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A performance evaluation method for energy storage systems adapted to new power system interaction requirements

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In recent years, China's new energy storage application on a large scale has shown a good development trend; a variety of energy storage technologies are widely used in renewable energy development, consumption, integrated intelligent energy systems, distribution grids, and microgrids; and substantial progress has been made in the research and development of technology and equipment, construction of demonstration projects, exploration of business models, and construction of standard systems. Up to now, a unified statistical index system and evaluation method standard for new energy storage has not yet been formed domestically or even internationally. The work takes the *status quo* of the new power system construction of the Hebei South Network as the research object and carries out research on the new energy storage statistical index system and evaluation method. It constructs a new energy storage power station statistical index system centered on five primary indexes: energy efficiency index, reliability index, regulation index, economic index, and environmental protection index; proposes Analytic Hierarchy Process (AHP)–coefficient of variation combination assignment method; and evaluates the development level of the new energy storage power station by adopting a comprehensive evaluation model based on the object element topology method. The new energy storage statistical index system and evaluation method are designed to provide a scientific index system and evaluation method for comprehensively monitoring, assessing and measuring the comprehensive performance and effect of new energy storage power plants in the process of operation and development, and optimizing the operation strategy of new energy storage power plants as well as the development and promotion of energy storage technology.

KEYWORDS

new energy storage, statistical indicator system, AHP–coefficient of variation combination weighting method, indicator weight calculation, comprehensive evaluation

1 Introduction

In recent years, China's new energy storage applications have shown a good development trend; a variety of energy storage technologies are widely used in renewable energy integration, power system regulation of distribution grids, and off-grid technology and other fields; and breakthroughs have been made in the research and development of technology and equipment, the construction of demonstration projects, and the construction of standardized systems (Yu-chi et al., 2022). The marketized scale of new energy storage involved in peak shaving and valley filling has been steadily expanding, strongly supporting the energy transition.

New energy storage is used to build a new type of power system with stronger new energy consumption capacity, and realizing the efficient use of renewable energy is an important means to help support "carbon peak, carbon neutral (Alizadeh et al., 2016; Guerra et al., 2022; Zheng et al., 2022; Hu et al., 2023)". Compared with Europe and the United States, China's energy storage industry layout is relatively late but the development speed is faster. In 2018, the installed capacity exceeded 1 GW. In 2019, affected by the security of some storage power stations, China's electrochemical energy storage growth slowed down. Since 2020, the number of electrochemical energy storage power station projects has been steadily increasing. The energy storage industry is about to explode after a short winter.

In order to comprehensively and objectively reflect the operation and development process of the new energy storage power station and understand its development law, it is planned to carry out a research on the new energy storage statistical index system. There have been certain research results at home and abroad. Wang et al. (2022a) established the risk assessment index system of an electrochemical energy storage power station and used comprehensive evaluation for risk assessment. Katsanevakis et al. (2019) and Yang et al. (2022) constructed the grid connection index system of electrochemical energy storage power station and voltage stability measurement index. Elnozahy et al. (2021), Zhao (2021), and Wang (2022) started from the perspective of economic indicators to clarify the influencing factors of energy storage power stations and optimize the development strategy. Guo et al. (2020) constructed a multi-attribute comprehensive index assessment model to optimize the multi-point siting of an energy storage system. Huang et al. (2020) proposed similarity, delay, deviation, and contribution indicators to measure the energy storage regulation performance based on the Fréchet distance algorithm. Baomin et al. (2022) proposed metrics to measure the active power fluctuation of wind and storage co-generation systems. Xiao et al. (2023) constructed a comprehensive evaluation index system for grid-side battery energy storage power plant from the aspects of technology, economy, and social benefits. Up to now, a unified statistical index system and evaluation method standard for the new energy storage have not been formed, which cannot support the construction of the new power system.

Comprehensive evaluation can scientifically assess the current situation and trend of energy storage development. The current research on comprehensive evaluation of energy storage has a certain theoretical basis. Bihui et al. (2011) combined energy storage capacity with reliability indexes to realize the comprehensive evaluation of total output power. Baomin et al. (2022) and Xiao et al. (2023) proposed a comprehensive evaluation model of grid-side battery energy storage power plant and shared the comprehensive evaluation method of the energy storage market. Dai (2021) established a model based on fuzzy comprehensive evaluation to comprehensively evaluate the integrated benefits of grid-side energy storage projects. Liu et al. (2022) proposed an energy storage selection evaluation system that combines the hierarchical analysis method and the superiority and inferiority solution distance method with the fuzzy comprehensive analysis method. Qinlin (2023) established a comprehensive evaluation system for user-side battery energy storage selection. Chen et al. (2022) established a comprehensive evaluation model based on the whole life cycle of the energy storage power plant. Wang et al. (2022b) established the matter-element extension comprehensive evaluation model, of object element topable, combined with energy storage characteristics, to assess the service grid of the pumped storage power station. Literature (Jiang et al., 2021) combined with hierarchical analysis method for the comprehensive evaluation of electrochemical energy storage power station for new energy consumption.

In the treatment of weights, Wang et al. (2007) proposed a combination assignment method based on subjective and objective weighted consistency for indicator assignment. Literature [(Yuan, 2007); (Duan, 2012); (Shang-Ping et al., 2018); and (Hong et al., 2023)] respectively proposed a variety of combination methods, subjective weight setting methods such as Delphi method, ordinal relationship analysis, hierarchical analysis, etc., and objective weight setting methods such as coefficient of variation method, entropy weight method, etc.

It can be seen that the research of the hierarchical analysis method has been more mature; however, the current research is not comprehensive in the use of indicator data, and there is less research in the field of objective comprehensive evaluation. In the research of data processing, the research of normalization processing is more perfect, but due to the difficulty of quantifying some of the indicators of the new type of energy storage power station, it has been plagued by subjective factors in the evaluation, and it is especially necessary to have a set of objective and comprehensive evaluation model, so there is an urgent need to carry out in-depth research and application of related contents in China.

The article takes the current situation of the construction of the new energy storage power station in the Hebei South Network as its research object and carries out research on the statistical index system and evaluation method of new energy storage, constructs the statistical index system of new energy storage, and establishes the evaluation method of new energy storage development.

2 Construction of a new statistical indicator system for energy storage

Based on the characteristics of the operation and development of new energy storage power stations, a new energy storage statistical index system applicable to their operation and development is constructed to ensure that the system is scientific, reasonable, and evidence based for monitoring and evaluating the current status and future planning of new energy storage power stations.

2.1 Construction of a system of statistical monitoring indicators

2.1.1 Principles for the selection of indicators

When constructing a new type of energy storage statistical indicator system, the accessibility, reliability, and relevance of the indicators should be fully considered.

(1) Indicator accessibility: Due to the limitation of the development level of new energy storage, the actual data of some indicators cannot be accurately obtained or scientifically quantified; some indicators are not the focus of the actual work of the local energy storage power station and are not included in the statistical data system. Therefore, the data should be selected in combination with the actual situation of the region and the development focus of the energy storage power station.
(2) Reliability of indicators: In statistics, some indicators that can be obtained through actual measurements, precise calculations, or standardized statistics are more reliable, whereas indicators that can only be estimated or judged qualitatively do not have a high degree of credibility and should be considered. In addition, some indicators may not be available in some regions, and more consideration should be given to them when counting.
(3) Indicator relevance: The new energy storage statistical indicator system established in this work contains three levels of indicators, and there is a correlation between the indicators. For example, the energy efficiency indicators in the power station energy storage loss rate and power station charging and discharging energy conversion efficiency may have a strong correlation. In addition, the comprehensive efficiency of the power station and the station electricity rate are substitutable to a certain extent. For these indicators, they cannot be weighted by a simple four-pronged algorithm; otherwise, the final scoring results will be affected.

2.1.2 Constructive factors

The statistics of new energy storage power plant needs to consider the orientation and practical significance of the statistical results for its development. In the construction of energy storage statistical index system, need to choose some can directly or indirectly in the new energy storage power plant development process reflected in the parameter as the index construction factors.

2.1.3 Structure of the indicator system

Based on the hierarchical analysis method, the indicator system is composed of three layers, from high to low: the target layer, benchmark layer, and indicator layer. The target layer refers to the construction of a new type of energy storage statistical indicator system, which is specifically divided into five guideline layers: energy efficiency statistical indicators, reliable statistical indicators, regulation statistical indicators, economic statistical indicators, and environmental statistical indicators. The detailed description of the indicator layer is shown in Section 2.2 below.

2.2 Definition and calculation of statistical monitoring indicators

The new energy storage statistical indicator system is centered on five major first-level indicators, namely, energy efficiency statistics, reliability statistics, regulation statistics, economic statistics, and environmental protection statistics, as shown in Figure 1.

The following content mainly focuses on the second-level indicators in the new energy storage power plant statistical indicator system from the two aspects of indicator interpretation and calculation formula.

2.2.1 Energy efficiency statistical indicators

(1) Depth of discharge

The ratio of electrical energy released in a single discharge cycle relative to its total energy storage capacity is calculated as follows:

$$\text{Depth of discharge} = \frac{\text{Maximum discharge}}{\text{Rated capacity}} \times 100\%, \tag{1}$$

where the unit of the indicator is %.

(2) Average energy density

The average value of energy stored per unit mass is calculated as follows:

$$\text{Average energy density} = \frac{\text{Rated capacity}}{\text{Sum of masses of energy storage units}}, \tag{2}$$

where the indicator is given in MWh/m^3.

(3) Overall efficiency of the power station

The ratio of power on-grid to power off-grid during production operation is calculated as follows:

$$\text{Overall plant efficiency} = \frac{\text{On} - \text{grid electricity}}{\text{Off} - \text{grid electricity}} \times 100\%, \tag{3}$$

where the unit of the indicator is %.

(4) Power plant energy storage loss rate

The ratio of energy loss during storage is calculated as follows:

$$\text{Plant energy storage loss rate} = \frac{\text{Sum of charges} - \text{Sum of discharges}}{\text{Sum of off} - \text{grid}} \times 100\%, \tag{4}$$

where the unit of the indicator is %.

2.2.2 Reliability statistical indicators

(1) Coefficient of unplanned outage of the power station

The ratio of unplanned outage to total operation time within a certain period of time is calculated as follows:

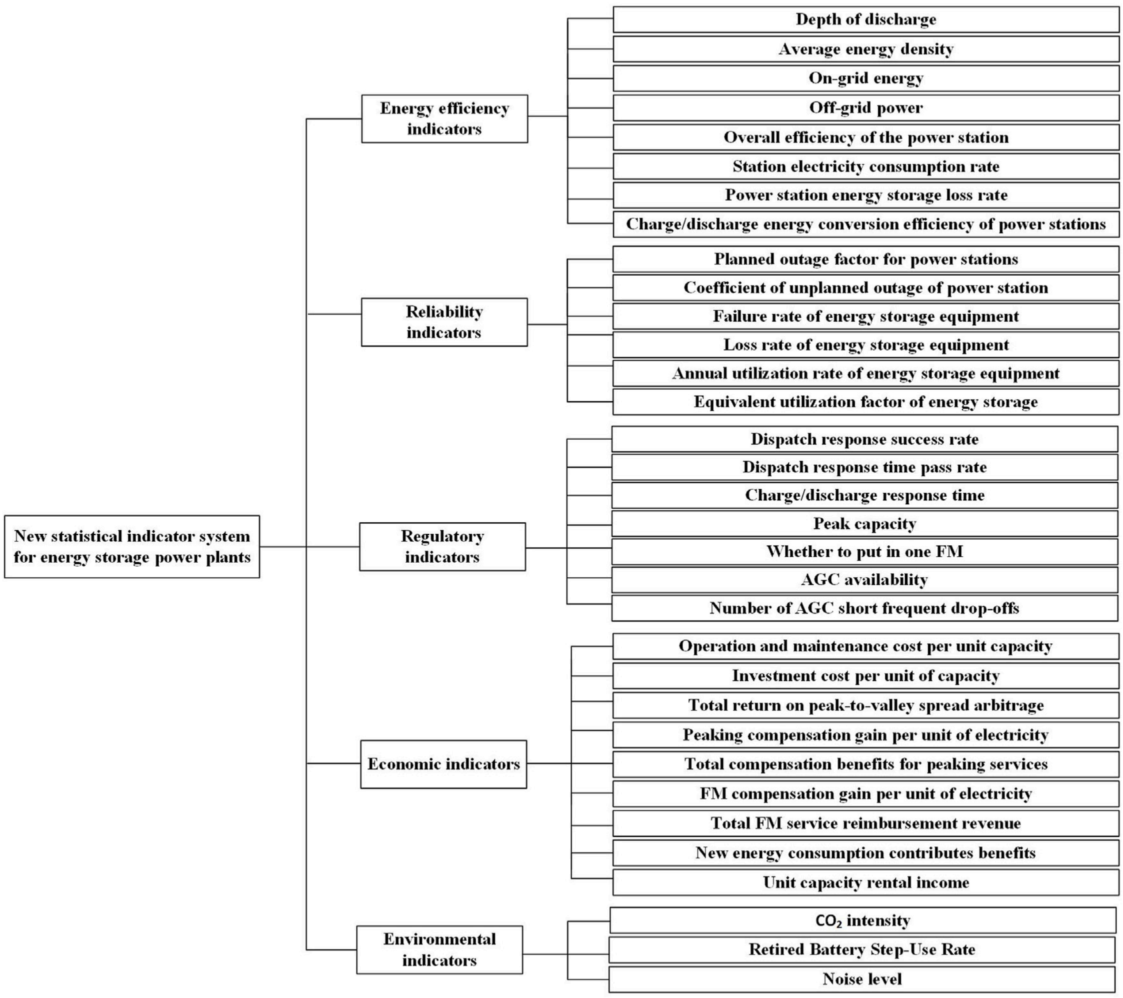

FIGURE 1
New statistical indicator system for energy storage.

$$\text{Unscheduled outage factor} = \frac{\text{Number of hours of unscheduled outage in the statistical period}}{\text{Total number of hours of statistical time in the statistical period}} \times 100\%, \tag{5}$$

where the unit of the indicator is %.

(2) Loss rate of energy storage equipment

The ratio of energy loss caused by internal resistance, conversion efficiency, self-discharge, and other factors of energy storage equipment during the energy storage process is calculated as follows:

$$\text{Loss rate of energy storage equipment} = \frac{\text{Maximum charging capacity of energy storage equipment}}{\text{Nominal charging capacity of energy storage equipment}} \times 100\%, \tag{6}$$

where the unit of the indicator is %.

(3) Annual utilization rate of energy storage equipment

The ratio of the actual utilization time of the energy storage equipment within a certain period of time to its design life is calculated as follows:

$$\text{Utilization rate of energy storage equipment} = \frac{\text{Normal use time of energy storage equipment}}{\text{Design life of energy storage equipment}} \times 100\%, \tag{7}$$

where the unit of the indicator is %.

(4) Equivalent utilization coefficient of the power station

The ratio between the actual operation time and the total operation time within a certain period of time is calculated as follows:

$$\text{Equivalent utilization factor of the power station} = \frac{\begin{array}{c}\text{Number of hours of cumulative actual operation}\\ \text{in the statistical period}\end{array}}{\begin{array}{c}\text{Total number of hours of statistical time in the statistical}\\ \text{period Total number of hours}\end{array}} \times 100\%, \tag{8}$$

where the unit of the indicator is %.

2.2.3 Regulatory statistical indicators

(1) Dispatch response success rate

The probability of successfully completing the scheduling task after receiving a scheduling command is calculated as follows:

$$\text{Scheduling response success rate} = \frac{\text{Number of scheduling commands actually executed}}{\text{Number of scheduling commands issued}} \times 100\%, \tag{9}$$

where the unit of the indicator is %.

(2) Dispatch response time pass rate

The probability of completing the response task within the specified time after receiving the scheduling command is calculated as follows:

$$\text{Scheduling response time pass rate} = \frac{\text{Number of scheduling commands response time passes}}{\text{Number of scheduling commands issued}} \times 100\%, \tag{10}$$

where the unit of the indicator is %.

For the energy storage system, its response time shall be no more than 200 ms, and the Automatic Generation Control (AGC) response time pass rate shall be no less than 98%.

(3) Peaking capacity

The difference between the maximum technical output and the minimum technical output is calculated as follows:

$$\text{Peaking capacity} = \text{Maximum technical output} - \text{Minimum technical output}, \tag{11}$$

where the unit of the indicator is kWh.

(4) AGC availability

The proportion of the time for which the automatic generation control system operates normally and provides regulation service to the total time is calculated as follows:

$$\text{AGC availability rate} = \frac{\text{Number of actual AGC operating hours}}{\text{Number of theoretical AGC available hours}} \times 100\%, \tag{12}$$

where the unit of the indicator is %.

2.2.4 Economic statistical indicators

(1) Operation and maintenance cost per unit capacity

The cost required for the operation and maintenance of the generation equipment or power system per unit capacity is calculated as follows:

$$\text{Operation and maintenance costs per unit capacity} = \frac{\text{Total O\&M cost of storage plant during the statistical period}}{\text{Rated capacity}}, \tag{13}$$

where the unit of the indicator is yuan/kWh.

(2) Total gain from peak–valley spread arbitrage

The total gain from purchasing and storing electricity from the trough time and then selling it in the peak time by utilizing the peak–valley spread in the electricity market is calculated as follows:

$$\text{Total gain from peak and valley spread arbitrage} = (\text{Peak price} \times \text{Total discharges}) - (\text{Valley price} \times \text{Total charging}), \tag{14}$$

where the unit of the indicator is yuan.

(3) Benefit from contribution to new energy consumption

The degree of contribution to and benefit from new energy consumption is calculated as follows:

$$\text{Benefit from new energy consumption contribution} = \frac{\text{Additional renewable energy} \times \text{Renewable energy feed} - \text{in tariffs}}{\text{Rated capacity}}, \tag{15}$$

where the unit of the indicator is 10,000 yuan.

(4) Unit capacity leasing revenue

The revenue gained from leasing each unit of its capacity is calculated as follows:

$$\text{Rental income per unit capacity} = \frac{\text{Total rental income of storage plant}}{\text{Rated capacity}}, \tag{16}$$

where the unit of the indicator is yuan/kWh.

2.2.5 Environmental statistical indicators

(1) CO_2 intensity

Carbon dioxide (CO_2) emissions per unit generated during power generation are calculated as follows:

$$CO_2 \text{ intensity} = \frac{CO_2 \text{ emissions}}{\text{Rated capacity}}. \tag{17}$$

(2) Retired battery step–use rate

The ratio of the number of retired batteries used to the total number of retired batteries is calculated as follows:

$$\text{Decommissioned battery cascade utilization rate} = \frac{\text{Number of batteries that are reused after decommissioning}}{\text{Total number of retired batteries}} \times 100\%, \tag{18}$$

where the unit of the indicator is %.

(3) Noise level

TABLE 1 Criterion level judgment matrix.

Synthesized assessment	Energy efficiency indicator	Reliability indicator	Regulatory indicator	Economic indicator	Environmental indicator
Energy efficiency indicators	1	4/3	4/3	2	2
Reliability indicators	3/4	1	1	3/2	3/2
Regulatory indicators	3/4	1	1	3/2	3/2
Economic indicators	1/2	2/3	2/3	1	1
Environmental indicators	1/2	2/3	2/3	1	1

The noise level refers to the degree of noise influence of the new energy storage power station on the surrounding environment and the population. It can be used to measure the noise impact of energy storage stations, usually in the form of decibels (dB).

3 Validation of a new statistical indicator system for energy storage

3.1 Calculation and optimization of indicator weights

The weight coefficient represents the importance of the index and the degree of influence on the final goal. To a certain extent, whether the setting of the weight system is appropriate determines the accuracy of the evaluation conclusion. This work takes the statistical data of three energy storage power stations in the Hebei South Network as the example, calculates, and verifies the comprehensive evaluation effect of the new energy storage statistical index system and the evaluation method of development level; the relevant statistical data are shown in Supplementary Table SA1.

Based on the indicator combination assignment process of AHP–coefficient of variation method, the subjective weight of the criterion layer is first calculated based on the hierarchical analysis method, and then the subjective–objective combined weight of the indicator layer is calculated using the AHP–coefficient of variation combination assignment method.

Among them, the AHP–coefficient of variation combination empowerment method, on the one hand, takes the AHP method to determine the subjective weight, grasps the direction of the evaluation problem, and enhances the adaptability of evaluation results; on the other hand, the coefficient of variation method determines the objective weight, makes full use of the index data, and reduces the interference of subjective factors; at the same time, when compared with the traditional entropy weight method, the coefficient of variation method can reduce the sensitivity of special data and has a stronger practicability.

First, the five indicators of the target layer are compared two by two, and the judgment matrix is constructed as shown in Table 1.

The AHP method is used to calculate the criterion layer weights, and the AHP–coefficient of variation combination assignment method is used to calculate the final comprehensive weights. Taking energy efficiency indicators as an example, the calculation steps of subjective weights of the criterion layer are as follows:

Step 1.1: The eight indicators are compared two by two, and the judgment matrix is constructed, as shown in Table 2.

Step 1.2: After the judgment matrix is normalized, the corresponding weight vector is calculated. Taking energy efficiency indicators as an example, the process of calculating objective weights by the coefficient of variation method is as follows:

Step 2.1: For each indicator, calculate its mean and standard deviation vector.

Step 2.2: For each indicator, calculate the coefficient of variation vector.

Step 2.3: For each indicator, calculate its coefficient of variation weight vector.

The process of calculating subjective weights by the AHP method and objective weights by the coefficient of variation method for reliability indicators, regulation indicators, economic indicators, and environmental indicators is the same as the above steps.

The final results of weight calculation for each layer of indicators are shown in Supplementary Table SA2.

3.2 Synthesis of evaluation results and analysis

In order to solve the problem of the lack of unified evaluation standards for the development level of new energy storage power stations, this work divides the development level grade of new energy storage power stations into five grades (unqualified, qualified, intermediate, good, and excellent) by clearly defining the technical requirements.

The comprehensive evaluation model introduces the object elements to be evaluated, calculates the correlation of each index to each grade, and progresses step by step. The degree of affiliation of each energy storage power station relative to each grade is finally derived. According to the principle of maximum affiliation, the evaluation grade of the new energy storage development level of the energy storage power station is determined.

By multiplying the correlation value of each index with the corresponding weight, the correlation degree of the energy storage power station and the eigenvalue of the grade variable are calculated. Based on the maximum membership principle, the evaluation level of the energy storage power station is calculated, and the results are shown in Table 3.

TABLE 2 Judgment matrix for energy efficiency indicators.

Synthesized assessment	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	4/5	5/2	5/2	5/4	5/3	5/2	5/3
C2	4/5	1	2	2	1	4/3	2	4/3
C3	2/5	1/2	1	1	1/2	2/3	1	2/3
C4	2/5	1/2	1	1	1/2	2/3	1	2/3
C5	4/5	1	2	2	1	4/3	2	4/3
C6	3/5	3/4	3/2	3/2	3/4	1	3/2	1
C7	2/5	1/2	1	1	1/2	2/3	1	2/3
C8	3/5	3/4	3/2	3/2	3/4	1	3/2	1

Among them, C1, C2, and C3–C8, respectively, refer to the discharge depth, average energy density, on-grid power, off-grid power, comprehensive efficiency of the power station, station power consumption rate, energy storage loss rate of power station, and charge and discharge energy conversion efficiency of the power station.

TABLE 3 Comprehensive development level of new energy storage power plants.

Energy storage plant	$K_1(N)$	$K_2(N)$	$K_3(N)$	$K_4(N)$	$K_5(N)$	Hierarchy	k^*
A	−0.4816	−0.2928	−0.0089	0.0360	−0.3095	Good	3.4981
B	−0.5817	−0.4501	−0.2787	−0.0866	0.0858	Excellent	4.0634
C	−0.4420	−0.2633	0.0167	−0.0896	−0.3198	Intermediate	3.3760

It can be seen that the development level of new energy storage of energy storage station A is "good grade," of energy storage station B is "excellent grade," and of energy storage station C is "intermediate grade." According to the eigenvalues of the rank variables, it is seen that the eigenvalue of the rank variables of energy storage plant A is less than 3.5, and the development level of new energy storage is more inclined to "intermediate"; the eigenvalue of the rank variables of energy storage plant B is more than 4.0, which indicates that energy storage plant B is stable at the development level of "excellent"; similar to A, the eigenvalue of the rank variables of energy storage plant C is less than 3.5, and the development level of new energy storage is more inclined to "good." Similar to A, the eigenvalue of the grade variable of energy storage plant C is less than 3.5, which means that the development level of the new energy storage of energy storage plant C tends to be more "qualified." As a whole, the development level of new energy storage in energy storage plant B is optimal, the development level of energy storage plant C is slightly lower, and the development level of energy storage plant A is moderate.

4 Summary and outlook

On the basis of analyzing the characteristics of the operation and development of new energy storage power stations, this work constructs a new energy storage statistical index system that builds the core of five first-level indexes, namely, energy efficiency statistical indexes, reliability statistical indexes, regulation statistical indexes, economic statistical indexes, and environmental protection statistical indexes and adopts a comprehensive evaluation model based on the object-element topology method for evaluating the level of the development of new energy storage power stations, which is used to comprehensively monitor, assess, and promote the planning and development of new energy storage power stations and optimize the sustainable energy transition and the upgrading and development of the power industry.

In the future, new energy storage power stations will continue to develop and improve, and according to the development trend, this study will further improve the monitoring index system, optimize the evaluation method, and enhance the generalization ability of the evaluation method.

Data availability statement

The data sets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Author contributions

ZZ: Formal analysis, methodology, and manuscript writing—original draft. Guozhen Ma: Data curation, investigation, and manuscript writing—review and editing. NS: Conceptualization, methodology, and manuscript writing—review and editing. YW: Methodology, validation, and manuscript writing—review and editing. JX: Methodology, software, visualization, and manuscript writing—review and editing. XX: Manuscript writing—review and editing, methodology, software, and visualization. NS: Software, visualization, and manuscript writing—review and editing.

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Conflict of interest

Authors ZZ, GM, NS, YW, JX, and XX were employed by the company State Grid Hebei Electric Power Co.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2024.1365419/full#supplementary-material

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