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Full-length article

Evaluation index system of shared energy storage market towards renewable energy accommodation scenario: A China's Qinghai province context

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Abstract: With the ever-increased installed capacity of renewable energy generation units in a power system, the so-called shared energy storage (SES), a novel business model under the umbrella of the shared economy principle, has the potential to play an essential role in the accommodation of renewable energy generation. However, unified evaluation standards and methods, which can help decision-makers analyze the performance of the SES market, are still not available. In this paper, an evaluation index system of the SES market is designed based on the trading rules of China's Qinghai province and the structure-conduct-performance (SCP) analytical model. Moreover, the definition and characteristics of the indices, which can show the performance of the SES market from different perspectives, are given. Furthermore, the ideal cases are presented as the evaluation benchmark based on the development expectation of the SES market, and the analytic hierarchy process (AHP) and the technique for order preference by similarity to an ideal solution (TOPSIS) are applied to evaluate the SES market comprehensively. Finally, a case study based on actual data of the SES trading pilot project in Qinghai shows that the evaluation index system can reflect the operation status, existing problems and influencing factors of the SES market.

Keywords: Shared energy storage (SES), Renewable energy accommodation scenario, Evaluation index system, Ancillary service market.

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0 Introduction

With the solemn promise of "China aims to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060", renewable energy sources (RESs) will be the core development direction of the energy sector in the future undoubtedly [1]. In recent years, due to the ever-maturing technology and decreasing cost, the installed capacity of the renewable energy generation units, represented by wind power generation and photovoltaic (PV) power generation, is increasing yearly in China [2]. By the end of 2020, the grid-connected installed capacity has been up to 930 million kW, where wind power generation and PV power generation account for 59.1%. Currently, the main problem faced by the development of RESs in China has changed from striving for the large-scale and high-speed installed capacity to balancing the contradiction between renewable energy accommodation and construction speed. The national PV curtailment ratio, for instance, was 2% in the first three quarters of 2021. However, the PV curtailment ratio of northwest China, where the RESs have been developed rapidly in recent years, was still at a high level. For example, the PV curtailment ratio of Qinghai province in China was up to 14.4% due to the significantly increased installed capacity and the maintenance of the long-distance transmission lines. Consequently, the existing methods for accommodating renewable energy, including the power export and the peak regulation of conventional units, may encounter bottlenecks with the further improvement of RESs in the future. The flexibility capacity will be gradually exhausted, and the accommodation space is challenging to expand by the methods [3]. In view of this, it is imperative to develop new technologies and new schemes for renewable energy accommodation [4], [5].

As an emerging power technology, the energy storage system (ESS) can decouple power generation and consumption in time and space, and alleviate the contradiction between renewable energy generation and accommodation [6], [7]. In recent years, many ESSs have been deployed in power systems because of the decreased cost. However, there is a lack of commercial modes of ESSs. For example, the reasonable payment mechanisms are obscure, compared with the enthusiasm for constructing ESS projects, causing massive energy storage resources to be idle [8]. In this context, shared energy storage (SES), combined energy storage technology with shared economy principle, has the potential to become a breakthrough to realize the commercialization of ESSs [9-11]. At present, there are research works on the SES involving many fields, such as the energy management of microgrid [12-14], the optimal sizing and real-time control for the community energy storage [15-19], the fluctuation mitigation of RESs [20], [21] and the peak regulation of power systems with a high proportion of RESs [22]. The practicability and effectiveness of SES have been verified by these research works.

From the aforementioned analysis, it can be found that most studies about SES mainly focus on the control strategy, transaction model, dispatching method and so on, because the current SES is still in preliminary research and pilot stage. Considering that SES is a market-oriented business model of energy storage, the development and operation of the market are the core factors of its further promotion. Therefore, the decision-makers and managers have an urgent requirement for a set of evaluation index systems that can reflect the operation state of the SES market to help them understand and evaluate the operation performance, existing problems, and change trends of the market. With the utilization of the evaluation index system, it is expected that more effective market supervision could be achieved.

In the context of renewable energy accommodation, the SES market can be considered as a part of electricity markets, where energy storage resources will be seen as a trade product. There are some research works on the evaluation index system of electricity markets around the globe [23-25]. In [23], the market monitoring activities of four independent system operators in the United States are reviewed, and some performance metrics and indices, such as grid statistics, market states, competition and market power, are summarized. Similarly, a novel method for the comprehensive evaluation of electricity markets based on fuzzy set theory and analytic hierarchy process (AHP) is presented in [26], which is a step forward concerning the previous approaches in China. In addition, some research focuses on market power which is seen as a critical factor in market supervision. In [27], a fuzzy estimator is proposed to measure every power supplier's market power. Moreover, a pre-assessment framework for market power is proposed in [28] for the electricity markets with the RESs. It is worth mentioning that an evaluation index system of SES under targets of carbon emission peak and carbon neutrality is designed in [29]. However, the impact of the specific trading rules of a SES market on the evaluation index system has not been considered.

In this paper, the trading rules of the SES market in Qinghai, China, are analyzed and summarized, and an evaluation index system of the SES market is designed under the renewable energy accommodation scenario. The evaluation index system aims to effectively evaluate the performance of the SES market and provide a reference for decision-makers. More evaluation indices, corresponding to the characteristics of the SES market in Qinghai, are added to the proposed evaluation index system compared with the market part of the one in [29]. To sum up, the main contributions of this paper are presented as follows.

Firstly, the exploration and practice of the SES in Qinghai, China, are introduced. To the best of our knowledge, the SES trading pilot project in Qinghai is the first SES project towards centralized renewable energy power plants worldwide. Based on the trading rules of the SES market, the transaction methods, the price mechanism and the market dispatching mechanism are analyzed, which have a significant influence on the selection of the index.

Secondly, an evaluation index system of the SES market and its comprehensive evaluation method are built to show the performance of the SES trading pilot project in the current stage. Based on the actual data from the pilot project, the performance of the SES market is analyzed by the above methods, and the existing problems are summarized. Besides, the two key influencing factors are evaluated, which proves that adjusting the peak-regulation price and increasing energy storage facilities are two practical approaches to improve the SES market in the current stage.

1 Exploration and practice of the SES towards renewable energy accommodation scenario

1.1 SES and renewable energy accommodation

SES is a novel business model combined with energy storage technology and the shared economy principle. The core idea lies in the separation of the ownership and the use right of the energy storage resources, i.e., the owners of energy storage resources can lease the use rights with respect to the idle energy storage resources out to the demanders who are eager for the service provided by energy storage resources, including power plants, industrial and commercial users and home users. In the shared process, the utilization rate of energy storage resources can be improved so that the owners obtain additional benefits and the cost recovery period will be shortened. On the other hand, the demanders who purchase the use rights can enjoy the corresponding energy storage service such as abandoned electricity accommodation and peak load shifting, improving industrial production and daily life and obtaining excess profits [30], [31].

Currently, renewable energy accommodation is one of the application scenarios with the most development potential and implementation conditions of the SES business model. On the one hand, there is still a large gap in peak-regulation resources as the pressure of renewable energy accommodation is increasing yearly. Therefore, the SES assisting to accommodate renewable energy has a reasonable prospect due to the prosperous demand, especially after setting the carbon emission target. On the other hand, the deployment and configuration of ESS projects are accelerating significantly with the rapid decrease of electrochemical energy storage costs. Taking the "RESs added with ESSs" mode as an example, there have been 20 provinces in China, such as Qinghai, Jiangsu, Hebei and Fujian provinces, issuing documents to encourage or compel the new RES projects to deploy a certain proportion of ESSs by November 2021. Based on this, a large number of ESS projects will provide sufficient energy storage resources for the renewable energy accommodation scenario.

A typical framework of SES towards the renewable energy accommodation scenario is shown in Fig. 1. It can be seen that the energy storage facility and renewable energy power plants reach an agreement through negotiation or bidding in the SES market. When the power system cannot accommodate all the electricity generated by the renewable energy power plants, the energy storage facility will store the abandoned electricity according to the agreement, and release the stored electricity during peak loads or low power generation. In the circulating process, the space-time translation of the abandoned electricity is realized, and renewable energy is accommodated. It is worth mentioning that the abandoned electricity from different renewable energy power plants may be stored in an energy storage facility simultaneously.

From the perspective of energy, the storage space of the energy storage facility is shared with multiple renewable energy power plants. It is the main difference between the energy storage facility in the SES business model and a single entity-owned energy storage facility that only the electricity of the owner can be stored. Besides, the energy storage facilities in the SES market can be independent energy storage power stations or energy storage systems owned by renewable energy power plants and thermal power plants. Theoretically, the technology type and capacity of the SES facilities are unlimited based on the shared economy principle. However, long-term energy storage technologies, such as battery energy storage, pumped hydroelectric storage, compressed air energy storage, are more suitable to be applied in the renewable energy accommodation scenario because of the larger electricity storage space. For example, the SES facilities

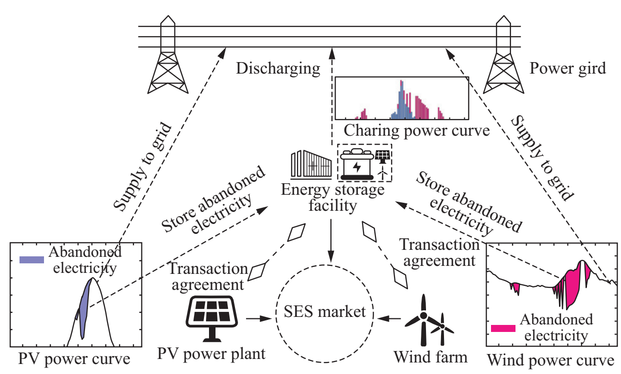


Fig. 1 A typical framework of SES towards renewable energy accommodation scenario

with at least 10 MW power capacity and 20 MWh energy capacity are approved to access the ancillary service market in Qinghai to accommodate renewable energy.

1.2 Development and practice of the SES in Qinghai

Qinghai, one of the regions with the most abundant renewable energy in China, has long been at the forefront of the development speed and scale of RESs over all provinces. Fig. 2 shows the renewable energy installed capacity in Qinghai from 2015 to 2021, and the planned installed capacity in 2025 and 2030. By the end of 2021, the total installed electricity generating capacity of Qinghai was 42.86 million kW, of which 38.93 million kW is renewable energy installed capacity, accounting for 90.83% and ranking first in provincial power systems. It is worth noting that the non-hydro renewable energy install capacity is up to 29.19 million kW, accounting for 68.11% of the total installed capacity. This proportion will rise to 74.95% and 82.9% in 2025 and 2030, further increasing the uncertainty of power generation. Meanwhile, there are some characteristics in the Qinghai's power system, including the slow increase of the local loads and transmission congestion, resulting in frequent wind and solar power curtailment. Consequently, Qinghai faces a severe situation of renewable energy accommodation due to the shortage of peak-regulation resources.

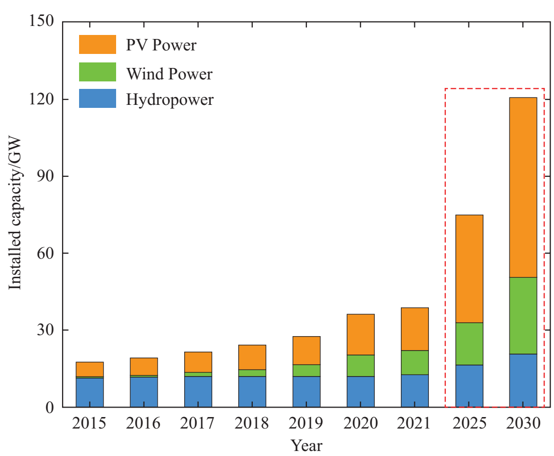


Fig. 2 Renewable energy installed capacity in Qinghai

In order to solve the problem as mentioned above, Qinghai launched the first SES trading pilot project in 2019. Moreover, the peak-regulation ancillary market was launched subsequently, which can mobilize the initiative of market entities and improve the allocative efficiency of ancillary service resources. By October 2021, the cumulative charging electricity of the ESSs in the SES market has reached 85.53 million kW·h.

1.3 Analysis of the trading rules of the SES market in Qinghai

In effect, SES can be regarded as a market-driven energy storage business model. If there is no corresponding market to trade the use rights, it is unlikely that the energy storage resources are shared between suppliers and demanders. In order to construct the SES market, Qinghai issued *The Operation Rules of Ancillary Service Market in Qinghai (Trial)*, bringing the SES transaction into the ancillary service market. The operation rules define the access condition, transaction mode, clearing and settlement method, and price mechanism of ESSs.

It is noteworthy that the ancillary service market of Qinghai only includes the peak-regulation service at present. The participation modes of ESSs in the ancillary service market can be divided into marketized transaction mode and paid ancillary service mode. Although all the energy storage resources in the two participation modes are designed to provide the peak-regulation service and promote the accommodation of renewable energy, there are several differences in the design idea, transaction method, price mechanism and income source as shown in Table 1. It can be seen that the peak-regulation units, interruptible loads, and energy storage facilities are the peak-regulation resources in the paid ancillary service mode. These resources are dispatched on demand by the power dispatching agency according to the state of the power system and are compensated for some expenses that shall be apportioned by the renewable energy power plants based on the increased on-grid electricity. Different from the paid ancillary service mode, the target of the marketized transaction mode is to achieve accurate peer-to-peer matches between suppliers and demanders, i.e., matching the renewable energy power plants with the electricity to be abandoned and the energy storage facilities with the idle capacity through the bilateral negotiation and centralized bidding. Renewable energy power plants purchase the use rights of the idle energy storage resources and store the electricity to be abandoned during the wind or solar power curtailment period. This part of stored electricity will be released to the power system according to the instructions from the power dispatching agency during peak loads or low power generation. In the process, energy storage facilities will obtain income from transferring the use rights.

On the other hand, the organization and bidding methods of the ancillary service market are also defined in the trading rules. As for the centralized bidding transaction method, suppliers and demanders need to declare the capacity and

Table 1 Participation mode of energy storage in peak-regulation ancillary service market of Qinghai

Characteristics	Marketized transaction mode	Paid ancillary service mode
Design idea	Renewable energy power plants purchase use rights of energy storage facilities and then store the electricity to be abandoned when the power curtailment occurs	Energy storage facilities, as the peak-regulation resources, are dispatched on demand by the power dispatching agency and are compensated for some expenses which should be apportioned by the renewable energy power plants based on the increased on-grid electricity
Transaction method	Bilateral negotiation and centralized bidding	Dispatching on demand by the power dispatching agencies
Price mechanism	Bilateral negotiation: the price negotiated by a supplier and a demander Centralized bidding: the average declared price of the matched supplier and demander	Fixed price set by the power dispatching agencies
Income source	Fees of use rights paid by renewable energy power plants	Compensated fees apportioned by the beneficial renewable energy power plants

price of energy storage resources the day ahead. According to the real-time electricity curtailment, the traded electricity between suppliers and demanders will be cleared by a one-minute cycle within a day. The supplier's energy storage facility with the lowest declared price will be dispatched preferentially to store the abandoned electricity from the renewable energy plant with the highest declared price. If the supplier (demander) has the remaining energy storage capacity (abandoned electricity), the demander (supplier) has the second-highest (-lowest) declared price will be matched. Based on the method, the users are matched sequentially until the declared price of the reminding demanders is less than the minimum one of the reminding suppliers, or the resources of one side are exhausted. The transaction price is the average of the declared prices of the supplier and the demander. Besides, the actual charge-discharge data in the real-time clearing stage will be the proof of settlement. As for the bilateral negotiation transaction method, the transaction price is determined by the offline negotiation between the supplier and the demander, which is usually a long-term agreement. The suppliers and demanders with a long-term agreement will be matched mutually with the highest priority.

In summary, in a settlement period, the total income of the energy storage facility i in the ancillary service market of Qinghai can be expressed as

$$R_i^{\mathrm{T}} = R_i^{\mathrm{M}} + R_i^{\mathrm{S}} \tag{1}$$

$$R_i^{\mathrm{M}} = \sum_{j=1}^{J}\sum_{t=1}^{T}\left(E_{i,j,t}^{\mathrm{Bid,D}}\frac{P_{i,t}^{\mathrm{ES}} + P_{j,t}^{\mathrm{RES}}}{2} + E_{i,j,t}^{\mathrm{Con,D}}P_{i,j,t}^{\mathrm{Con}}\right) \tag{2}$$

$$R_i^{\mathrm{S}} = \sum_{t=1}^{T} E_{i,t}^{\mathrm{Call,D}} P^{\mathrm{CP}} \tag{3}$$

It can be found from (1)–(3) that the income of the energy storage facility depends on the discharged electricity and the corresponding dealing price. If the charged electricity is certain, the higher the charge-discharge efficiency of ESSs, the higher the income, encouraging the configuration of high-quality energy storage technology and equipment. It is noteworthy that the incomes from the on-grid electricity charged and discharged by the energy storage facilities are owned by renewable energy power plants. Correspondingly, the power plants need to pay the rental fee of use rights to energy storage facilities. Therefore, for a renewable energy power plant, the larger the difference between its on-grid price and the dealing price of energy storage resources, the higher the profits. At present, the on-grid price of renewable energy power plants is different because they are subsidized by the additional funds of the national renewable energy price in different degrees. In this situation, the renewable energy power plant with the higher on-grid price is more willing to participate in the SES market. The additional power generation space generated by the purchased energy storage resources can accelerate the cost recovery. Consequently, the SES business model can promote the coordinated development of energy storage technology and renewable energy power generation technology.

In the aforementioned market, the SES transaction clearing is carried out in the order of bilateral negotiation, centralized bidding, and power system dispatching. It means that the marketized transaction mode is encouraged to utilize the energy storage resources to achieve the peak regulation. The decisive role of the market in the allocation of resources can be brought into full play. On the other hand, based on the current situation of renewable energy accommodation, the power system plays the role of minimum purchase through the paid ancillary service mode. The strategy ensures the full utilization of peak-regulation resources and the basic income of energy storage facilities, especially the independent energy storage power stations with the commercial operation.

Qinghai province has initially established the peak-regulation ancillary service market covering SES nowadays. However, it is necessary to develop a complete evaluation index system of the SES market to direct the revision of the market rules in time according to the market performance.

Finally, the SES transaction in the ancillary service market is defined as an SES market in consideration of the relative independence of the SES transaction.

2 Evaluation index system of SES market

With the continuous operation of the SES market in Qinghai, it is urgent for the decision-makers to know the performance of the SES market, and then analyze its operation status, existing problems and influencing factors. Only by evaluating the performance of the SES market scientifically can decision-makers introduce incentive policies, revise market rules and adjust the intensity of market supervision in time. In this context, an evaluation index system of the SES market towards renewable energy accommodation scenario is proposed in this paper.

2.1 Basic framework of the evaluation index system for SES market

The evaluation index system of the SES market is built according to the structure-conduct-performance (SCP) analytical model [32]. Therefore, the evaluation index system, as shown in Fig. 3, is composed of three types of primary indices, i.e., market structure, market conduct and market performance. Besides, the evaluation index system can be further divided into several secondary indices that are subordinate to the benefit type, cost type or fixed type. For a benefit-type index, such as the market activity of supplier, the larger the value is, the better the evaluation is, while a cost-type index, such as supplier concentration, is on the contrary. Besides that, the closer to a certain value, the better the evaluation is for a fixed-type index, such as the declared price volatility of suppliers. The secondary indices of the evaluation index system mainly refer to the indices of electricity markets proposed in [23-26, 32]. This is because the use right of the storage energy resources can be seen as a particular commodity in the electricity market, and there have been some complete index systems in the literature and the actual market such as PJM and CAISO in the United States. Based on the characteristics of the SES business model and the trading rules of the SES market, the selected indices are revised, constituting the secondary indices of the evaluation index system. It is noteworthy that the evaluation period of the evaluation index system is one month because both the settlement period and information disclosure period of the ancillary service market in Qinghai is one month.

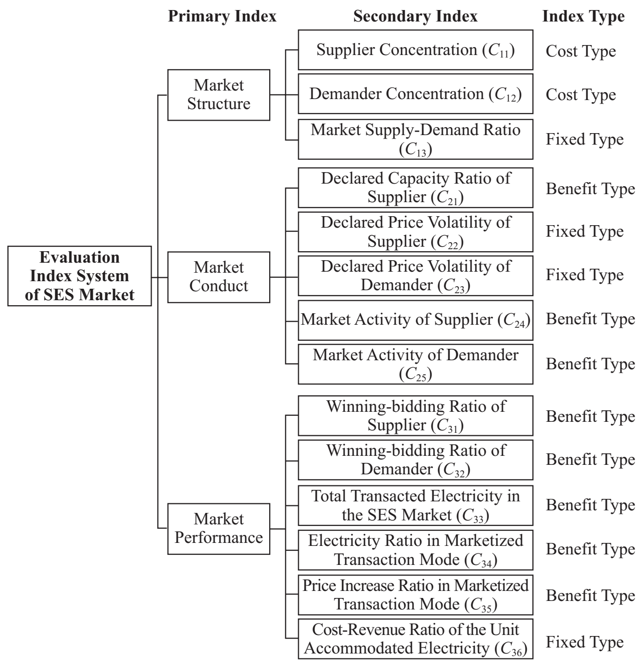


Fig. 3 Evaluation index system of SES market

2.2 Overview of the evaluation indices for the SES market

2.2.1 Market structure

(1) Supplier concentration

Supplier concentration reflects the degree of resource aggregation of the supply side in the SES market. The larger the supplier concentration is, the stronger the ability of the members on the supply side to abuse market power. Herfindahl-Hirschman Index (HHI) is utilized in this paper as the index of supplier concentration, which can be expressed as

$$C_{11} = \sum_{i=1}^{I}\left(Q_i^{\mathrm{Equ}} / \sum_{i=1}^{I} Q_i^{\mathrm{Equ}} \right)^2 \times 10000 \tag{4}$$

$$Q_i^{\mathrm{Equ}} = \sum_{t=1}^{T} Q_{i,t}^{\mathrm{ES}} / \sum_{t=1}^{T} u_{i,t}^{\mathrm{ES}} \tag{5}$$

where C_{11} denotes the first secondary index (i.e., supplier concentration) of the first primary index (i.e., market structure) of the evaluation index system. All indices in the following will be expressed in the same way, and therefore it will not be repeated. Considering that it is allowed for energy storage facilities to put a certain proportion of the idle energy storage resources into the SES market and hold the residual capacity to meet their demands, with the further improvement of the market rules, $Q_{i,t}^{\mathrm{ES}}$ may change dynamically in an evaluation period. Therefore, the equivalent energy capacity Q_i^{Equ} can reflect the accurate market share in the supply side for energy storage facilities instead of the installed energy capacity Q_i^{IE}. If the index C_{11} is larger, it reflects that the supply side of the SES market is high-concentrated. When the value of HHI is 10000, the market is a perfect monopoly market. In general, a market with the HHI of less than 1800 can be regarded as more competitive.

(2) Demander concentration

Demander concentration reflects the degree of resource aggregation of the demand side in the SES market. Though the demander concentration is less used in the traditional retail market due to the scattered buyers, there is also market power on the demand side because the demanders in the SES market are the renewable energy power plants with the larger installed capacity. The demander concentration also uses the HHI as the index, which can be expressed as

$$C_{12} = \sum_{j=1}^{J}\left(S_j^{\mathrm{RES}} / \sum_{j=1}^{J} S_j^{\mathrm{RES}}\right)^2 \times 10000 \tag{6}$$

The larger the index C_{12} is, the higher concentration the demand side of the SES market is, which means that the renewable energy power plants can influence the market price easier.

(3) Market supply-demand ratio

Market supply-demand ratio is the ratio of the total equivalent energy capacity of the suppliers and the total abandoned electricity without SES market of demanders in an evaluation period, which can be expressed as

$$C_{13} = \frac{dn^{\mathrm{C}} \sum_{i=1}^{I} Q_i^{\mathrm{Equ}} \times 100\%}{\sum_{j=1}^{J}\left(E_j^{\mathrm{Aban}} + \sum_{i}^{I}\sum_{t}^{T}\left(E_{i,j,t}^{\mathrm{Bid}} + E_{i,j,t}^{\mathrm{Con}}\right)\right) + \sum_{i}^{I}\sum_{t}^{T} E_{i,t}^{\mathrm{Call}}} \tag{7}$$

where n^{C} is the cycle number of suppliers in a trading day. Based on the current trading rules, n^{C} is equal to 1 in the current stage of the SES market. The index reflects the supply and demand relationship in the SES market and the accommodation capability provided by energy storage facilities. The larger index C_{13} illustrates the more energy storage resources on the supply side and the more abundant accommodation ability from energy storage resources. However, suppose the index is too large or too small. In that case, a severe imbalance between the supply and demand sides may occur, causing the waste of energy storage resources or renewable energy. Therefore, the market supply-demand ratio is a fixed-type index, and relevant departments can regulate the evaluation effect by setting the fixed value.

2.2.2 Market conduct

(1) Declared capacity ratio of suppliers

Based on the trading rules, suppliers may retain a part of the declarationable capacity and declare the lower capacity day ahead. There are three main reasons for the suppliers to retain the declarationable capacity. Firstly, as the energy storage facilities are the supporting projects for some suppliers, a part of the energy storage capacity is retained for own use. Secondly, suppliers may attempt to make the supply of energy storage resources nervous by retaining the reserve to gain a greater price advantage in the bidding process. Thirdly, suppliers may put the energy resources into the markets with the higher profits, such as frequency regulation market and the power market with the peak-valley price difference, if the expected profit of the SES market towards renewable energy accommodation is not satisfactory.

Consequently, the declared capacity ratio of suppliers is the share of the declared capacity of the suppliers in the market as a percentage of their total installed energy capacity, which can be expressed as

$$C_{21} = \frac{\sum_{i=1}^{I}\left(\sum_{d=1}^{D} Q_{i,d}^{\mathrm{ES,De}} / \sum_{d=1}^{D} u_{i,d}^{\mathrm{ES,De}}\right)}{\sum_{i=1}^{I} Q_i^{\mathrm{IE}}} \times 100\% \tag{8}$$

The index C_{21} reflects the supplier participation in the SES market. The larger the index is, the higher the supplier participation is and the stronger the market attraction is.

(2) Declared price volatility of suppliers

Declared price volatility of suppliers reflects the varying intensity of the day-ahead declared price of the suppliers in the evaluation period, which can be expressed as

$$C_{22} = \frac{f_{\mathrm{std}}(P_{1,1}^{\mathrm{ES,De}}, P_{1,2}^{\mathrm{ES,De}}, \cdots, P_{i,d}^{\mathrm{ES,De}})}{f_{\mathrm{mean}}(P_{1,1}^{\mathrm{ES,De}}, P_{1,2}^{\mathrm{ES,De}}, \cdots, P_{i,d}^{\mathrm{ES,De}})} \times 100\% \tag{9}$$

where f_{std} and f_{mean} are the standard deviation function and the mean value function respectively. If the index C_{22} becomes larger, it means that the price variation is more intense, and the market risk also becomes greater. However, if the index is too small, there may be a lack of competition in the market, or suppliers may be suspected of jointly manipulating the market price. Therefore, the declared price volatility of suppliers is a fixed-type index.

(3) Declared price volatility of demanders

Declared price volatility of demanders reflects the varying intensity of the day-ahead declared price of the demanders, which can be expressed as

$$C_{23} = \frac{f_{\mathrm{std}}(P_{1,1}^{\mathrm{RES,De}}, P_{1,2}^{\mathrm{RES,De}}, \cdots, P_{j,d}^{\mathrm{RES,De}})}{f_{\mathrm{mean}}(P_{1,1}^{\mathrm{RES,De}}, P_{1,2}^{\mathrm{RES,De}}, \cdots, P_{j,d}^{\mathrm{RES,De}})} \times 100\% \tag{10}$$

In fact, energy storage resources are not the basic demand for renewable energy power plants. For these power plants, the purpose of participating in the SES market is to gain the profits from the price difference of the electricity to be abandoned. Therefore, the declared price of the demanders reflects that the economic cost that demanders are willing to pay for energy storage resources based on profits. The characteristics of the index C_{23} are the same as the index C_{22}.

It is noteworthy that the declared capacity and price of suppliers and demanders at time t are determined by the declared ones in the corresponding trading day d under the current trading rule, which can be expressed as

$$Q_{i,t}^{\mathrm{ES}} = Q_{i,d}^{\mathrm{ES,De}} \qquad t \in \boldsymbol{T}_d \tag{11}$$

$$P_{i,t}^{\mathrm{ES}} = P_{i,d}^{\mathrm{ES,De}} \qquad t \in \boldsymbol{T}_d \tag{12}$$

$$P_{j,t}^{\mathrm{RES}} = P_{j,d}^{\mathrm{RES,De}} \qquad t \in \boldsymbol{T}_d \tag{13}$$

(4) Market activity of suppliers

Market activity of suppliers refers to the ratio of the active suppliers in the evaluation period to all suppliers, which can be expressed as

$$C_{24} = \frac{I^{\mathrm{Act}}}{I} \times 100\% \tag{14}$$

If a supplier makes at least a declaration in the evaluation period, the supplier can be considered as an active one. The larger the index is, the more suppliers participate in the SES market and provide more sufficient energy storage resources. Moreover, it also indirectly reflects that the supply side of the current market is in a good status, where suppliers can make profits.

(5) Market activity of demanders

Market activity of demanders refers to the ratio of the active demanders in the evaluation period to all demanders, which can be expressed as

$$C_{25} = \frac{J^{\mathrm{Act}}}{J} \times 100\% \tag{15}$$

where the basis for judging the activity of the demander is whether at least a declaration is made in the evaluation period. The characteristics of the index C_{25} are the same as the index C_{24}, which reflects the status of the demand side of the SES market.

2.2.3 Market performance

(1) Winning-bidding ratio of suppliers

Winning-bidding ratio of suppliers refers to the ratio of the winning-bidding declaration times of suppliers to the total declaration times of suppliers, which can be expressed as

$$C_{31} = \frac{\sum_{i=1}^{I}\sum_{d=1}^{D} u_{i,d}^{\mathrm{ES,Win}}}{\sum_{i=1}^{I}\sum_{d=1}^{D} u_{i,d}^{\mathrm{ES,De}}} \times 100\% \tag{16}$$

The centralized bidding of the SES market is to match the declaration from suppliers and demanders in the real-time clearing stage according to the day-ahead declared price. The supplier can be regarded as winning the bidding if the energy storage facilities of the supplier are used in the trading day. The index C_{31} reflects the accuracy of the suppliers' evaluation of the market state and their strength. If the index is small, the bidding strategies that suppliers utilize may be incorrect. In this situation, decision-makers need to guide the suppliers through information disclosure and bidding training.

(2) Winning-bidding ratio of demanders

Winning-bidding ratio of demanders refers to the ratio of the winning-bidding declaration times of demander to the total declaration times of demander, which can be expressed as

$$C_{32} = \frac{\sum_{j=1}^{J}\sum_{d=1}^{D} u_{j,d}^{\mathrm{RES,Win}}}{\sum_{j=1}^{J}\sum_{d=1}^{D} u_{j,d}^{\mathrm{RES,De}}} \times 100\% \tag{17}$$

In the real-time clearing stage, the abandoned electricity of the demanders will be sequentially stored in energy storage facilities of the suppliers based on high to low prices, until the declared price of the demanders is less than the minimum one of the suppliers or the energy storage resources are exhausted. The demander can be regarded as winning the bidding if its abandoned electricity is stored in the SES facilities in the trading day. The index C_{32} is similar to the index C_{31}, reflecting the accuracy of the demanders' evaluation of the market state and their strength.

(3) Total transacted electricity in the SES market

Total transacted electricity in the SES market refers to the sum of the electricity traded by the marketized transaction mode and paid ancillary service mode in the SES market, which can be expressed as

$$C_{33} = \sum_{i=1}^{I}\sum_{t=1}^{T}\left[\sum_{j=1}^{J}\left(E_{i,j,t}^{\mathrm{Bid}} + E_{i,j,t}^{\mathrm{Con}}\right) + E_{i,t}^{\mathrm{Call}}\right] \tag{18}$$

The index C_{33} can reflect the accommodating performance of the SES market for renewable energy because the transacted electricity in the SES market is the abandoned electricity from renewable energy power plants.

(4) Electricity ratio in marketized transaction mode

Electricity ratio in marketized transaction mode refers to the ratio of the electricity traded by the marketized transaction mode (i.e., bilateral negotiation and centralized bidding) to the total accommodated electricity, which can be expressed as

$$C_{34} = \frac{\sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{j=1}^{J}\left(E_{i,j,t}^{\mathrm{Bid}} + E_{i,j,t}^{\mathrm{Con}}\right)}{\sum_{i=1}^{I}\sum_{t=1}^{T}\left[\sum_{j=1}^{J}\left(E_{i,j,t}^{\mathrm{Bid}} + E_{i,j,t}^{\mathrm{Con}}\right) + E_{i,t}^{\mathrm{Call}}\right]} \times 100\% \tag{19}$$

The index C_{34} is used to evaluate the marketized degree of the SES transaction. The larger the index is, the more marketized the SES transaction is. It means that suppliers and demanders have the more vital ability to accommodate renewable energy through the marketized transaction to dispatch energy storage resources.

(5) Price increase ratio in marketized transaction mode

Price increase ratio in marketized transaction mode refers to the increased ratio of the average price of the electricity traded by the marketized transaction to the peak-regulation price P^{CP} of ESSs dispatched by the power system, which can be expressed as

$$C_{35}=\left[\frac{\sum_{i=1}^{I} R_i^{\mathrm{M}} / P^{\mathrm{CP}}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}(E_{i,j,t}^{\mathrm{Bid,D}}+E_{i,j,t}^{\mathrm{Con,D}})}-1\right]\times 100\% \tag{20}$$

The larger the index C_{35} is, the greater the deviation between the price formed by market competition and P^{CP} will be, and then the higher marketized degree will be. Moreover, the index also reflects the rationality of P^{CP}, which will provide a reference for the departments concerned to revise the price to further promote the marketization of SES transactions.

(6) Cost-revenue ratio of the unit accommodated electricity

Cost-revenue ratio of the unit accommodated electricity refers to the ratio of the average revenue that suppliers can earn from the unit accommodated electricity (i.e., 1 kWh in this work) to the levelized cost of energy of the unit accommodated electricity [33]. The index can be expressed as

$$C_{36}=\frac{R^{\mathrm{Aver}}}{C^{\mathrm{LCOE}}}\times 100\% \tag{21}$$

$$R^{\mathrm{Aver}}=\frac{\sum_{i=1}^{I} R_i^{T}}{\sum_{i=1}^{I}\sum_{t=1}^{T}\left[\sum_{j=1}^{J}\left(E_{i,j,t}^{\mathrm{Bid}}+E_{i,j,t}^{\mathrm{Con}}\right)+E_{i,t}^{\mathrm{Call}}\right]} \tag{22}$$

$$C^{\mathrm{LCOE}}=\frac{C^{\mathrm{Cap}}+\sum_{y=1}^{Y^{\mathrm{Max}}} C^{\mathrm{OM}}(1+i_{\mathrm{c}})^{-(y-1)}}{\sum_{y=1}^{Y^{\mathrm{Max}}} N^{\mathrm{cycle}}(1+i_{\mathrm{c}})^{-(y-1)}} \tag{23}$$

where C^{Cap} is the capital cost of an energy storage system with 1 kWh energy capacity; C^{OM} is the total operation and maintenance cost during the lifetime of the energy storage system; N^{cycle} is the cycle number in a year; i_{c} is the benchmark yield; Y_{Max} is the lifetime of the energy storage system. In this paper, the capital cost C^{Cap} of different evaluation periods is determined according to the bid-winning price of similar projects in China because the cost of energy storage has decreased significantly in recent years, and C^{OM} is a fixed cost. Decision-makers need to maintain the cost-revenue ratio within a specific range by regulating the SES market, making the suppliers obtain reasonable profits. Therefore, C_{36} is defined as a fixed-type index.

3 AHP-TOPSIS based comprehensive evaluation method of SES market

The evaluation index system of the SES market includes multiple levels and indices, and therefore it is difficult for the staff of the departments concerned without professional training to judge the operation state of the SES market intuitively according to the index value of an evaluation period. To address this problem, combined with the AHP and the technique for order preference by similarity to an ideal solution (TOPSIS), a comprehensive evaluation method towards the evaluation index system of the SES market is proposed in this paper. Generally speaking, the decision-makers who use the evaluation index system have a higher professional quality. Meanwhile, they clearly understand the relative importance of these indices by analyzing the policy orientation, construction target and current market state. Consequently, the AHP with the subjectivity and flexibility is more suitable for the proposed evaluation index system.

The specific stages of the AHP-TOPSIS based comprehensive evaluation method of the SES market are summarized as follows.

(1) Forming the judgment matrix of the evaluation index system for the SES market. Some experts in this field are invited to score the evaluation index system, where the 1-9 scale method is used. Specifically, the experts give the scale of each index according to its importance at the same level relative to its superordinate upper-level index. Moreover, the scales of indices at the same level form the judgment matrix of this level, and all judgment matrices of the evaluation index system are formed by turn according to the rules from top to bottom.

(2) Calculating the index weight for the SES market. Firstly, the maximum eigenvalue and its eigenvector of the judgment matrix at different levels are calculated. The weighting eigenvector can be obtained by normalizing the eigenvector, and the components in the weighting eigenvector are the weights of these indices. For example, the judgment matrix is formed for the three secondary indices subordinating to market structure, and the weighting eigenvector $\boldsymbol{W}_1=(\omega_{11}, \omega_{12}, \omega_{13})$ can be obtained by the aforementioned method. For the weighting eigenvector, ω_{11} is the weight of the index C_{11} (i.e., supplier concentration).

Secondly, the consistency test is carried out by calculating the random consistency ratio (CR). The calculating process is detailed in [34]. If CR⩽0.1, the consistency test passes; otherwise, the judgment matrix needs to be revised. Finally, the weight of an index relative to the general objective of the top-level can be calculated by multiplying the weight of the index with that of its upper levels successively. For example, there is an equation $\xi_{11}=\omega_1\omega_{11}$, where ξ_{11} is the weight of the index C_{11} relative to the general objective (i.e., the evaluation index of SES market).

(3) Designing an ideal case of the evaluation index system of the SES market. In general, TOPSIS is used to select the best decision from multiple alternative evaluation cases, and therefore the positive and negative ideal solutions are selected in these cases. However, considering that the evaluation for the SES market is not limited to the relative advantages and disadvantages among multiple evaluation periods, it is necessary to design the ideal cases as the evaluation benchmark of TOPSIS according to the development expectation of the SES market.

First of all, the maximum and the minimum of all indices are determined based on the possible value range, forming the sets of the maximum and the minimum as

$$\boldsymbol{C}^{\max}=\{C_{11}^{\max},C_{12}^{\max},\cdots,C_u^{\max}\}\quad u\in\mathbf{\Omega}_U \tag{24}$$

$$\boldsymbol{C}^{\min}=\{C_{11}^{\min},C_{12}^{\min},\cdots,C_u^{\min}\}\quad u\in\mathbf{\Omega}_U \tag{25}$$

where the subscript set $\mathbf{\Omega}_U=\{11,12,...,35,36\}$ is the set of the subscripts of all secondary indices of the evaluation index system. For an index, the value of each evaluation period is in the closed interval between the minimum and the maximum.

Next, for the fixed-type index, the fixed value is determined according to the experience and requirement of decision-makers, forming the set of fixed values as

$$\boldsymbol{C}^{\mathrm{Fix}}=\{C_{13}^{\mathrm{Fix}},...,C_u^{\mathrm{Fix}}\}\quad u\in\mathbf{\Omega}_F \tag{26}$$

where the subscript set $\mathbf{\Omega}_F=\{13,22,23,36\}$ is the set of the subscripts of the fixed-type indices of the evaluation index system.

Finally, the positive ideal solution and the negative ideal solution of each secondary index are determined, forming the positive ideal case and the negative ideal case. For the fixed-type index, it is noteworthy that the positive ideal solution is the fixed value, and the negative ideal solution is the value, within the value range, with the largest distance from the fixed value. Therefore, the negative ideal solution of the fixed-type index can be expressed as

$$C_u^{\mathrm{Ide-}}=\begin{cases}C_u^{\max} & C_u^{\max}-C_u^{\mathrm{Fix}}>C_u^{\mathrm{Fix}}-C_u^{\min}\\ C_u^{\min} & C_u^{\max}-C_u^{\mathrm{Fix}}\leqslant C_u^{\mathrm{Fix}}-C_u^{\min}\end{cases}\quad u\in\mathbf{\Omega}_F \tag{27}$$

(4) Standardizing index for evaluating SES market through range transformation. For the benefit-type index, its range transformation can be expressed as

$$C_u^{h,\mathrm{S}}=\frac{C_u^h-C_u^{\mathrm{Ide+}}}{C_u^{\mathrm{Ide+}}-C_u^{\mathrm{Ide-}}}\quad u\in\mathbf{\Omega}_B \tag{28}$$

where the subscript set $\mathbf{\Omega}_B=\{21,24,...,35\}$ is the set of the subscripts of the benefit-type indices of the evaluation index system.

For the cost-type index, its range transformation can be expressed as

$$C_u^{h,\mathrm{S}}=\frac{C_u^{\mathrm{Ide-}}-C_u^h}{C_u^{\mathrm{Ide-}}-C_u^{\mathrm{Ide+}}}\quad u\in\mathbf{\Omega}_C \tag{29}$$

where the subscript set $\mathbf{\Omega}_C=\{11,12\}$ is the set of the subscripts of the cost-type indices of the evaluation index system. There is a relationship $\mathbf{\Omega}_U=\mathbf{\Omega}_B\cup\mathbf{\Omega}_C\cup\mathbf{\Omega}_F$ for the subscript sets of the evaluation index system.

For the fixed-type index, its range transformation can be expressed as

$$C_u^{h,\mathrm{S}}=\begin{cases}1-\dfrac{C_u^{\mathrm{Ide+}}-C_u^h}{D_u^{\max}}, & C_u^h<C_u^{\mathrm{Ide+}}\\ 1, & C_u^h=C_u^{\mathrm{Ide+}}\\ 1-\dfrac{C_u^h-C_u^{\mathrm{Ide+}}}{D_u^{\max}}, & C_u^h>C_u^{\mathrm{Ide+}}\end{cases}\quad u\in\mathbf{\Omega}_F \tag{30}$$

$$D_u^{\max}=f_{\max}\begin{pmatrix}C_u^{\mathrm{Ide+}}-f_{\min}\left(C_u^h\right),\\ f_{\max}\left(C_u^h\right)-C_u^{\mathrm{Ide+}}\end{pmatrix}\quad u\in\mathbf{\Omega}_F \tag{31}$$

where $f_{\max}$ and $f_{\min}$ are the maximum function and the minimum function respectively.

Next, the weighting standardizing values of the indices in all evaluation cases and ideal cases are calculated by using the weight obtained in step (2), which can be expressed as

$$V_u^{h,\mathrm{S}}=C_u^{h,\mathrm{S}}\xi_u\quad u\in\mathbf{\Omega}_U \tag{32}$$

(5) Calculating Euclidean distance for evaluating the SES market. The Euclidean distances between the positive ideal case (the negative ideal case) and each evaluation case are calculated, which can be expressed as

$$D^{h+}=\sqrt{\sum_u^{\mathbf{\Omega}_U}\left(V_u^{h,\mathrm{S}}-V_u^{\mathrm{Ide+,S}}\right)^2}\quad u\in\mathbf{\Omega}_U \tag{33}$$

$$D^{h-}=\sqrt{\sum_u^{\mathbf{\Omega}_U}\left(V_u^{h,\mathrm{S}}-V_u^{\mathrm{Ide-,S}}\right)^2}\quad u\in\mathbf{\Omega}_U \tag{34}$$

(6) Calculating relative closeness for evaluating the SES market. The relative closeness between the positive ideal case and each evaluation case are calculated, which can be expressed as

$$C^{h+}=\frac{D^{h-}}{D^{h+}+D^{h-}} \tag{35}$$

The larger the relative closeness is, the closer the evaluation case is to the positive ideal case, and the better the evaluation case is.

4 Case study

In this paper, the SES trading pilot project in Qinghai province is utilized as an example to demonstrate the feasibility and applicability of the proposed evaluation index system of the SES market. The data set is the trading data of 6 typical months, i.e., 6 evaluation periods, in the pilot project, including the entity information of suppliers and demanders, the daily declared price, the traded electricity in marketized transaction mode and the dispatched electricity in paid ancillary service mode. It is noteworthy that the electricity in the data set is the stored electricity of energy storage resources. Each typical month is regarded as an evaluation case. In order to make these cases more representative, the 6 typical months belong to different quarters. At the initial stage of the pilot project, the pilot project only includes a supplier, i.e., an energy storage facility with a 50 MW/100 MWh lithium iron phosphate battery. Afterward, an energy storage facility with an installed capacity of 32 MW/64 MWh also participates in the SES market. In addition, there are 379 renewable energy power plants with a total install capacity of 23.2 GW in the SES market by July 2021. The peak-regulation price P^{CP} of ESSs dispatched by the power system is 700 CNY/MWh. The parameters of the energy storage system in (24) are shown in Table 2.

Table 2 Parameters of the energy storage system

Parameter type	Parameter values of the evaluation cases					
	1	2	3	4	5	6
C^{Cap} [CNY/kWh]	2085	1975	1920	1795	1620	1510
C^{OM}	12 CNY/(kWh·year)					
N^{cycle}	300 cycles/year					
i_c	5%					
Y_{Max}	15 years					

Fig. 4 illustrates the evaluation process of the SES market. Based on the flowchart, the data set of the 6 typical months is calculated firstly to obtain the original values of the indices, as shown in Table 3, through the index calculation method proposed in this paper, i.e., (4)-(24). It can be seen that the supplier concentration (C_{11}) is 10000 in Case1-Case4. The reason is that there is only a supplier in the SES market. With the participation of the second supplier, the supplier concentration reduces to 5240.9. Besides, The market supply-demand ratio (C_{13}) is about 3%. It seems that the current SES market should be regarded as a pure seller's monopoly market according to the index. However, it is not necessary for the renewable energy power plants to purchase the use right of the energy storage resources which is utilized to accommodate the abandoned electricity unless the income can exceed the cost of renting the energy storage resources. Consequently, demanders will not increase their declared price even if the supply of energy storage resources is short but determine the declared price based on their on-grid price. The influence of the seller's monopoly market on the price is limited. The supplier concentration will also drop rapidly when more suppliers participate in the SES market. As for the demanders of the SES market, the number of renewable energy power plants is large and the installed capacity is scattered, making the demander concentration (C_{12}) much smaller than 1800.

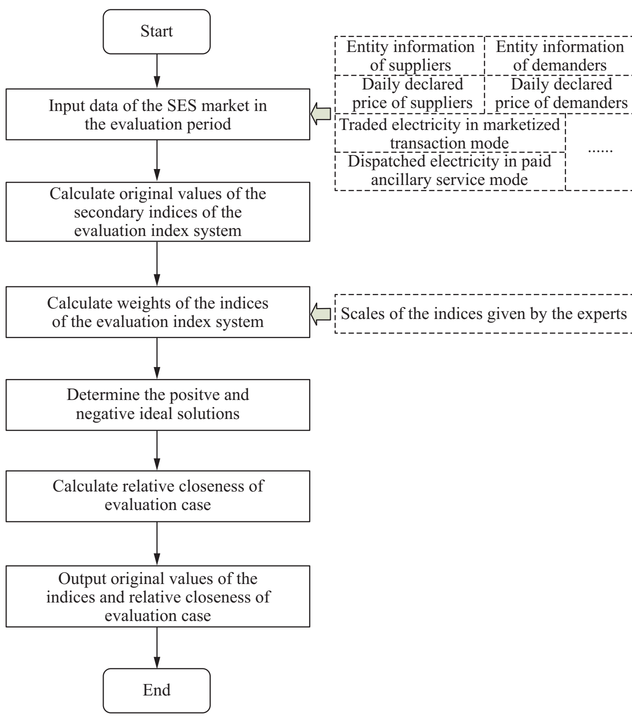


Fig. 4 Flowchart of the evaluation process for the SES market

Currently, the dispatchable peak-regulation resources are insufficient to accommodate all the renewable energy due to the higher PV curtailment ratio of Qinghai. When power curtailment occurs in Qinghai, the power dispatching agency will inevitably dispatch the idle energy storage resources if the declared capacity of energy storage facilities is not utilized thoroughly. Given this, the declared price of the supplier is not lower than P^{CP} generally. It can be seen that the declared price volatility of suppliers (C_{22}) is zero. It means that the declared price of the supplier is always the same as P^{CP}. Due to the above situation, only the demanders with higher on-grid prices are willing to make daily declarations in the SES market. Meanwhile, the other demanders will give up declaring after several unsuccessful declarations because the declared price based on their on-grid price cannot match the supplier. Moreover, it can be verified from the market activity of demanders (C_{25}) that the demanders are not active in the current SES market, and the activity is decreasing from 6.78% to 1.94% due to the long-term unsuccessful declarations. The declared price volatility of demanders (C_{23}) remains around 28%. By contrast, the declared capacity ratio of suppliers (C_{21}) and the market activity of suppliers (C_{24}) are 100% in all cases because it is the primary earning way for the suppliers to accommodate renewable energy in the current stage.

The indices of the market performance are further analyzed. It can be seen that the winning-bidding ratio of suppliers (C_{31}) is 100% based on the above reason, and the winning-bidding ratio of demanders (C_{32}) is gradually increasing from Case1 to Case6 due to the reduced number of the active demanders. The total transacted electricity in the SES market (C_{33}) shows that more than 2000 MWh/month of renewable energy electricity is accommodated in Case1 to Case4. The accommodated electricity is up to more than 3000 MWh/month along with the participation of the second supplier. The index shows that the SES market can achieve a good result in the renewable energy accommodation scenario, and many demanders can use the SES resources to reduce the abandoned electricity. Another noteworthy index is the electricity ratio in marketized transaction mode (C_{34}). Its value is less than 20% except for the value of Case4, which means that the marketized degree of the SES transaction is low. With the reduction of the renewable energy subsidies from the government, there will be more and more renewable energy power plants with grid parity in the future. If the declared price of suppliers remains stable, the market activity of demanders will still be in the doldrums. The electricity accommodated by the paid ancillary service mode is still dominant in this trend. The price increase ratio in marketized transaction mode (C_{35}) is meager, even 0 in Case5 and Case6. It can be considered as the result of market information and experience feedback. Eventually, with the decreased cost of energy storage recently, the cost-revenue ratio of the unit accommodated electricity (C_{36}) is increasing from 104.8% to 140.9% continuously. Though the costs already spent by the existing suppliers will not be reduced, it is necessary for decision-makers to adjust the peak-regulation price to make the overall cost-revenue ratio of the SES market reasonable.

From the aforementioned analysis, it can be found that the practical evaluation needs to analyze the original value of the index through professional knowledge. It is difficult for the decision-makers to judge whether the performance of the SES market is good or bad the first time, and the intuition of the original value is poor. In addition, because the importance between the indices is challenging to be grasped in this situation, the evaluation and the subsequent decision-making for the whole market are easily disturbed by individual indices. Therefore, the comprehensive evaluation method based on AHP-TOPSIS is used to solve the above problems. By consulting the experts and decision-makers, the weight of the evaluation index system is obtained based on AHP, as shown in Table 4.

Table 3 Index values of the typical months of the SES market in Qinghai

Index \ Case	1	2	3	4	5	6
C_{11}	10000	10000	10000	10000	5240.9	5240.9
C_{12}	137.45	133.09	128.93	128.77	127.56	118.85
C_{13}	3.38%	3.01%	2.88%	2.69%	3.19%	3.03%
C_{21}	100%	100%	100%	100%	100%	100%
C_{22}	0%	0%	0%	0%	0%	0%
C_{23}	28.00%	28.11%	26.20%	28.29%	28.33%	25.23%
C_{24}	100%	100%	100%	100%	100%	100%
C_{25}	6.78%	5.70%	3.67%	3.99%	2.55%	1.94%
C_{31}	100%	100%	100%	100%	100%	100%
C_{32}	31.58%	32.31%	42.66%	40.45%	50.24%	59.66%
C_{33}	2106.4	2429.6	2527.4	2017.4	3343.8	3640.9
C_{34}	19.08%	14.31%	10.65%	36.28%	18.09%	11.51%
C_{35}	1.47%	0.73%	1.47%	0.86%	0%	0%
C_{36}	104.8%	109.3%	113.6%	119.9%	130.8%	140.9%

Table 4 Weight of evaluation indices of the SES market

Primary index	Weight	Secondary index	Weight
Market structure	0.1095	C_{11}	0.0153
		C_{12}	0.0364
		C_{13}	0.0578
Market conduct	0.3090	C_{21}	0.0368
		C_{22}	0.0232
		C_{23}	0.0936
		C_{24}	0.0279
		C_{25}	0.1275
Market performance	0.5816	C_{31}	0.0310
		C_{32}	0.0834
		C_{33}	0.1509
		C_{34}	0.1440
		C_{35}	0.0629
		C_{36}	0.1094

It can be seen from the weight result in Table 4 that the weight of market performance is 0.5816, which is the largest in the three primary indices, and the weight of the market structure is lowest, i.e., 0.1095 only. The reason is that the market structure is considered not to change significantly in the short term because the SES business model of Qinghai is still in the early stage of the pilot project. Moreover, the market conduct will also be stable if there is no drastic change in the policies and market rules. Relatively speaking, the market performance should be paid more attention at the current stage. In all secondary indices, the weights of C_{25}, C_{33}, C_{34} and C_{36} are larger than 0.1, which illustrates the focuses of the SES market are the marketized degree, accommodated effect and income level in the current stage.

Next, the value range and the positive and negative ideal solution of each secondary index, as shown in Table 5, are determined according to the definition of the index, the current operation state of the SES market, and the reasonable expectation for future development.

Table 5 Value range and ideal solutions of evaluation indices of the SES market

Index	Value range	Positive ideal solution	Negative ideal solution	Index type
C_{11}	0~10000	0	10000	Cost Type
C_{12}	0~10000	0	10000	Cost Type
C_{13}	0%~150%	10s0%	0%	Fixed Type
C_{21}	0%~100%	100%	0%	Benefit Type
C_{22}	0%~50%	10%	50%	Fixed Type
C_{23}	0%~50%	10%	50%	Fixed Type
C_{24}	0%~100%	100%	0%	Benefit Type
C_{25}	0%~100%	100%	0%	Benefit Type
C_{31}	0%~100%	100%	0%	Benefit Type
C_{32}	0%~100%	100%	0%	Benefit Type
C_{33}	0~10000	10000	0	Benefit Type
C_{34}	0%~100%	100%	0%	Benefit Type
C_{35}	0%~50%	50%	0%	Benefit Type
C_{36}	0%~200%	130%	0%	Fixed Type

In addition, the relative closeness of each evaluation case is calculated by using (25)-(36), where the ideal cases are as the benchmark. The results of the relative closeness are shown in Table 6. It can be seen that the relative closeness of the 6 evaluation cases is all lower, and the largest value is only 0.4090, which illustrates that there is a gap between the performance of the SES market in the 6 typical months and the one of the positive ideal case. This is because the construction of the SES market in Qinghai is imperfect at the current stage, where the trading rules, dispatching strategy, matching method are still being explored. For the market structure, its relative closeness is gradually increasing. The participation of the new supplier, which improves the supply side of the SES market, significantly increases the value by 0.0111 in Case5. The relative closeness of market conduct is lowest due to the inactive demanders, which is required to be improved urgently for the overall performance. At present, the relative closeness of market performance is dominated by C_{33} and C_{34}, therefore the values of Case4-Case6 are larger than the first three cases because of the higher marketized degree or the more supplier. In a word, it is known from the evaluation results that the decision-makers urgently need to improve the activity of demanders and the marketized degree of the SES transaction through adjusting the peak-regulation price and encouraging more energy storage facilities to participate in the SES market.

Table 6 Relative closeness of the evaluation cases of the SES market

Evaluation target	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Overall	**0.3623**	0.3650	0.3745	0.4010	**0.4090**	0.4069
Market structure	**0.3760**	0.3761	0.3762	0.3762	0.3873	**0.3874**
Market conduct	0.3627	0.3591	0.3669	0.3536	**0.3500**	**0.3692**
Market performance	**0.3606**	0.3666	0.3777	0.4245	**0.4362**	0.4257

As for AHP-TOPSIS based evaluation method, the impact on the evaluation results of ideal solutions needs to be analyzed. The ideal solutions of evaluation indices are adjusted by adjusting the value range in a certain proportion. For example, when the adjustment proportion is 20%, the value range of C_{11} changes to 2000~8000. Besides, if the index values of the evaluation cases exceed the value range of the index, the maximum (minimum) of the index values in these evaluation cases will be the upper (lower) bound of the value range. Therefore, when the adjustment proportion is 100%, the ideal solution is selected from the evaluation cases. Fig. 5 shows the results of the sensitivity analysis. It can be seen that the overall relative closeness decreases firstly with the increase of the adjustment proportion. When the adjustment proportion is 100%, the ranking result changes to 3, 6, 5, 1, 2 and 4 for Case1 to Case6. This is because the relative closeness is affected significantly by the relative difference between the index values in the evaluation cases. The ranking result can reflect the relative good or bad of the evaluation cases with the limited value range determined by these cases, however, the gap between these evaluation cases and the SES market that decision-makers want to build cannot be evaluated.

In order to further verify the effectiveness of the evaluation method and the robustness of the evaluation results, the best-worst method (BWM) [35] and the matter-element extension model (MEEM) [36] are compared with the evaluation method applied in this paper. Generally, BWM is used as a subjective weighting method in the comprehensive evaluation process. Therefore, the BWM-TOPSIS based evaluation method is used to evaluate 6 cases. The comparative results are shown in Fig. 6. It can be seen that the relative closeness of BWM-TOPSIS is slightly smaller than the one of AHP-TOPSIS. This is because the weights obtained by the two methods are different, even if the ideas of experts likely maintain consistency in the scoring process of the two methods. However, the influence on relative closeness is limited because the importance of the indices is all reflected effectively through the two methods. Moreover, the ranking results of the two methods are the same. The comparative results illustrate that evaluation results are stable when the weighting method changes.

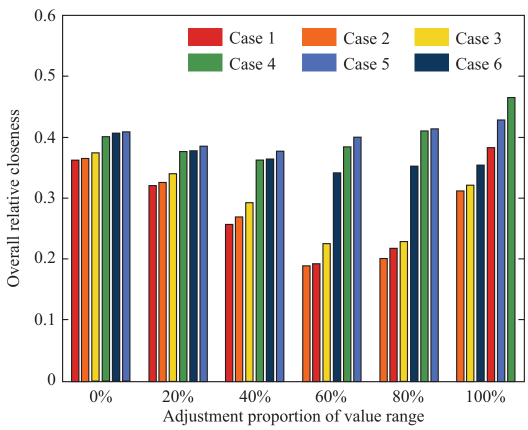


Fig. 5 Sensitivity to the ideal solution of evaluation indices of the SES market

Next, the comparison of the decision-making methods is considered. Combining 2 weighting methods, i.e., AHP and BWM, with 2 decision-making methods, i.e., TOPSIS and MEEM, 4 evaluation methods that will be compared in this part can be obtained. The ranking results of the evaluation cases under the above evaluation methods are shown in Table 7. The ranking results of AHP-TOPSIS, AHP-MEEM and BWM-TOPSIS are consistent. However, the ranks of Case5 and Case6 in BWM-MEEM exchange compared with the other three. It may be the error caused by the subjective idea of the weighting and grade classifying process. In addition, the grades of MEEM are classified into two types: Good (corresponding to the relative closeness which is larger than 0.6 in TOPSIS) and Need-to-Improve. The grades of all evaluation cases in AHP-MEEM and BWM-MEEM are Need-to-Improve. The evaluation results are consistent with AHP-TOPSIS. In the current stage, AHP-TOPSIS based evaluation method is more suitable to evaluate the performance of the SES market because it is practical and easy-to-use in the lack of massive data support and in-depth mechanism analysis. When more experience and knowledge about the SES market are obtained with further research, MEEM may be considered an alternative to TOPSIS due to the richer grade setting.

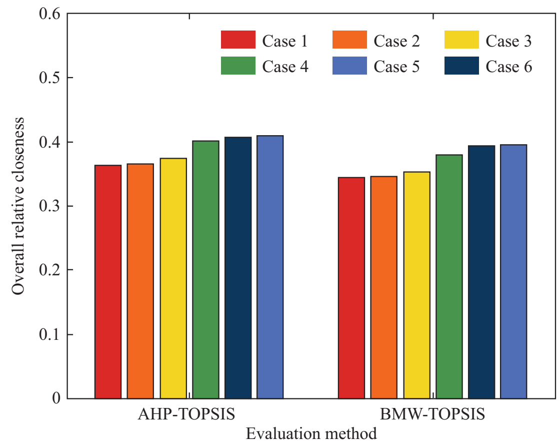


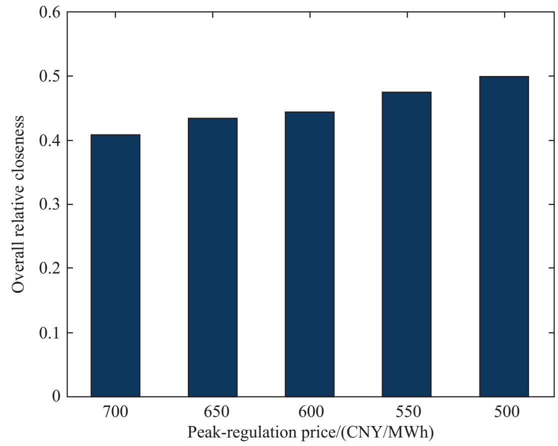
Fig. 6 Relative closeness of AHP-TOPSIS based and BMW-TOPSIS based evaluation methods

Table 7 Ranking results of the evaluation cases under the different evaluation methods for the SES market

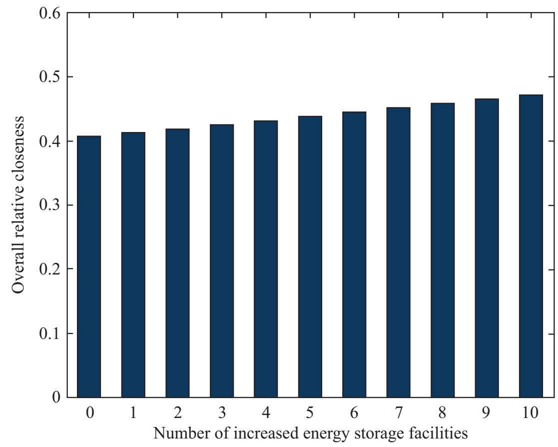
Evaluation methods	Ranking results					
	Case1	Case2	Case3	Case4	Case5	Case6
AHP-TOPSIS	6	5	4	3	1	2
AHP-MEEM	6	5	4	3	1	2
BWM-TOPSIS	6	5	4	3	1	2
BWM-MEEM	6	5	4	3	2	1

Finally, two key influencing factors, peak-regulation price, and the suppliers' number and energy storage resources, of the SES market in the current stage are analyzed. On the basis of Case6, adjusting peak-regulation price and increasing energy storage facilities are applied respectively. In order to ensure the rationality of the evaluation results, the impact of the influencing factors on the index values is inferred from the historical data. For example, some demanders will be active based on their historical bidding data if the peak-regulation price decreases. According to the analysis of historical data, the adjustment of the peak-regulation price will have a quantifiable impact on the declared price volatility of demanders (C_{23}), the market activity of demanders (C_{25}), the electricity ratio in marketized transaction mode (C_{34}) and the cost-revenue ratio of the unit accommodated electricity (C_{36}). It is assumed that the installed capacity of the newly-increased energy storage facilities is 10 MW/20 MWh, which is the minimum installed capacity that can access the SES market nowadays. Similarly, the increase of the energy storage facilities will have a quantifiable impact on the supplier concentration (C_{11}), the market supply-demand ratio (C_{13}), the total transacted electricity in the SES market (C_{33}) and the electricity ratio in marketized transaction mode (C_{34}). The values of other indices are the same as the ones of Case6. The evaluation results are shown in Fig. 7. It can be seen from Fig. 7(a) that the overall relative closeness increases from 0.4069 to 0.4932 when the peak-regulation price decreases to 500 CNY/MWh. Moreover, the electricity ratio in marketized transaction mode will exceed 50% due to the increased demanders. The impact of the decreased peak-regulation price on the cost-revenue ratio of the unit accommodated electricity is first positive and then negative. The determination of the peak-regulation price needs to consider both the performance of the SES market and the reasonable income of suppliers, which will affect the long-term development and investment of the SES industry. As for energy storage facilities, the increased number improves the supply-side structure greatly. Due to the higher PV curtailment ratio of Qinghai province, the increased energy storage facilities will be fully utilized as the first two facilities. In this situation, the total transacted electricity in the SES market increases linearly, promoting the overall relative closeness as shown in Fig. 7(b).

In summary, the selected two key influencing factors can improve the performance of the SES market respectively according to the aforementioned analysis. Nevertheless, the analysis results are still conservative because the indirect impact of the key influencing factors on the other indices is not considered. The impact is mostly positive (e.g., increased energy storage facilities deployed in different regions making some demanders active), but the quantitative analysis is impossible in the current stage due to incomplete knowledge and data. Besides, a combination of influencing factors can achieve more excellent results. However, the quantification is difficult due to the coupling mechanism, which is out of scope for this article.



(a) Adjust peak-regulation price



(b) Increase energy storage facilities

Fig. 7 Analysis on influencing factors of the SES market

5 Conclusion

An evaluation index system of a SES market under the scenario of the renewable energy accommodation is presented in this paper based on the SES trading pilot project and trading rules in Qinghai. Moreover, an AHP-TOPSIS based comprehensive evaluation method is proposed to improve the intuitiveness and assist the decision-making in the SES market. Finally, the data set of the four typical months from the trading pilot project in Qinghai is evaluated by the proposed method. The results indicate that:

The evaluation index system of the SES market and the comprehensive evaluation method proposed in this paper can achieve the quantitative analysis and comparison of the performance of the SES market towards the renewable energy accommodation scenario, in full consideration of the development expectation and decision-making tendency for the SES model. It can provide the reference for formulating the macro-control policies, the design of incentive mechanisms, and the revision of trading rules. Based on the trading pilot project in Qinghai, the performance of the SES market is analyzed. It can be seen from the results that there is a larger gap between the current SES market and the ideal case. In the current stage, the lack of energy storage resources and the market activity is a central problem for the SES market. In the future, Qinghai should further explore and study the SES model in several aspects, including designing the price mechanism that balances the reasonable profits and market activity, and formulating the incentive policy that encourages users to build the energy storage facilities and participate in the SES market.

As for future work, the evaluation index system could be improved with more entities in the SES market and revised trading rules. In addition, the direct and indirect impact of the other influencing factors or the combination of multiple influencing factors on the indices will be studied.

Nomenclature

A. Subscripts

i	Index of energy storage facilities, i.e., suppliers of energy storage resources in SES market, from 1 to I
j	Index of renewable energy power plants, i.e., demanders of energy storage resources in SES market, from 1 to J
t	Index of time intervals in a settlement period from 1 to T
d	Index of trading days in a settlement period from 1 to D
u	Index of subscripts of secondary indices
h	Index of evaluation cases from 1 to H

B. Sets

$\boldsymbol{T}_d$	Set of time interval in trading day d
$\boldsymbol{C}^{\max}$,$\boldsymbol{C}^{\min}$	Set of the maximum and the minimum of secondary indices, respectively
$\boldsymbol{C}^{\mathrm{Fix}}$	Set of fixed values of fixed-type indices

C. Variables

R_i^{T}, R_i^{M}, R_i^{S}	Total income, income from marketized transaction mode and income from paid ancillary service mode of energy storage facility i, respectively
P^{CP}	Peak-regulation price of ESSs dispatched by power system
$E_{i,j,t}^{\mathrm{Bid,D}}$, $E_{i,j,t}^{\mathrm{Con,D}}$	Discharged electricity corresponding with traded electricity of energy storage facility i and renewable energy power plant j at time t through centralized bidding and bilateral negotiation, respectively
$P_{i,t}^{\mathrm{ES}}$,$P_{j,t}^{\mathrm{RES}}$	Declared price of energy storage facility i and renewable energy power plant j at time t, respectively
$P_{i,j,t}^{\mathrm{Con}}$	Price agreed in bilateral negotiation contract
$E_{i,t}^{\mathrm{Call,D}}$	Discharged electricity corresponding with stored electricity dispatched by power dispatching agency at time t
$Q_{i,t}^{\mathrm{ES}}$	Energy capacity of energy storage facility i participating in SES market at time t
Q_i^{Equ}	Equivalent energy capacity of energy storage facility i participating in SES market in the evaluation period
$u_{i,t}^{\mathrm{ES}}$	A 0-1 variable, and if $u_{i,t}^{\mathrm{ES}}=1$, it means that energy storage facility i participates in SES market at time t
S_j^{RES}	Installed capacity of renewable energy power plant j
E_j^{Aban}	Abandoned electricity of renewable energy power plant j in the evaluation period
Q_i^{IE}	Installed energy capacity of energy storage facility i
$u_{i,d}^{\mathrm{ES,De}}$,$u_{j,d}^{\mathrm{RES,De}}$	0-1 variables, and if $u_{i,d}^{\mathrm{ES,De}}=1(u_{j,d}^{\mathrm{RES,De}}=1)$, it means that energy storage facility i (renewable energy power plant j) make a transaction declaration in trading day d
$Q_{i,d}^{\mathrm{ES,De}}$	Declared capacity of energy storage facility i in trading day d
$P_{i,d}^{\mathrm{ES,De}}$,$P_{j,d}^{\mathrm{RES,De}}$	Declared price of energy storage facility i and renewable energy power plant j in trading day d, respectively
I^{Act},J^{Act}	Number of active suppliers and demanders in the evaluation period, respectively
$u_{i,d}^{\mathrm{ES,Win}}$,$u_{j,d}^{\mathrm{RES,Win}}$	0-1 variables, and it means that energy storage facility i (renewable energy power plant j) that declares in trading day d wins bidding when $u_{i,d}^{\mathrm{ES,Win}}=1$ ($u_{j,d}^{\mathrm{RES,Win}}=1$), respectively
R^{Aver}	Average revenue that suppliers can earn from the unit accommodated electricity in the SES market
C^{LCOE}	Levelized cost of energy of the unit accommodated electricity
$C_u^{\mathrm{Ide+}}$,$C_u^{\mathrm{Ide-}}$	Positive and negative ideal solution of the index, respectively
C_u^h,$C_u^{h,\mathrm{S}}$	Original and standardized values of the index with subscript u in evaluation case h, respectively
$D_u^{\max}$	Maximum distance of the index with subscript u between ideal solution and original value
$V_u^{h,\mathrm{S}}$	Weighting standardizing value of the index with subscript u in evaluation case h
$V_u^{\mathrm{Ide+,S}}$,$V_u^{\mathrm{Ide-,S}}$	Weighting standardizing value of the index with subscript u in positive and negative cases, respectively

D^{h+},D^{h-}	Euclidean distance of the index with subscript *u* between the positive and negative cases and evaluation case *h*, respectively
C^{h+}	Relative closeness between evaluation case *h* and positive case

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Declaration of Competing Interest

We declare that we have no conflict of interest.

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(Editor Yajun Zou)