transmission line is quantified through calculating the corresponding "shift-factor".

Step 3: ERCOT identifies the potential market power participants for which congestion can be relieved.

Step 4: the mitigation bidding prices are executed.

The result of CCT in ERCOT is reflected in the element competitiveness index [118]. The market power assessment and control test may be run periodically (e.g., annually, monthly, or daily) to identify which transmission constraints should be considered non-competitive.

3) CIT

Except for the 3JPS and CCT mentioned above, MISO, NYISO, ISO-NE, and PJM rely more on the CIT, which place greater emphasis on the monitoring of market suppliers' specific conduct and their impact on market clearing prices [119].

CIT involves the following two steps. Firstly, ISO determines whether the bidding price of the market participants is higher than the reference price. Then, compared with the reference bidding curve, the impact of generation units' bids on the market clearing price will be tested by ISO. If the market entity cannot pass both the conduct and impact tests, its bidding price will be replaced by the reference price. In NYISO, the methodology of CIT is integrated into the RT generation unit commitment and dispatch software system (i. e., the RT commitment automated mitigation procedures) [120].

Much stricter CIT will be also applied in regional grids with heavier congestions. For instance, the testing reference values of ISO-NE are set as 25 \$/MWh and 50% of the reference market clearing price, which will also rise with the increase of the historical market prices and lower with the decrease of congestion time [121]. In PJM, when generation units bid over 100 \$/MWh or three times the reference price, the impact test will be executed. When the impact of the biddings on market clearing price is over 100 \$/MWh or two times the market settlement price, the market participants will be regulated.

The market power mitigations in US are summarized in Table VIII.

TABLE VIII
OVERVIEW OF MARKET POWER MITIGATION TECHNIQUE IN US MARKET

Market	PJM	ISO-NE/NYISO/MISO	CAISO	ERCOT
DA market	3JPS test	CIT	CCT	
RT market	3JPS test	CIT	CCT	CCT

B. Electricity Market of Nordic and UK

Compared with the PJM, New England, or other electricity markets of the US, the market power abuse in the electricity market of Nordic and UK is not severe. In addition, the ex-post mitigation measurements or punishments are more likely to be utilized. Taking the Nord Pool as an example, market power will be monitored from the market information. When complaints and reports against market bodies arise, the market regulators will start the supervision procedure. Besides, following the bids of market participants, the Nord Pool will compare these bids with the generation cost based on the coal consumption rate. The generation units bidding much higher than the marginal generation cost will be regarded as the price takers [122].

In the UK electricity market, the market power mitigation also mainly relies on the ex-post punishment rather than the ex-ante measures (such as price-cap). For example, if the market regulators identify that some generation units may obtain extra revenues through taking advantage of transmission congestion in the balancing market, the transmission constraint license condition of these generation units will be revoked [123]. It is widely believed that the reason for the weak market power in the UK electricity market is related to the following two aspects.

1) Low Market Concentration

During the construction of the UK electricity market , the two generation giants, National Power and Power Gen have been split and reorganized. Meanwhile, various new independent generators are introduced, which further reduces the market concentration and promotes the competition of the electricity market. For example, in the England and Wales market, the regulator may intervene periodically to ensure efficient competition.

2) NETA Market Mode

The UK electricity market mode is changed from a centralized clearing Pool to the NETA mode, which is an electricity market consisting of a bilateral trade and balance mechanism. The regulatory requirements and difficulties of NETA are much lower than those in the Pool-type market.

C. Electricity Market of China

The most recent electric power system reform of China started in 2015 [124]. The first eight market pilots [125], i. e., the China Southern region (starting with Guangdong province), western Inner Mongolian region, Zhejiang province, Shanxi province, Shandong province, Fujian province, Sichuan province, and Gansu province, have all started trial operations. Based on their regional or provincial background, different market power mitigation mechanisms are designed.

As an emerging electricity market, the power market in China is not competitive enough. Therefore, traditional market power assessment indices such as the HHI may not be applicable currently. Considering the primary target of constructing the market framework and formulating the price signal [126], several spot pilots paid more attention to behavior supervision in market power mitigation [127]-[129]. Taking the Guangdong and Zhejiang spot market pilots as examples, this section introduces the market power mitigation mechanisms utilized in China.

1) Guangdong Spot Market

The market power evaluation method in the Guangdong spot market pilot is similar to the CIT [130]. Specifically, the price bidding from generation units is compared with the reference price in the first-round conduct test. If the units cannot pass the CIT, the bidding price will be replaced by the reference price. In addition, the difference of generation revenue is calculated through market clearing. When the difference value of generation revenue exceeds the predetermined ceiling value, the generation unit will be judged not to pass the second-round impact test.

In Guangdong province, both the reference and the revenue ceiling are determined by the market management committee (MMC) approved by the government department and energy regulatory agency. At present, market power monitoring only includes the conduct test.

2) Zhejiang Spot Market

The electricity market design group of Zhejiang province summarizes the influences of market power abuse as follows: ① load or local load; ② unit commitment; ③ the power from the outside region (province); ④ transmission congestion; and ⑤ market concentration, etc. According to these factors, several well-known mitigation measures, such as 3JPS test, are also recommended in the market power assessment in Zhejiang province.

Moreover, the residential supply index (RSI) and CIT are combined in the Zhejiang electricity market. The RSI of the generation supplier i at time t is defined as:

$$RSI_{i,t} = \frac{\sum_{j=1}^{N_g} P_{j,t} - P_{i,t}}{\sum D_t} \tag{21}$$

where $P_{i,t}$ is the supplier that will be tested; $\sum P_{j,t}$ is the units belonging to the supplier j; and $\sum D_t$ is the total load demand at time t. Except for the supplier i, if the generation of other suppliers j cannot meet the total load ($RSI < 1$), this supplier can be regarded as the critical generation supplier. In addition, the RSI can be utilized in advance of the CIT (e.g., a month before the generation dispatch). If the generation units cannot pass the RSI, they will be further tested with CIT. Moreover, the consortium of PJM technologies, Inc. and China Electric Power Research Institute, SGCC also recommend the following considerations in market power mitigation.

1) The concept of "market power" or "market power abuse" will be identified.

2) As many as generation units will be included in the market power test.

3) The process of market power assessment is open and transparent.

4) The combination of ex-post and ex-ante evaluation methods can be used.

5) The over-mitigation market power should be avoided as much as possible.

6) The reference bidding price and punishment fee should be analyzed.

The measures for market power monitoring used by the spot market pilots in China are summarized in Table IX.

TABLE IX
MARKET POWER MITIGATION MEASURES USED BY SPOT PILOTS IN CHINA

Spot market	Measures	Reference
Guangdong	Conduct test of CIT	[130]
West Inner Mongolia	Bidding price monitoring	[128]
Zhejiang	RSI/CIT	[131]
Shandong	Conduct test	[132]
Fujian	Dynamic HHI/RSI/3JPS	[133]

V. UNSOLVED ISSUES AND POSSIBLE RESEARCH AREAS

Despite the progress of the literature mentioned above for market power assessment and mitigation, there remain several unsolved issues and potential topics to be investigated further.

A. Extended Assessment Methods Considering Interactional Games at Supply and Demand Sides

The current research has mainly focused on the generation units at the supply side or the retailers at the demand side. More in-depth evaluation techniques are needed to account for the interactions of LSEs, ancillary service, conventional generation units, etc. [134]. Previous studies [135] - [137] show that the increasing number of pro-consumers is reshaping the market trades and thus may bring new requirements for modifying market rules. The strategic decision-making by the aggregators and their market power are investigated in [138] - [140]. Accordingly, future work needs to further model and simulate the games of market participants by considering the interactions at the supply and demand sides. An illustrative figure is shown in Fig. 8. Under such circumstances, more advanced metering and information technologies provide advantages in collecting more market trade data [141], [142]. The data-driven technology (e. g., multi-agent simulation methodology) can also be adopted to investigate the strategies of various participants for market power research.

B. Modeling Algorithm of Multi-type Participants in Multi-energy System

The coupling of multiple energy networks and multi-energy market participants increases the difficulty of market power modeling and evaluation [107], [108]. The interdependent relationship within electricity and multi-energy systems affects the operational flexibility and price elasticity of the resources [143]-[145]. Optimal scheduling and market mechanisms are proposed in [146]-[148] to account for the impact of integrated energy systems on the market operation. Similarly, the coupled power, heat, and cooling flow also aggravate the market power by further adding uncertainties and complexities to the modeling. Therefore, the corresponding assessment and mitigation methods should be extended to evaluate the market power of multi-energy suppliers or consumers in an IES. The framework of the research on multi-energy participants in multiple network coupling is shown in Fig. 9. By utilizing complex network equalization and modeling technology, the multi-energy network can be unified in the power grid framework. This unified network topology can potentially make the investigation of market operation and market power assessment more convenient.

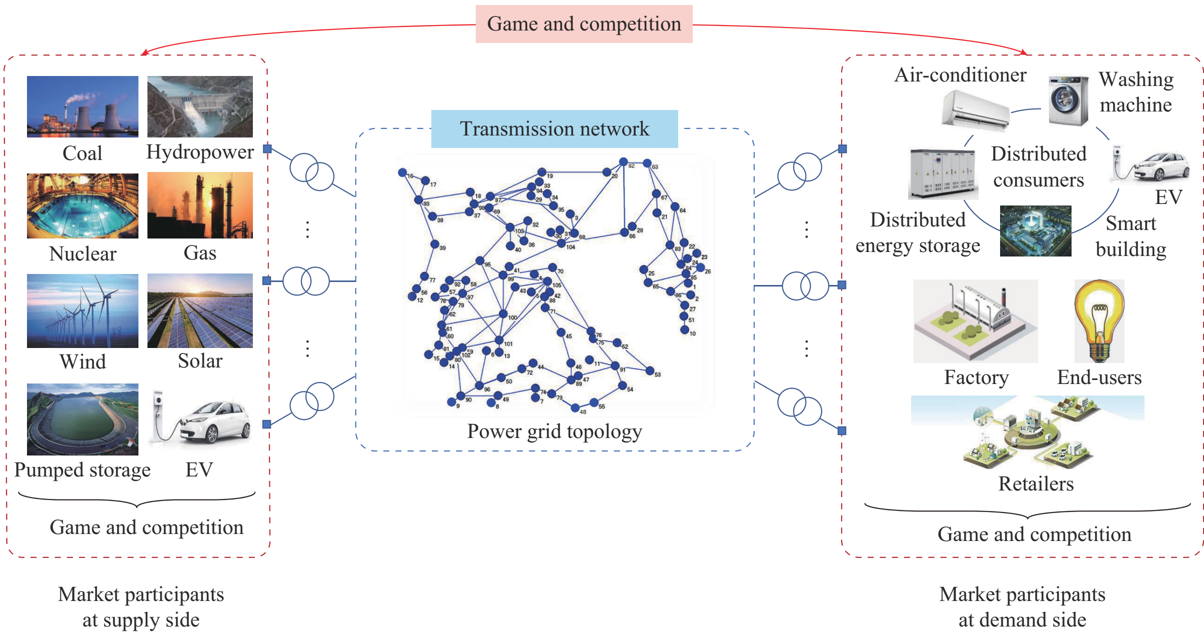

Fig. 8. Illustrative framework of games at both supply and demand sides.

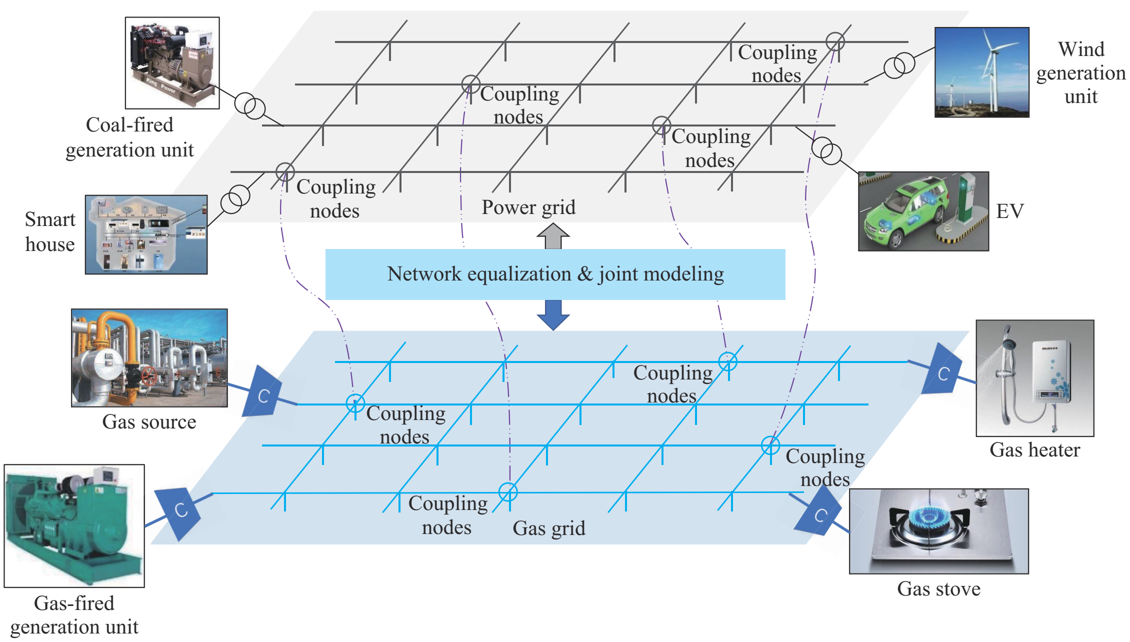

Fig. 9. Market power assessment in multi-energy system network.

C. Accurate Measures for Distinguishing Reasonable Profit and Market Power Abuse

Another critical issue is the clear definition of market power abuse and the reasonable profit of market participants. The existing procedure to identify potential market power commonly suffers from complicated judgment criteria, excessive supervision probability, or requirements for complete information [52]. Moreover, the "price spike" or high prices quoted by generation units are not necessarily the signs of market power abuse [149]. Attempts have also been made to integrate a market power mitigation clearing mechanism in the common market clearing procedure in order to avoid overregulation [52], [150]. One preliminary solution for the unclear judgement of market power is accurate cost monitoring. As shown in Fig. 10, not only the marginal costs but also the fixed costs should be considered. Moreover, the construction of the capacity market can separate the cost into different components (e. g., fuel cost, building cost, etc.), which may ease the difficulty of market power assessment among various types of generation units. Additionally, more advanced power flow tracing technology [151] may also provide an approach to identify the participants who cause the unreasonable market operation states.

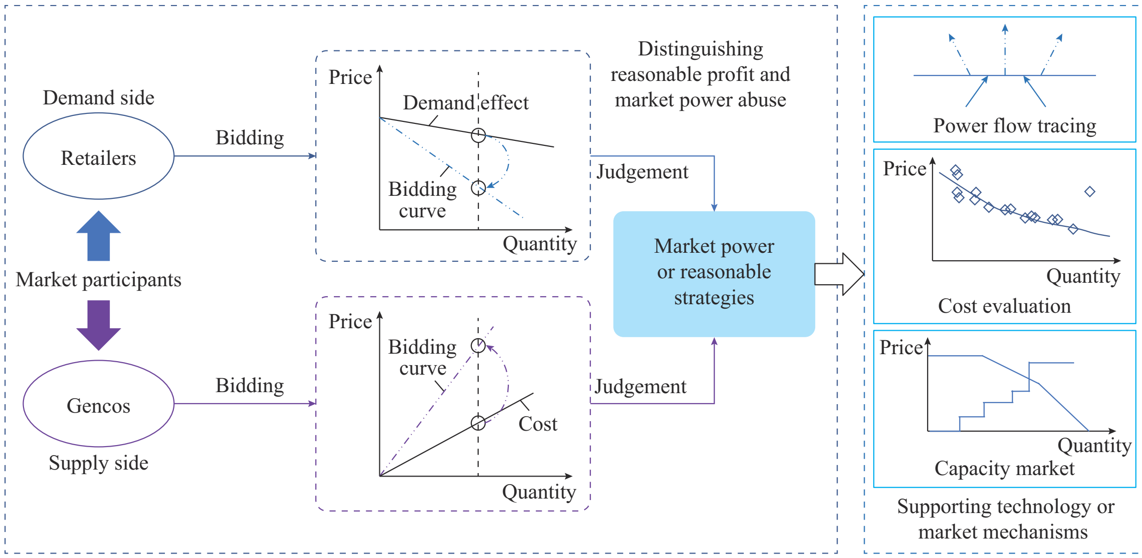

Fig. 10. Distinguishing reasonable profit and market power.

VI. Conclusion

The increasing penetration of RES and flexible DRSs brings new challenges for market power assessment and mitigation. Under such new circumstances, this paper presents an extended review of market power assessment. The structural market power indices, the market power evaluation methodologies at the supply side, the market power manifestation and assessment methods at the demand side, and the market power abuse scenario in multi-energy systems have been overviewed comprehensively.

In addition, a series of mitigation mechanisms against market power in various electricity markets have been detailed. Based on market power mitigation practices in the US, the Nordics, UK, and China, this paper classifies market power measurement including the 3JPS test, CCT, CIT, and RSI.

Furthermore, the unsolved issues to address in future research are discussed. With the targets of the energy transition and carbon neutrality, new concerns are raised about the regulation of market power for sufficient competition.

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