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Value Evaluation Model of Multi-Temporal Energy Storage for Flexibility Provision in Microgrids

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Abstract: With the advancement of distributed power generation technology and the deepening of the low-carbon transformation of energy structure, a high proportion of renewable energy has become an inevitable trend in future energy systems, especially for microgrids. However, the volatility and uncertainty associated with renewable energy pose significant challenges to the secure and stable operation of power systems, necessitating the exploration of the flexible regulation of resources. Energy storage, as a crucial flexible resource characterized by technological diversity and a variety of regulation capabilities, has been extensively studied and applied. Nonetheless, the high investment costs and limited returns of energy storage technology, coupled with the ambiguous utility in different scenarios under the current electricity market's framework, complicate its broader application. To thoroughly analyze the utility of energy storage in facilitating flexible adjustments in microgrids, this study developed a composite weight-TODIM (an acronym in Portuguese for interactive and multi-criteria decision making) model for assessing the utility of energy storage that incorporates heterogeneity in the risk preferences. This model enabled a comparative analysis of the utility of energy storage technology across multiple scenarios, taking the risk preferences of decision-makers into account, thereby providing strategic insights for the application of multi-temporal energy storage in microgrids. The feasibility and effectiveness of the model were validated through a case study analysis.

Keywords: multi-temporal energy storage; flexibility provision; utility evaluation; multi-criteria decision making

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1. Introduction

In pursuit of China's ambitious "dual carbon" goals, the development of a novel electric power system predominantly fueled by renewable energy sources has emerged as a critical pathway. Electricity, serving as a dynamic and efficient secondary energy source, holds immense significance within the contemporary societal framework [1]. The construction of a new power system, where renewable energy serves as the primary source, thereby effectively substituting fossil fuels, is paramount for fostering a low-carbon and sustainable evolution of the power system [2]. Nonetheless, renewable energy generation methods, primarily wind and photovoltaic power, are substantially influenced by uncontrollable environmental elements, resulting in variability and uncertainty [3,4]. With the increasing reliance on renewable energy within the new power system and the clean construction of microgrids, the operational safety and stability are jeopardized, underscoring the pressing need for flexible resource solutions to continuously monitor and adjust the balance between supply and demand, as well as ensuring the safety of power lines. Energy storage, as a versatile technology for flexible adjustment, boasts a wide array of technological variations and application scenarios, and has thus been extensively adopted in the establishment of new power systems [5,6]. Energy storage technologies can be classified on the basis of operational principles into mechanical, electrochemical, electromagnetic, and thermal storage; on the basis of the duration of the response into short-term, medium-to-long-term, and long-term storage; and on the basis of the function of the flexible adjustment into power-type and capacity-type storage, as illustrated in Figure 1. The horizontal coordinates represent the response time of energy storage, from milliseconds to hours. Vertical coordinates divide the application scenarios of different energy storage technologies according to the power and energy-based support.

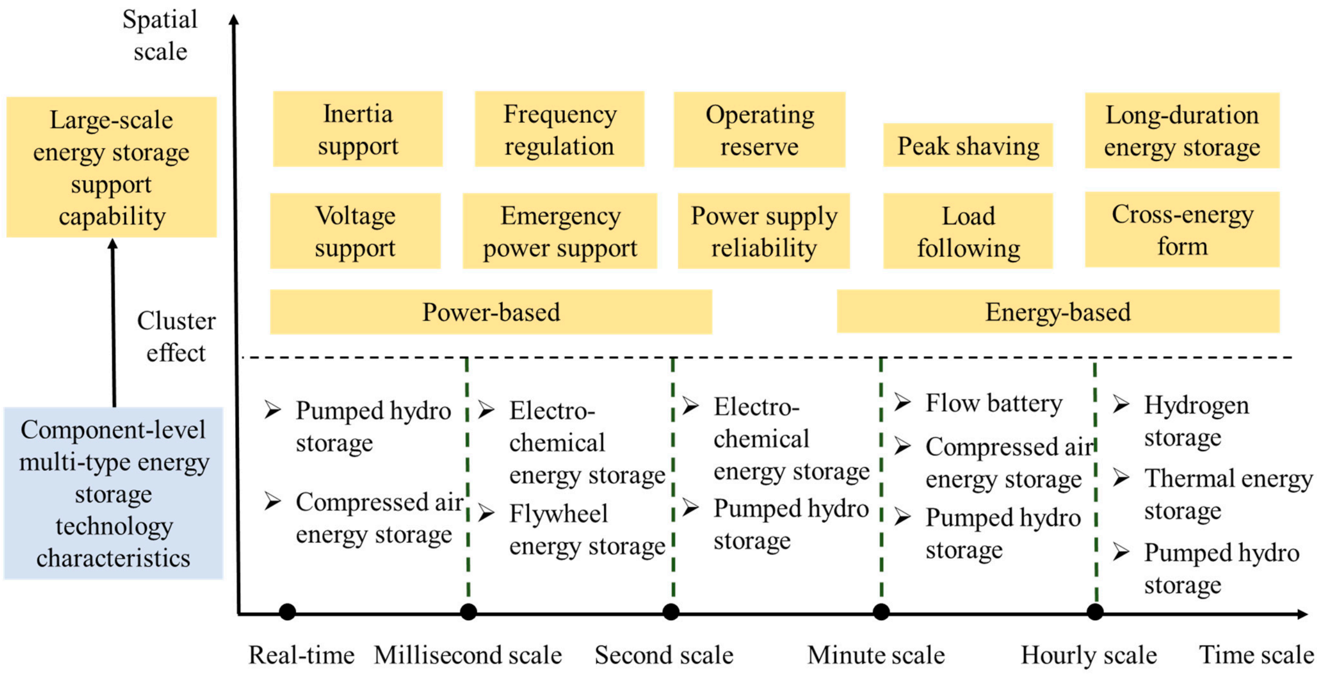

Figure 1. Classification of typical energy storage technologies.

Evaluating the value of flexibility provided by existing energy storage technologies is the first step towards improving the efficiency of energy storage technology applications, saving resources, and protecting the environment. However, the comprehensive evaluation of the planning and operational safety of various energy storage technologies has not been paid enough attention, mainly in the fields of how to efficiently and effectively plan and schedule the limited resources in the microgrids. Reference [7] proposed a multi-objective optimization scheduling method for mobile energy storage in active distribution networks. Reference [8] explored the value of energy storage, considering the coupling effect of electricity and the carbon market. Reference [9] developed a comprehensive benefit evaluation model for battery energy storage systems and conducted a case study. Reference [10] introduced a strategy for smoothing the output fluctuations of new energy sources using hybrid energy storage. Reference [11] presented a hybrid energy system scheduling model to alleviate grid congestion. However, there is a notable scarcity of in-depth analytical research into the comprehensive utility of energy storage technologies within the context of constructing efficient microgrids. A holistic utility evaluation of energy storage not only serves to validate the efficacy of existing construction plans, offering constructive feedback to power system developers, energy storage investors, and governmental bodies but also facilitates a longitudinal comparison of the value of energy storage across different stages of the construction of new power systems, promoting the coordinated planning and development among different units within the system.

As a result of this, this study embarked on an investigation into a utility evaluation model for energy storage's participation in the electricity market's flexible adjustment throughout the construction phase of new power systems. Initially, this study introduced a comprehensive set of evaluation indicators for assessing the utility of energy storage flexible adjustment. Subsequently, it established a composite weight-TODIM (an acronym in Portuguese for interactive and multi-criteria decision making) evaluation framework for the utility of energy storage and a methodology that accounted for the heterogeneity in risk preferences. Moreover, it outlines a procedure for evaluating the utility of energy storage predicated on the optimization of the system's operations. This approach facilitated both a cross-sectional analysis and a longitudinal comparison of the utility of energy storage under diverse environmental conditions, thereby contributing to the formulation of a comprehensive evaluation model for the utility of energy storage, which, in turn, supports the construction of an efficient and clean new power system.

2. Analysis of the Indicators of the Flexible Regulation of Utility

This study comprehensively considered the effectiveness of energy storage in terms of storage performance, emission reductions, and increased revenue for the power system. Through a literature review [12–14], consultation with experts, and a project report analysis, it constructed a comprehensive evaluation index system for the utility of energy storage power plants participating in the electricity market's flexible adjustment, as shown in Figure 2. The evaluation index system constructed in this study consists of three parts, including the utility of energy storage, social welfare benefits, and the incremental revenue effects of power systems, which were further divided into 10 secondary indicators. The detailed explanations of the index system are given below.

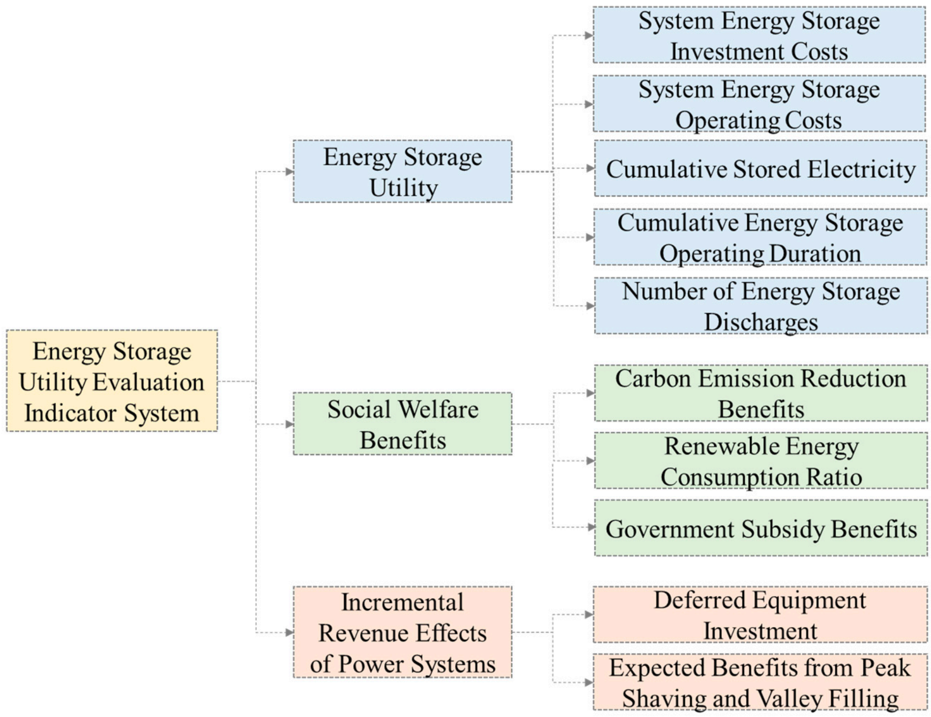

Figure 2. Evaluation index system of the flexible regulation of the utility of energy storage power plants.

2.1. Utility of Energy Storage

2.1.1. The System's Energy Storage Investment Cost

In the process of evaluating the utility of energy storage, it is desirable for the system to incur minimal costs to meet the substantial flexible adjustment demands. Hence, lower investment and operational costs of the energy storage system are preferable. The corresponding cost calculation model is as follows

$$C_{construction-in} = (\beta_1 \times \overline{P_{es}} + \beta_2 \times \overline{E_{es}}) \times \frac{\chi(1+\chi)^{T_{es}}}{(1+\chi)^{T_{es}} - 1} \tag{1}$$

where $C_{construction-in}$ represents the total investment cost of energy storage over its entire lifecycle; β_1 and β_2 , respectively, represent the construction costs per unit of rated power and rated capacity for energy storage; $\overline{P_{es}}$ and $\overline{E_{es}}$ represent the rated power and rated capacity of the energy storage station, respectively; χ is the discount rate; and T_{es} is the lifespan of the energy storage station.

2.1.2. The System's Energy Storage Operational Cost

Similar to investment costs, the operational costs of energy storage are determined by the charge and discharge power, as well as the price per unit of operation, as illustrated in Formula (2)

$$C_{om} = \sum_{t=1}^{T} \beta_3 \times (\kappa_{es,dis}(t) \times P_{dis}(t) + \kappa_{es,cha}(t) \times P_{cha}(t)) \tag{2}$$

where C_{om} denotes the operational and maintenance costs of the energy storage station; β_3 represents the per-unit operational cost of the energy storage unit; $P_{dis}(t)$ and $P_{cha}(t)$, respectively, are the generation and charging power of the energy storage unit at time t; and $\kappa_{es,dis}(t)$ and $\kappa_{es,cha}(t)$, respectively, are the constraint variables for the operational state of energy storage. If the energy storage is discharging, then $\kappa_{es,dis}(t) = 1$, $\kappa_{es,cha}(t) = 0$; if it is charging, then $\kappa_{es,dis}(t) = 0$, $\kappa_{es,cha}(t) = 1$; if it is not activated, then $\kappa_{es,dis}(t) = 0$, $\kappa_{es,cha}(t) = 0$.

2.1.3. Cumulative Amount of Energy Storage

The cumulative amount of energy storage reflects the total amount of electricity stored during the flexible adjustment period, indicating the energy storage's capacity of flexible adjustment. Its calculation method is shown in Formula (3)

$$P_{cha}^{total} = \sum_{t=1}^{T} (1-\eta_1) P_{cha}(t) \times \Delta t \tag{3}$$

where P_{cha}^{total} represents the total electricity stored within the system during a given period, and η_1 is the system's leakage coefficient.

2.1.4. Cumulative Operational Duration of Energy Storage

The cumulative duration of energy storage refers to the total operational duration of the energy storage within the system, measured in hours. Its calculation formula is shown in Formula (4):

$$T_{ess}^{total} = \sum_{t=1}^{T} (\kappa_{es,dis}(t) \times \Delta t + \kappa_{es,cha}(t) \times \Delta t) \tag{4}$$

2.1.5. Number of Energy Storage Discharges

The number of charging and discharging cycles of energy storage demonstrates its participation in flexible adjustment, further illustrating its contribution to flexible adjustment. The calculation method is as shown in Formula (5):

$$U_{ess}^{dis} = \sum_{t=1}^{T} (\kappa_{es,dis}(t)) \tag{5}$$

2.2. Social Welfare Outcomes

2.2.1. Effectiveness of Reducing Carbon Emissions

With a high proportion of renewable energy integrated into the new power system, the system's supply variability and instability will significantly increase. The participation of energy storage in the flexible adjustment of the power system can reduce the frequency of operation of traditional energy sources to a certain extent, implementing a flexible substitution plan for traditional energy. The calculation method is shown in Formula (6):

$$C_{carbon} = \sum_{t=1}^{T} c_{carbon} \times P_{dis}(t) \tag{6}$$

2.2.2. Absorption Rate of Renewable Energy

Due to the variability and uncertainty of renewable energy, phenomena such as curtailment of wind and solar energy frequently occur during the operation of the power system. The involvement of energy storage in adjustments to the power system can further reduce the occurrence of the aforementioned situations, thus enhancing the utilization rate of renewable energy. Therefore, the absorption rate of renewable energy can serve as one of the comprehensive evaluation indicators for the utility of applying energy storage. Its calculation method is as shown in Formula (7)

$$F_{res} = \frac{\sum\limits_{t=1}^{T} \left(P_{res}(t) - P_{res}^{cut}(t)\right)}{\sum\limits_{t=1}^{T} P_{res}(t)} \tag{7}$$

where $P_{res}(t)$ represents the actual electricity generated from renewable sources, and $P_{res}^{cut}(t)$ represents the actual amount of renewable energy curtailed.

2.2.3. Government Subsidy Benefits

Faced with the high investment costs of energy storage technology, the government has issued a series of favorable policies, including electricity price subsidies. This study utilized the government's electricity price subsidies to calculate the additional income from energy storage, with the corresponding formula shown in Formula (8)

$$F_{sub} = \sum_{t=1}^{T} P_{dis}(t) \times c_{sub} \tag{8}$$

where $P_{dis}(t)$ represents the discharged power of energy storage at time t, and c_{sub} is the government's subsidized electricity price.

2.3. Enhancement of the Power System's Revenue

2.3.1. Delaying Investment in Equipment

The participation of energy storage in the flexible adjustment of the power system can delay investment in the system's equipment; its benefit function is shown in Formula (9)

$$F_{du} = \lambda \times \delta \times C_{distribution} \times P_{est} \tag{9}$$

where δ represents the fixed depreciation rate for the distribution network's equipment, typically set at 3%; λ represents the charge and discharge efficiency of the energy storage system; $C_{distribution}$ indicates the per-unit capacity cost of the distribution equipment; and P_{est} is the rated power of the energy storage system.

2.3.2. Expected Benefits from Peak Shaving and Valley Filling

Under the influence of time-of-use electricity pricing, energy storage can discharge electricity at peak prices and charge at low prices, thereby achieving arbitrage during peak shaving and valley filling. The calculation formula is presented in Formula (10)

$$F_{up-low} = \sum_{t=1}^{T} \rho_t \times (P_{dis}(t) - P_{cha}(t)) \tag{10}$$

where ρ_t represents the time-of-use electricity price of the power system.

3. Framework of Composite Weights Based on TODIM Utility Evaluation

This section develops an evaluation model for the utility of energy storage participating in the electricity market's flexible adjustment during the construction of new power systems. The model uses a composite weighting approach to achieve both subjective and objective weighting of the evaluation indicators and utilizes the TODIM method to calculate the results of evaluating the utility that takes the risk preferences of decision-makers into account. This approach enables the integration of multi-dimensional information, further ensuring the scientific validity and effectiveness of the evaluation's results. The evaluation framework for the utility of energy storage is outlined as follows. Firstly, we clarified the power market system's architecture and the operational status of transactions in different years, organized and collected the annual operational information of the power system to be evaluated, and constructed an initial matrix of the evaluation indicators of the utility of energy storage. Next, we developed a composite weight evaluation matrix for the indicator system. This began by inviting experts from relevant fields to use the analytic hierarchy process (AHP) to perform a subjective analysis of the importance of various indicators within the system of evaluation indicators for the utility of energy storage and calculate the subjective weight values for the respective indicators. Then, based on the variability in the characteristics of the values of the evaluation indicators for the utility of energy storage, we used the entropy weight method to calculate the objective weight values of the indicator system. We constructed a composite weight evaluation matrix using a subjective and objective weight aggregation operator. Further, on the basis of consultation with experts and a literature review, we set the initial values for decision-makers' risk preferences and applied the TODIM method to sort all the indicators' information for the evaluation of the objects under risk preference, obtaining the results of evaluating the utility of energy storage at different renewable energy penetration rates. Finally, we summarized and analyzed the current application status and characteristics of energy storage in the new power system based on the evaluation results of the utility of energy storage, providing recommendations for the further construction and operation of energy storage to governments and power system builders, aiding in the creation of a clean, flexible, and efficient new power system. The related methodology and the process of the evaluation of the utility of energy storage in this study are described below.

3.1. Method for Combining Weights in Assessments of the Utility of Energy Storage

The analytic hierarchy process (AHP) enables the systematic, model-based, and data-driven transformation of complex problems, thereby enhancing the scientific nature of decision-making and reducing the difficulty of decision-making. It has been widely applied across multiple research domains, especially in subjective weighting [15,16]. AHP can simulate human cognitive characteristics during the process of systematically weighting the assessment indicators of the utility of energy storage, primarily through the following steps.

Step 1: Construct an initial judgment matrix for the subjective weighting of indicators. Invite multiple experts to describe the importance of the assessment indicators of the utility of energy storage, using the 1–9 scale method referenced in Table 1 for pairwise comparisons among the different evaluation indicators. For example, for the first-level indicators of Layer A, the initial decision results are shown in Table 2, with each indicator's relative importance to itself being 1.

Table 1. The 1–9 scaling method.

Scaling α_{ij}	Definition
1	Factor i is equally important to factor j
3	Factor i is slightly more important than factor j
5	Factor i is moderately more important than factor j
7	Factor i is significantly more important than factor j
9	Factor i is absolutely more important than factor j
2, 4, 6, 8	Intermediate scaling values between the two judgments
Reciprocal	If the judgment value of factor i compared with factor j is α_{ij}, then $\alpha_{ji} = 1/\alpha_{ij}$

Table 2. Judgment matrix.

A	α_1	α_2	...	α_n
α_1	1	f_{12}	...	f_{1n}
α_2	f_{21}	1	...	f_{2n}
...	...	...	...	...
α_n	f_{n1}	f_{n2}	...	1

Step 2: Solve the judgment matrix of the indicators of the utility of energy storage through the row geometric mean method. This method, represented by Formulas (11) and (12), facilitates the single-level sorting of the secondary evaluation indicators under the primary evaluation indicators of the utility of energy storage.

$$w_i = \sum_{j=1}^{n} \frac{a_{ij}}{n} \tag{11}$$

$$\vec{w} = \{w_1 \quad w_2 \quad w_3 \quad \ldots \quad w_n\}^{\lambda}, i = 1, 2, 3, \ldots, n \tag{12}$$

Step 3: Conduct a consistency check for the weight information of the evaluation indicators of the utility of energy storage. Initially, determine the maximum eigenvalue of the judgment matrix for the evaluation indicators of the utility of energy storage using Formula (13), and perform a consistency test using Formula (14). The consistency of the judgment matrix generally improves as the consistency index (CI) decreases, achieving perfect consistency when CI equals zero. However, due to factors such as objective environmental influences, the decision-maker's decision constraints, and the order of the matrix, evaluating the matrix's CI value in isolation can be somewhat one-sided. Therefore, decision-makers introduce the random index (RI) to further mitigate the inconsistency in the correction factor caused by the matrix's order, with the range of values shown in Table 3.

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(Aw_i)_i}{nw_i}, i = 1, 2, \ldots, n \tag{13}$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{14}$$

$$CR = \frac{CI}{RI} \tag{15}$$

where λ_{max} and n, respectively, represent the maximum eigenvalue and the order of the judgment matrix, and A refers to the judgment matrix of the first-level indicators of Layer A. Generally, when the order of the judgment matrix exceeds 3 and the consistency ratio $(CR) \leq 0.1$, the consistency of the judgment matrix is deemed to be acceptable; otherwise, the judgment matrix must undergo consistency adjustments until the aforementioned condition of consistency is satisfied.

Table 3. The relationship between the value of RI and the order of the judgment matrix.

Order	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI Value	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

As a quintessential objective weighting method, the entropy weight method effectively measures the impact of diversity in the indicators' information on the weighting of the indicator system and has been widely applied across various types of research [17,18]. To comprehensively reflect the subjective and objective weight attributes of the evaluation indicators of the utility of energy storage, this study used the entropy weight method to determine the objective weights of the indicators for evaluating the utility of energy storage participating in flexible adjustment during the construction of new power systems. This may aid in achieving an objective, scientific, and comprehensive expression of the evaluation indicators' information. We set e_i as the entropy of evaluation indicator i, with the calculation formula for e_i shown in Formula (16) [19]. If w_i is the weighted value of the entropy in evaluation indicator i, with $w_i \in [0,1]$, $\sum_{i=1}^{m} w_i = 1$, the calculation formula for w_i is shown in Formula (18), where the characteristics of the values of w_i can further reveal the pattern of changes in the indicators' values.

$$e_i = -\frac{1}{\ln n}\sum_{k=1}^{m}\left\langle \frac{h_{ki}}{\sum\limits_{k=1}^{m} h_{ki}} \times \ln\left(\frac{h_{ki}}{\sum\limits_{k=1}^{m} h_{ki}}\right)\right\rangle e_i \in [0,1\,] \tag{16}$$

$$g_i = 1 - e_i \tag{17}$$

$$w_i = \frac{g_i}{\sum\limits_{i=1}^{n} g_i} \tag{18}$$

To reasonably display both the subjective preferences of decision-makers and the objective attributes of the decision criteria, this study used Formula (19) to aggregate the subjective and objective weights.

$$w_{com} = \alpha_1 \times w_{sub} + \alpha_2 \times w_{ob} \tag{19}$$

3.2. Method of Evaluating the Utility of Energy Storage—The TODIM Method

As an extension of prospect theory, the TODIM method incorporates decision-makers' risk preferences when evaluating the utility of energy storage applications, thereby reflecting the impact of decision-makers' psychological behavior on the results of evaluation and aligning the evaluation's outcomes more closely with the objective evaluation environment [20–22]. By calculating and analyzing the dominance of the evaluation' objects, the TODIM method facilitates the analysis of the approximate dominance levels of different evaluation objects, assisting decision-makers in excavating the horizontal evaluation information. The TODIM evaluation process encompasses three steps [23]: firstly, standardizing the evaluation information as shown in Formulas (20) and (21); secondly, calculating the relative importance of the indicators as indicated in Formula (22); and lastly, using the dominance function within the TODIM model to calculate the relative dominance of the evaluation objects for the utility of energy storage under each indicator, using the calculation formula presented in Formula (23). The loss aversion coefficient θ represents the decision-makers' attitude towards risk; a lower value indicates a stronger desire to avoid losses. Finally, Formula (24) is used to aggregate the dominance of all evaluation indicators for the alternative options. On the basis of the aggregated results, we can evaluate the strengths and weaknesses of the evaluation objects, and further analyze improvement measures and policy recommendations.

$$x'_{pj} = \left(x_p^+ - x_{pj}\right) / \left(x_p^+ - x_p^-\right), x_{pj} \in C \tag{20}$$

$$x'_{pj} = \left(x_{pj} - x_p^-\right) / \left(x_p^+ - x_p^-\right), x_{pj} \in B \tag{21}$$

$$w_{jr} = \frac{w_r}{\max\{w_j | j = 1, 2, \ldots, m\}} \tag{22}$$

$$\varphi_j(T_p, T_q) = \begin{cases} \sqrt{\frac{d(x_{pj}, x_{qj}) w_{jr}}{\sum_{j=1}^{m} w_{jr}}} & if\ d(x_{pj}, x_{qj}) > 0 \\ 0 & if\ r_{pj} - r_{qj} = 0 \\ -\frac{1}{\theta}\sqrt{\frac{-d(x_{pj}, x_{qj}) \sum_{j=1}^{m} w_{jr}}{w_{jr}}} & if\ d(x_{pj}, x_{qj}) < 0 \end{cases} \tag{23}$$

$$\delta(T_p, T_q) = \sum_{j=1}^{m} \varphi_j(T_p, T_q) \tag{24}$$

where x_{pj} represents the performance score of alternative p with respect to criterion j; x_p^+ and x_p^-, respectively, represent the best and the worst performance scores among all alternatives for criterion j; w_{jr} refers to the weight of criterion j in the context of reference r; C refers to the set of criteria where the alternative p is better than the reference; B refers to the set of criteria where the alternative p is worse than the reference; $\varphi_j\left(T_p, T_q\right)$ is the partial value function for criterion j when comparing alternative T_p with reference T_q; θ is an attenuation factor; $d\left(x_{pj}, x_{qj}\right)$ represents the difference in the performance scores between alternatives p and q for criterion j; and $\delta\left(T_p, T_q\right)$ refers to the overall dominance of alternative T_p over reference T_q across all criteria.

3.3. Quantification Method for the Evaluation Indicators of the Utility of Energy Storage

To facilitate the optimization simulation of a power system's operations and thereby quantify the evaluation indicators of the utility of energy storage, this study constructed the following system optimization model:

$$\max f = F_{up-low} + F_{sub} - C_{carbon} - C_{loss} - C_{in} - C_{con} \tag{25}$$

$$C_{carbon} = \sum_{t=1}^{T} \sum_{i=1}^{I} c_i \times P_{con,i}(t) \tag{26}$$

$$C_{loss} = \left(\eta_w \sum_{t=1}^{T} P_{w,loss}(t) + \eta_s \sum_{t=1}^{T} P_{s,loss}(t)\right) \times \Delta t \tag{27}$$

$$C_{con} = \sum_{i=1}^{I} \sum_{t=1}^{T} \Big((p_{con,fuel} \times Q_{con,i,t}) + (c_{con} \times P_{con,i}(t)) \times \Delta t\Big) \tag{28}$$

Formula (25) has the goal of maximizing the difference between the benefits of flexible adjustment and the costs of flexible adjustment for the system, where F_{up-low} represents the expected benefits from peak shaving and valley filling, F_{sub} represents the government-subsidized income, and C_{carbon}, C_{loss}, C_{in}, and C_{con}, respectively, represent the costs of carbon emissions, wind and solar curtailment, total investment in energy storage, and the operational costs of traditional energy sources. The total investment cost of energy storage includes both investment and operational costs; this paper analyzed coal-fired power plants as a typical traditional energy source.

Formulas (26)–(28) detail the specific calculation methods for various costs, where the calculation methods for F_{up-low}, F_{sub}, and C_{in} are provided in Section 1. In the formulas, c_i represents the per-unit carbon emission cost of the i-th type of traditional energy source;

$P_{con,i}(t)$ represents the power generation of the i-th type of traditional energy source at time t; η_w and η_s, respectively, are the cost coefficients per unit of wind and solar curtailment; $P_{w,loss}(t)$ and $P_{s,loss}(t)$ are the amount of wind and solar curtailment at time t; $P_{con,fuel}$ denotes the per-unit fuel cost of traditional energy sources; $Q_{con,i,t}$ is the consumption of the i-th type of traditional energy source at time t; and c_{con} represents the per-unit variable operational cost.

$$s.t.\ \kappa_{es,dis}(t) + \kappa_{es,cha}(t) \leq 1 \quad (29)$$

$$SOC(t+\Delta t) = (1-\pi_{es})SOC(t) + \eta_c P_{cha,t} \times \Delta t / \overline{E_{es}} - P_{dis,t}\Delta t / \eta_d / \overline{E_{es}} \quad (30)$$

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \quad (31)$$

$$\kappa_{es,dis}(t) \times P_{dis,t,\min} \leq P_{dis,t} \leq \kappa_{es,dis}(t) \times P_{dis,t,\max} \quad (32)$$

$$\kappa_{es,cha}(t) \times P_{cha,t,\min} \leq P_{cha,t} \leq \kappa_{es,cha}(t) \times P_{cha,t,\max} \quad (33)$$

$$E_{es,\min} \leq E_{es}(t) \leq \phi \times \overline{E_{es}} \quad (34)$$

Formulas (29)–(34) outline the operational constraints for energy storage. Formula (29) concerns the operational state constraints of energy storage, where $\kappa_{es,dis}(t)$ and $\kappa_{es,cha}(t)$ represent the variables of the discharge and charge state of energy storage at time t, respectively. Formula (30) depicts the dynamic update of the energy storage system, with $SOC(t)$ representing the percentage of the energy storage's state of charge; π_{es} is the self-discharge rate of energy storage; η_c and η_d are, respectively, the charging and discharging efficiencies of energy storage; and $\overline{E_{es}}$ is the rated capacity of energy storage. Formulas (32) and (33) represent the upper and lower constraints on the discharging and charging power of the energy storage, with $P_{dis,t}$ and $P_{cha,t}$, respectively, denoting the discharging and charging power of the energy storage at time t. Formula (34) imposes a constraint on the capacity for energy storage, where ϕ is the degradation coefficient of capacity.

$$P_s(t) + P_w(t) + \sum_{i=1}^{I} P_{con,i}(t) + (P_{dis,t} - P_{cha,t}) = D(t) + P_{w,loss}(t) + P_{s,loss}(t) \quad (35)$$

$$0 \leq P_{w,loss}(t) \leq \delta_1 \times P_w(t), \forall t \quad (36)$$

$$0 \leq P_{s,loss}(t) \leq \delta_2 \times P_s(t), \forall t \quad (37)$$

$$P_{con,i}(t) \leq P_{con,i}^{\max}(t) \quad (38)$$

Formulas (35)–(38) delineate the operational constraints of the system. Formula (35) is the power balance constraint, where $P_s(t)$ and $P_w(t)$ represent the photovoltaic and wind power outputs at time t, respectively, and $D(t)$ is the load at time t. Formulas (36) and (37) specify the constraints on wind and solar curtailment, with δ_1 and δ_2 representing the maximum allowable rates of wind and solar curtailment, respectively. Formula (38) pertains to the output limitations of traditional energy sources.

3.4. Process of Evaluating the Utility of Energy Storage

To obtain scientifically valid and effective results for the evaluation of the utility of energy storage, this study established an evaluation process for the utility of energy storage based on simulations of multi-scenario system operation, detailed as follows.

Step 1: Calculate the relevant assessment indicators of the energy storage system's flexible adjustment effect using the planning model constructed in Section 2.3.

Step 2: Develop optimized operational scenarios for energy storage technology. Considering the increasing proportion of renewable energy in new power systems, this study proposed different evaluation scenarios for the utility of energy storage based on the proportion of renewable energy, including scenarios where the proportions of renewable energy were 20%, 50%, and 70%. The proportions of renewable energy were set according to expert consultation and industry development reports.

Step 3: Conduct a comprehensive evaluation of the utility of energy storage for different scenarios based on the outcomes of the optimized system's operation using the composite weight-TODIM evaluation model of utility.

Step 4: Analyze the utility of energy storage applications and discuss the utility of energy storage across multiple scenarios. Based on the results of the comprehensive the utility of energy storage evaluation, initially analyze the utility of energy storage in different scenarios to explore further applications and development directions of energy storage. Then, conduct a comprehensive comparison analysis of the utility of energy storage across different scenarios to establish the value positioning of energy storage in the development and construction process of new power systems with the current technological development levels, laying a theoretical foundation for its scientific investment and optimized operation.

3.5. Analysis of the Error Sources of the Comprehensive Evaluation Method

This study's comprehensive evaluation methodology primarily encompassed two components: computation of the weights and the calculation of evaluation indices of storage. Consequently, the primary sources of error in the aforementioned comprehensive evaluation method were as follows.

(1) The construction of assessment indicators for the value of storage and the computation of weights in this study involved subjective elements. Variations among decision-makers in determining the subjective indicators and weights may lead to discrepancies in the evaluation's outcomes, which can be interpreted as a form of error.

(2) In the operational-level assessment model of the value of storage, simplifications related to modeling storage and simulation of the system's operation may be necessary to ensure the model's solvability, potentially affecting the results of quantifying the value of storage at the operational level.

4. Case Study

Given that new power systems are still under construction and the construction data are not comprehensive, this study used the optimized configuration results of a system's energy storage under the actual annual load with different proportions of renewable energy applications in a specific region as the background. The local actual wind and solar resource endowments served as inputs, providing reliable indicator data as support for the case analysis of the assessment model for the utility of energy storage. The parameter settings refer to [24,25], and the energy storage technology selected for the case study in this research was pumped hydro storage.

The optimized indicator values for energy storage applications under different proportions of renewable energy are illustrated in Figure 3 according to Figure 2, with three first-level criteria and ten second-level criteria. Three experts in the fields of the development of new low-carbon power systems, energy storage system research, and carbon reduction studies were invited to subjectively weight the evaluation indicator system constructed in this study and to calculate the objective weights based on the indicators' values, as shown in Figure 4. Subsequently, the results of the subjective and objective weights were aggregated using Formula (19), and then we formulated the calculation of the degree of dominance if energy storage in different application scenarios. This section exhibits the results of the dominance calculation with 20%, 50%, and 70% permeability compared with other levels of permeability under different criteria, as shown in Figures 5–7. Finally, the TODIM model was applied to conduct a multi-scenario evaluation of the application value of the utility of energy storage in new power systems under different renewable energy application ratios, with the loss aversion coefficient set to 2, and it obtained the comprehensive evaluation results presented in Figure 8.

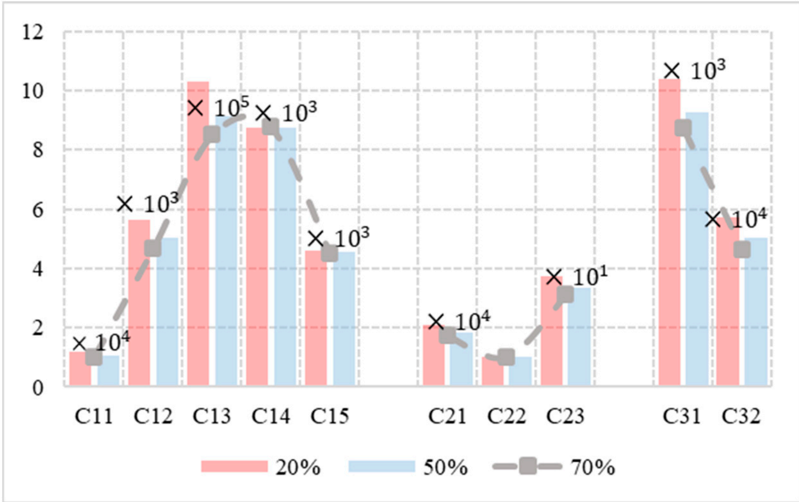

Figure 3. Results of optimization of the evaluation indicators.

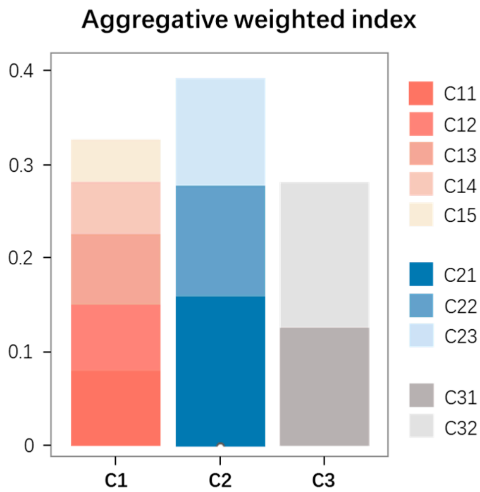

Figure 4. Subjective and objective comprehensive weighting results of the evaluation criteria for the effectiveness of energy storage.

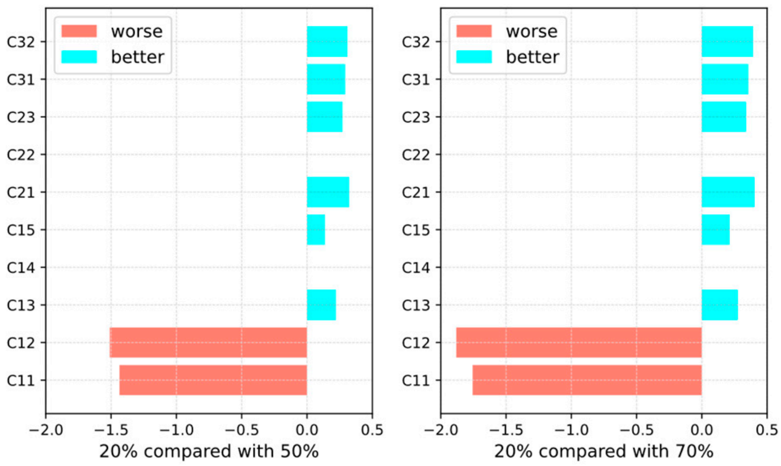

Figure 5. Calculated results of the dominance of 20% permeability compared with other levels of permeability.

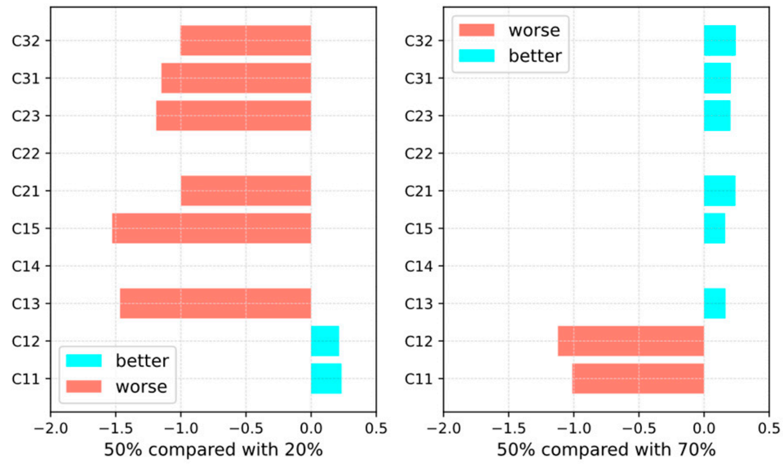

Figure 6. Calculated results of the dominance of 50% permeability compared with other levels of permeability.

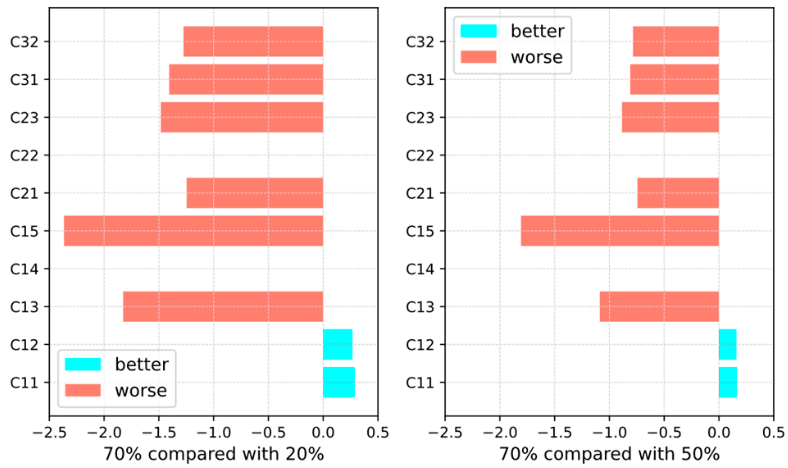

Figure 7. Calculated results of the dominance of 70% permeability compared with other levels of permeability.

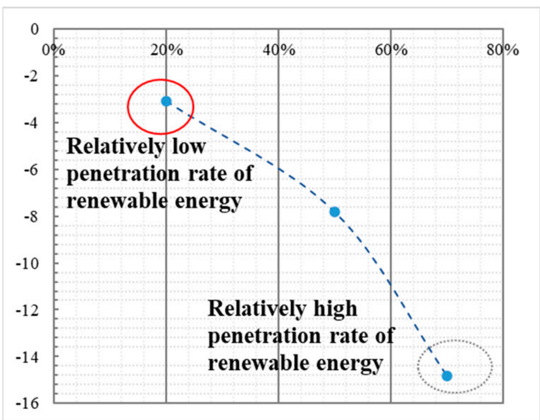

Figure 8. Results of evaluating the utility of energy storage under multiple scenarios.

From the results of calculation, it can be seen that in a single scenario, due to the high investment risk preference of decision-makers, the dominance of the utility of energy storage is negative. This is primarily attributed to the high overall investment costs and the ambiguous returns on investment of energy storage. When we compared the results of evaluating the utility of energy storage across different scenarios, energy storage exhibited higher utility at lower ratios of the application of renewable energy. As the proportion of application of renewable energy increases, the complementary characteristics of photovoltaic and wind power generation will be further highlighted. The scale benefits of renewable energy generation can be further developed, and the combined application of energy storage with traditional units, as well as reasonable wind and solar curtailment strategies, will further compensate for the limitations of balancing the system with individual flexibility resources.

Therefore, for power system constructors and the government, there are several areas to enhance the utility of energy storage in application, ensuring the security and reliability of the power supply while improving the system's capability for flexible adjustment.

(1) Technologically enhance the flexibility and response speed of energy storage while reducing its self-discharge rate. From a cost perspective, lower the costs associated with adjustment to alleviate the economic pressure of the initial investments in constructing energy storage stations, and develop diverse financing models, such as public–private partnerships (PPP) and build–operate–transfer (BOT) schemes. In terms of profit, expand the methods for recovering energy storage costs by reasonably allocating market profits through assessments of the value of flexibility.
(2) Considering resource endowments, exploit the complementary advantages of multiple flexibility resources, including traditional power units, energy storage stations, thermal storage facilities, gas storage facilities, appropriate wind and solar curtailment strategies, and demand response strategies, to build a clean, reliable, and convenient flexible adjustment system, and establish effective incentive mechanisms.
(3) Promote the large-scale construction of renewable energy sources, harness the complementary capabilities of wind and solar generation curves to stabilize the scale of construction of energy storage stations, and reduce the decline in resource utilization caused by excessive and disorderly construction. Thus, from the perspective of external environmental changes, enhance the utility of energy storage in applications.

5. Conclusions

To comprehensively evaluate the utility of energy storage in participating in the electricity market's flexible adjustment within new power systems under varying application ratios of renewable energy, this study initially established a comprehensive system of evaluation indicators for the utility of energy storage. Considering the impact of decision-makers' risk preferences on the evaluation's outcomes, an evaluation model for the utility of the flexible adjustment of energy storage based on composite weights and TODIM was constructed, using the attenuation coefficient in TODIM to reflect the heterogeneity of risk preferences across different types of energy storage. The model's validity and feasibility were verified through a case study analysis.

The evaluation's results indicated that when the application ratio of renewable energy is low, the complementary characteristics of renewable energy sources are not fully manifested, resulting in higher utility from flexible adjustments of energy storage. Conversely, as the application ratio of renewable energy significantly increases, the internal complementary features of renewable energy sources become more pronounced, leading to a decrease in the advantage of the utility of flexible adjustments to energy storage compared with scenarios with lower proportions of renewable energy. On the basis of these results, the study proposes policy recommendations for further promoting the construction of clean, flexible, and reliable new power systems, serving the planning of power systems and governmental decision-making. However, there were still certain limitations in this study. The research object of this study was the utility of existing energy storage technology applications, proposing strategies to improve the efficiency of applying energy storage resources. In the future, we will study the pre-construction planning issues of energy storage projects, including selecting which energy storage technology can further enhance the value of meeting requirements of flexible responses.

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