

## Reference Model and Quantitative Indicator System for Flexible Resource Aggregation

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### Abstract

High-penetration renewable energy generation introduces significant volatility and uncertainty to power grids. To address this challenge, substantial flexible resources must be engaged in grid dispatch and ancillary service provision. However, the large quantity, wide distribution, and heterogeneous characteristics of flexible resources present difficulties for cluster-based management, necessitating quantitative evaluation of the cluster's power regulation capability. This paper proposes a quantitative flexibility assessment indicator system based on the application requirements of flexible resource clusters in grid dispatch and electricity markets. According to the physical characteristics of flexible resources within clusters, they are categorized into generator-type and storage-type resources, which are respectively aggregated into equivalent generator and equivalent storage devices serving as aggregation reference models. The parameters of these two equivalent devices constitute the quantitative indicator system, offering intuitive physical interpretation, favorable multi-level nesting properties, and applicability across multiple time scales. The indicator system can be extensively applied in various scenarios, including asynchronous dispatch of distributed resource clusters, joint optimal dispatch of integrated energy systems, and bidding strategies for virtual power plants in electricity markets.

### Full Text

## Reference Model and Quantitative Metrics of Aggregated Flexible Energy Resources

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**Abstract**

The high penetration of renewable energy generation introduces significant volatility and uncertainty to power grids. To address this challenge, large quantities of flexible resources must be leveraged to participate in grid dispatch and provide ancillary services. The vast number, wide distribution, and diverse characteristics of these flexible resources pose difficulties for cluster-based management, necessitating a quantitative evaluation of the cluster's power adjustment range. This paper proposes a quantitative indicator system for flexibility assessment based on the application requirements of flexible resource clusters in grid dispatch and electricity markets. According to the physical characteristics of flexible resources within clusters, they are classified into generator-type and storage-type, and respectively aggregated into equivalent generator and equivalent storage devices as an aggregation reference model. The parameters of these two equivalent devices serve as the quantitative indicator system, possessing intuitive physical meaning, excellent nested characteristics, and applicability across multiple time scales. This indicator system can be widely applied in various scenarios, including asynchronous dispatch of distributed resource clusters, coordinated optimization dispatch of integrated energy systems, and bidding strategies for virtual power plants participating in electricity markets.

**Keywords:** flexible energy resources; aggregated reference model; quantitative metrics of flexibility; high-dimensional polytope projection

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With the implementation of China's "West-to-East Electricity Transmission" strategy and the proposal of carbon neutrality goals, the proportion of external power and renewable energy generation in eastern power grids has increased rapidly. Receiving-end grids face hollowing-out problems, with significantly insufficient primary frequency regulation capability and substantially increased volatility. Therefore, it is essential to fully utilize local flexible resources to participate in grid regulation, providing various types of ancillary service products to ensure safe and stable grid operation.

Flexible resources include distributed generation, distributed storage, and controllable loads, among other resources dispersed throughout distribution networks. With the advancement of smart grid construction, supporting communication and control technologies have developed rapidly, providing a solid foundation for optimizing the regulation of large-scale flexible resources. These resources are widely distributed, relatively small in scale, and capable of rapid response. They can adjust power consumption or supply power to the grid during peak demand periods, thereby reducing peak grid loads and minimizing redundant investments in grid and generation capacity. Furthermore, large-scale flexible resources can provide various ancillary services such as voltage

regulation, frequency regulation, peak shaving, and reserves.

However, due to the large number and wide distribution of flexible resources, along with their diverse characteristics, management in cluster form based on naturally defined areas within substation supply ranges is necessary. To more accurately characterize cluster flexibility, a quantitative indicator system must be constructed to evaluate the overall flexibility of clusters, thereby enabling the aggregation of flexible resources [?, ?].

Existing research has defined characteristic indicators for flexible resources and investigated cluster aggregation evaluation methods. Reference [?] explains the concept of “flexibility” and proposes a classification method for flexibility resource characteristics, categorizing them into quantitative, qualitative, controllability, and cost indicators. References [?, ?] characterize cluster flexibility using a generalized virtual energy storage device formulation. References [?, ?] propose flexibility aggregation methods for thermostatically controlled loads to leverage their energy storage characteristics. Some studies employ the probabilistic nature of flexibility supply and demand as evaluation metrics to assess system response capability. References [?] and [?] define flexibility indicators as the expected value and probability of ramping capability deficiency, respectively. Reference [?] expresses flexibility as the probability of adequate flexibility supply relative to demand within specific time periods. Additionally, some research adopts geometric methods to describe resource flexibility. Reference [?] introduces the concept of flexibility envelopes to represent power system operational planning across different time scales. Reference [?] presents the concept of dispatchable regions, using polytopes to represent the flexibility range of wind power equipment. Reference [?] constructs zonotope polytope-based flexibility aggregation results. Reference [?] aggregates numerous heat pumps into virtual energy storage or virtual synchronous machine forms based on the Minkowski Sum operator. Reference [?] first establishes a unified flexibility resource model, standardizes the geometric shapes of flexibility regions for various models, and then performs aggregation using the Minkowski Sum operator. Reference [?] proposes a vertex search method for calculating aggregated flexibility spaces in polytope form. Reference [?] aggregates flexible resource clusters into a special generator form. To account for the stochastic nature of flexible resources, reference [?] calculates the probabilistic adjustable range of virtual power plants using chance-constrained methods. Reference [?] performs scheduling decisions for regional power grids and energy capacity.

Among these, power capacity reflects the upper and lower limits of adjustable power for flexible resources. Ramp rate reflects the adjustment speed of flexible resources. In the U.S. PJM ancillary services market, the performance of reserve ancillary services is measured by the reserve response level within a specified time period [?]. Energy is the integral of power over time, and energy capacity reflects the adjustment capability of net output/input energy for flexible resources within a certain time period. For storage-type devices, their energy storage capacity has certain limitations; for generator-type devices, there are no

constraints on energy capacity.

- 2) **Frequency regulation.** In the document “Two Detailed Rules for Grid-Connected Power Plants in North China Region (2019 Revision)” issued by the North China Energy Regulatory Bureau of the National Energy Administration [?], three indicators are used to evaluate the primary frequency regulation performance of generating units: 15-second and 30-second output response indices and energy contribution index. The U.S. PJM ancillary services market measures the performance of frequency regulation ancillary services using three indicators: frequency regulation response delay, frequency regulation curve correlation, and frequency regulation accuracy [?]. In the performance indicators of the aforementioned ancillary services markets, requirements are imposed on participants’ response time and ramping capability to ensure the response speed of frequency regulation and reserves and the tracking accuracy of command signals. Additionally, the droop coefficient, inertia, and response time of flexible resources are important dynamic indicators for measuring primary frequency regulation performance.
- 3) **Voltage regulation.** The dynamic voltage regulation performance of flexible resources can be measured through reactive power adjustable capacity, droop coefficient, and response time.
- 4) **Regulation cost.** Depending on the type of flexible resource, regulation costs can be categorized into adjustment costs, fuel costs, curtailment costs, and maintenance costs. Adjustment costs primarily exist in resource types such as controllable loads and energy storage devices. Fuel costs mainly refer to fuel expenses consumed by small-capacity generators during power generation. Curtailment costs represent losses caused by new energy devices such as photovoltaics and wind turbines not operating at full capacity. Maintenance costs include equipment maintenance and repair expenses for flexible resources and replacement costs for energy storage battery modules.

Some flexible resources are affected by weather and social systems, resulting in stochastic flexibility parameters that can be addressed using interval theory or probability distribution functions. References [?, ?] propose a relative distance measure interval theory to achieve interval network optimization under uncertainty conditions. Additionally, reference [?] employs a Gaussian mixture model to fit the joint probability distribution function of random variables and uses chance-constrained methods to transform constraints containing random variables into deterministic constraints under a certain confidence level, thereby achieving flexibility evaluation at a given confidence level.

Existing research often adopts different flexibility indicators for various application requirements, lacking a systematic modeling approach that can consider the adjustable range of large-scale flexible resources and a universal quantitative indicator system. Therefore, a set of aggregation reference models with more

explicit physical meaning is needed to form a more intuitive indicator system applicable to multiple application scenarios.

This paper organizes the quantitative flexibility indicator system from the perspective of flexible resource clusters participating in dispatch and ancillary service markets, categorizing them into three types: generator-like characteristics, storage-like characteristics, and common characteristics. Subsequently, it constructs a flexible resource aggregation reference model composed of equivalent generators and equivalent storage devices, and provides solution methods for multi-type flexible resource aggregation and the indicator system. The proposed aggregation reference model possesses intuitive physical meaning and robust nested characteristics, applicable across multiple time scales, providing a foundation for grid regulation and ancillary service applications. The calculation method for the indicator system ensures the feasibility of disaggregation and obtains the largest possible power adjustment range for flexible resources, enabling accurate evaluation and full utilization of aggregated flexibility across multiple resource types.

The remainder of this paper is organized as follows: Section 1 introduces the quantitative indicator system for flexibility assessment; Section 2 presents the mathematical model for flexible resource aggregation. Based on the physical characteristics of flexible resources, this model constructs an aggregation reference model primarily composed of equivalent generators and equivalent storage devices, and provides a method for solving the indicator system parameters; Section 3 introduces the application of the flexible resource aggregation model in three aspects: asynchronous dispatch of distributed resource clusters, coordinated optimization dispatch of integrated energy systems, and bidding in electricity markets as virtual power plants; Finally, Section 4 concludes the paper.

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## 1 Quantitative Indicator System for Flexibility Assessment

Quantifying the overall characteristics of flexible resource clusters is a crucial prerequisite for evaluating their adjustable capability. In typical ancillary service markets both domestically and internationally [?, ?], performance indicators have been established for market entities providing ancillary services. Therefore, to construct an appropriate quantitative characteristic indicator system, suitable indicators must be selected based on performance requirements in different flexibility application scenarios.

- 1) **Peak shaving and reserves.** When flexible resources participate in grid peak shaving or reserve ancillary services, the dispatch center needs to confirm the power adjustment range of participating devices based on their power capacity and ramp rate.

Network constraints describe the constraints among various flexible resource

devices at a single time snapshot, exhibiting spatial coupling characteristics. Device constraints describe the constraints for a single device across different time points, exhibiting temporal coupling characteristics. The spatial coupling conditions and temporal coupling conditions among decision variables are intertwined.

To enable distributed resources to qualify for participation in grid dispatch and electricity markets, small-capacity flexible resources need to be aggregated into clusters. As shown in Figure 1, based on the application requirements of flexible resource clusters in grid dispatch and ancillary service markets, performance indicators across various scenarios can be categorized into three types: generator-like characteristics, storage-like characteristics, and common characteristics. The dynamic characteristic equivalent aggregation methods for flexible resources are introduced in references [?] and [?]. The following sections will primarily focus on the steady-state power adjustment range to explain how clusters can be equivalently aggregated into a reference model composed of equivalent generators and equivalent storage devices based on resource characteristics.

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## 2 Construction of Flexible Resource Aggregation Reference Model and Calculation of Quantitative Indicators

### 2.1 Mathematical Model for Flexible Resource Aggregation

Flexible resource aggregation refers to mapping the power adjustment range of each device at each time moment within a cluster to the point of interconnection with the upstream grid, considering both network constraints and device constraints of the resource cluster. This allows the power adjustment range at the interconnection point at each time moment to represent the power adjustment capability of all flexible resource devices in the cluster.

In the flexible resource aggregation problem, the decision variable represents a vector composed of the active and reactive power of each flexible resource device in the cluster at each time moment. In terms of constraints, the aggregation problem must consider network constraints and individual device constraints for each flexible resource, such as power and ramping constraints for generators, power and energy constraints for storage devices, and temperature comfort constraints for HVAC equipment. Network constraints describe the constraints among various flexible resource devices at a single time snapshot, exhibiting spatial coupling characteristics. Device constraints describe the constraints for a single device across different time points, exhibiting temporal coupling characteristics. The spatial coupling conditions and temporal coupling conditions among decision variables are intertwined.

From a mathematical perspective, the process of calculating can be viewed as a dimensionality reduction projection from a high-dimensional space to a slightly lower-dimensional space to obtain . Through projection operations, the dimen-

sions where decision variables reside are eliminated, while the dimensions where active power at the interconnection point resides are preserved. The parameters in the high-dimensional polytope are calculated based on projection operations. However, from a pure mathematical standpoint, calculating the parameters of the projected polytope from a high-dimensional polytope to a lower-dimensional space is an NP-hard problem. In this problem, the dimensionality may reach thousands, making it almost impossible to obtain exact solutions for the parameters in the projected polytope. Therefore, in practical applications, appropriate parameters must be selected based on physical meaning to construct a polytope for approximating the true projected polytope.

To ensure the feasibility of disaggregating flexible resource clusters, the approximate polytope should be contained within the original polytope. This is because, for an active power dispatch instruction at the interconnection point, only when can a corresponding solution for decision variables be found in to achieve disaggregation of the dispatch instruction. Additionally, to minimize approximation error, the volume of should be as large as possible. Therefore, in the ideal case, is inscribed in.

## 2.2 Physical Meaning of Flexible Resource Aggregation

Since flexible resource aggregation combines the power adjustment range characteristics of multiple devices into a single entity's adjustment characteristics, the aggregated result for multiple flexible resources with ramping constraints still exhibits ramping-constrained properties. Similarly, for multiple flexible resources with energy constraints, the aggregated result still exhibits energy-constrained properties. Therefore, based on these characteristics of flexible resources, the wide variety of flexible resources can be classified and aggregated according to their nature. For flexible resource devices with limited output power adjustment rates, they can be classified as generator-type, with characteristics manifested as upper and lower bound constraints on the time derivative of power. For flexible resource devices with limited input/output energy, they can be classified as storage-type, with characteristics manifested as upper and lower bound constraints on the time integral of power. Common classifications of flexible resource devices are shown in the following table:

**Table 1 Classification of Flexible Energy Resources** - Micro generators  
- Wind turbines - Curtailable loads - Non-adjustable loads - Transferable loads

For flexible resource devices that have no ramping constraints but only power constraints, they can also be classified as generator-type. Simply treat their ramping constraint parameters as a very large value.

Based on physical meaning, when calculating the flexible resource aggregation model, the flexible resources in the cluster can first be classified and separately aggregated into two devices: an equivalent generator and equivalent storage. The power adjustment ranges of the two devices are respectively expressed as follows:

where represents the set of all time points; the power adjustment range of the equivalent generator device is represented by the power upper and lower bounds and at each time moment, and the ramping constraint upper and lower bounds and at each time moment; the power adjustment range of the equivalent storage device is represented by the power upper and lower bounds and at each time moment, and the energy constraint upper and lower bounds and at each time moment.

After integrating the equivalent generator and equivalent storage, the aggregation model for the flexible resource cluster is finally expressed as follows: Devices in the flexible resource cluster can be divided into generator-type and storage-type devices, and respectively aggregated into equivalent generator and equivalent storage. However, due to the coupling between the two types of devices through network constraints, when the state of one type of device changes, the adjustable range of the other type changes, affecting the calculation results of the two equivalent models. Therefore, robust optimization methods are needed to decouple the network coupling constraints between the two device types. Subsequently, the parameters of the two equivalent devices—equivalent generator and equivalent storage—can be calculated separately. The following section introduces the parameter calculation process using the equivalent generator device as an example.

### 2.3 Calculation of Quantitative Indicators for Flexible Resource Aggregation

Figure 3 Schematic of High-Dimensional Polytope Projection [Figure 3: see original paper]

Figure 4 Schematic of Aggregated Flexible Energy Resources into Equivalent Generator and Equivalent Storage [Figure 4: see original paper]

To ensure the feasibility of disaggregating flexible resource clusters, the approximate polytope should be contained within the original polytope . This is because, for an active power dispatch instruction at the interconnection point, only when can a corresponding solution for decision variables be found in to achieve disaggregation of the dispatch instruction. Additionally, to minimize approximation error, the volume of should be as large as possible. Therefore, in the ideal case, is inscribed in .

Based on the mathematical meaning of flexible resource aggregation, the process of aggregating generator devices in a flexible resource cluster into an equivalent generator can be viewed as projecting the power adjustment range of all generator-type devices onto the active power adjustment range of the equivalent generator device at the interconnection point. Since the exact result of cannot be calculated, approximation is necessary. To ensure the feasibility of disaggregating flexible resource clusters, the parameters of its inscribed polytope need to be calculated. Existing calculation methods mainly include Fourier elimination [35], vertex search [36], inscribed high-dimensional cubes [37], and inscribed

high-dimensional ellipsoids [23]. This paper briefly introduces the calculation principle of the high-dimensional polytope projection and boundary contraction algorithm [38], with its main procedure as follows:

First, based on physical meaning, the aggregation result of generator-type devices still possesses generator characteristics. Accordingly, the mathematical form of the equivalent generator shown in Equation (5) can be specified, which is equivalent to providing a shape template for the inscribed polytope. The schematic of the calculation process is shown in Figure 5 [Figure 5: see original paper]. Since the parameters of the circumscribed polytope of the projected polytope can be conveniently obtained by directly solving optimization problems to find corresponding extreme points, the circumscribed polytope of the projected polytope can first be calculated, denoted as  $P$ .

Subsequently, based on the high-dimensional polytope projection and boundary contraction algorithm, each face is contracted inward while maintaining the slope of each face of the circumscribed polytope unchanged, until all vertices are completely contracted to the interior or boundary of the projected polytope  $P$ , becoming the inscribed polytope of  $P$ , denoted as  $P_{in}$ . This contraction process corresponds to changes in the four parameter groups  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$  of the equivalent generator device. After contraction is completed, the parameters corresponding to  $P_{in}$  are the parameters of the equivalent generator device.

Similar to the above process, the storage template shown in Equation (6) can be selected, and the high-dimensional polytope projection and boundary contraction algorithm can be used to calculate the four parameter groups  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$  of the equivalent storage device. Related technical details can be found in reference [38].

Additionally, it is worth noting that in integrated energy systems, gas networks and heat networks possess excellent energy storage endowments. From the perspective of the power grid, both gas networks and heat networks can be regarded as equivalent storage devices, thereby through gas-to-power conversion devices (e.g., gas turbines, power-to-gas devices) or heat-to-power conversion devices (e.g., electric boilers, combined heat and power units) providing peak shaving flexibility for the power grid. The equivalent storage parameter indicators for gas networks and heat networks can also be calculated using similar methods.

The proposed aggregation reference model and indicator system possess the following advantages:

- 1) **Intuitive physical meaning.** The equivalent generator device can represent equipment with certain response rate constraints but without requirements for long-term response persistence. Equivalent storage can represent equipment without response rate constraints but with constraints on cumulative response energy. This provides a highly intuitive indicator system parameter for large numbers of flexible resource clusters with diverse characteristics, offering effective reference for different ancillary service requirements needed by the upstream grid.

- 2) **Excellent nested characteristics.** The equivalent generator and equivalent storage devices obtained based on the above aggregation reference model can still participate in higher-level grid aggregation using the same method. This enables bottom-up hierarchical aggregation of the grid, thereby simplifying dispatch at higher grid levels.
  - 3) **Applicability across multiple time scales.** The time granularity in the aggregation reference model can be selected autonomously based on dispatch requirements. Therefore, whether for minute-level dispatch or second-level control, it can be applied as an indicator of the adjustable range. This enables the aggregation reference model to adapt to regulation demands across various time scales.
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## 3 Applications

### 3.1 Asynchronous Dispatch of Distributed Resource Clusters

Using the flexible resource aggregation reference model, asynchronous dispatch of massive distributed resources can be achieved through a hierarchical architecture. Traditional dispatch architectures for flexible resources typically include centralized or distributed approaches. In a centralized dispatch architecture, the power of all devices at all time moments must be treated as control variables, with unified optimization dispatch performed by the control center. This leads to excessively large optimization problem scales and long solution times, making it difficult to achieve unified dispatch of massive distributed flexible resources. Additionally, existing distributed computing methods decompose the optimization dispatch problem into a master problem and multiple sub-problems, exchanging boundary variables among optimization problems through repeated synchronous iterations until convergence to the optimal value. However, distributed methods suffer from slow convergence and may not converge at all. Moreover, the algorithm iteration process requires all problems to proceed synchronously, resulting in low tolerance for communication failures, which poses significant difficulties for practical application of distributed methods.

Based on the aggregation model of distributed resource clusters, asynchronous dispatch of distributed resource clusters can be implemented. First, massive distributed resources are organized into clusters according to their geographic relationships. Each cluster's aggregator calculates its cluster's aggregation model and uploads it to the upstream grid's control center. Since calculating a cluster's own aggregation model does not require interaction with devices in other clusters, the control center has no synchronization requirements for clusters uploading their aggregation models, and this process can be completed asynchronously. Subsequently, after the upstream grid has collected all clusters' aggregation models, it performs optimization dispatch based on these models and issues dispatch commands to each cluster. Finally, upon receiving dispatch commands from the upstream grid, cluster aggregators disaggregate the dispatch

instructions by solving intra-cluster optimization dispatch problems to decompose the dispatch instructions to individual distributed resources, forming the dispatch schedule for each distributed resource.

Figure 6 Schematic of Asynchronous Dispatch of Distributed Resources Based on Equivalent Model [Figure 6: see original paper]

This hierarchical dispatch mode effectively solves the problem of excessive computational complexity caused by the large number of distributed resource devices. Additionally, it provides a certain degree of privacy protection for detailed data information of individual flexible resource devices within clusters.

### 3.2 Coordinated Optimization Dispatch of Integrated Energy Systems

In integrated energy systems, gas networks and power grids achieve mutual conversion between natural gas and electrical energy through gas turbines and power-to-gas devices. From the perspective of the power grid, the conversion process between gas and electricity can be analogized to the discharging and charging processes of energy storage devices, respectively [39]. Similarly, heat networks and power grids achieve conversion from electrical energy to thermal energy and coupling between heat and power sources through devices such as electric boilers and combined heat and power units. Due to the thermal inertia present in heat loads, heat networks can also serve as energy storage from the power grid's perspective.

Based on the energy storage characteristics of gas networks and heat networks, they can be projected into the active power flexibility space and regarded as equivalent storage devices in the power system. The indicator parameters of equivalent storage can be calculated using the same principle based on the aforementioned high-dimensional polytope projection and boundary contraction algorithm. Taking the gas network as an example, the schematic of converting a gas network into an equivalent storage device is shown in Figure 7 [Figure 7: see original paper]. The state equations of the gas network can be approximated as linear [40]. The gas source pressure, compressor boost, gas flow rates of gas turbines and power-to-gas devices in the gas network can be regarded as decision variables in the gas network. The technical constraints of each device and the pressure constraints at each gas network node constitute the complete technical constraints of the gas network, which can be formulated in linear form as shown in Equation (1). The net power output from the gas network to the power grid can be regarded as the net output power of the gas network's equivalent storage and expressed through linear transformation as Equation (2).

Power conversion devices (e.g., gas turbines, power-to-gas devices) or heat-to-power conversion devices (e.g., electric boilers, combined heat and power units) provide peak shaving flexibility for the power grid. The equivalent storage parameter indicators for gas networks and heat networks can also be calculated using similar methods.

Figure 7 Schematic of Converting Gas Network into Equivalent Energy Storage Device [Figure 7: see original paper]

It is worth noting that since gas networks/heat networks and power grids are interconnected through multiple energy converter devices, in addition to calculating the energy parameters of equivalent storage devices, the coupling constraints among various energy converters must also be calculated. These coupling constraints are implicitly determined by the network constraints of the gas network, forming a complex high-dimensional spatial constraint condition. To obtain an explicit constraint expression, an inscribed high-dimensional single-quadrant ellipsoid model can be used to simplify the coupling constraint relationships among converter devices [41]. For example, the constraint relationships among three energy converters in Figure 7 can be represented as the adjustable range shown in Figure 8 [Figure 8: see original paper]. The calculation method for ellipsoid parameters can be found in reference [41].

Figure 8 Schematic of Coupling Relationship Among Energy Converters Described by Inscribed High-Dimensional Single-Quadrant Ellipsoids [Figure 8: see original paper]

### 3.3 Reference for Virtual Power Plant Participation in Electricity Market Bidding

With the rapid development of renewable energy and the advancement of power market reforms, virtual power plants will play an increasingly important role in the future. Virtual power plants integrate various dispersed distributed energy resources and utilize advanced digital technologies and intelligent control systems to achieve flexible dispatch and management of power systems, responding to energy and ancillary service demands in electricity markets.

The flexible resource aggregation reference model and indicator system provided in this paper can assist virtual power plant operators in evaluating the power adjustment range of distributed flexible resources under their management. Virtual power plant operators can combine electricity market price forecasts with the regulation costs of internal flexible resources to formulate bidding strategies for participating in energy markets and ancillary service markets, enabling virtual power plants to achieve optimal market participation.

This paper constructs a flexibility quantification indicator system adapted to multiple ancillary service requirements, establishes a flexible resource aggregation reference model composed of equivalent generators and equivalent storage devices, and presents a parameter solution method based on the high-dimensional polytope projection and boundary contraction algorithm, using the power and ramping capability of equivalent generator devices and the power and storage capacity of equivalent storage devices as quantitative indicators. The described aggregation reference model and indicator system possess intuitive physical meaning and robust nested characteristics, and are applicable across multiple time scales. The aggregation reference model can play a role in var-

ious aspects, including asynchronous dispatch of distributed resource clusters, coordinated optimization dispatch of integrated energy systems, and bidding in energy and ancillary service markets for virtual power plants, thus demonstrating promising prospects for widespread application.

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