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Multi-Level Coordination-Level Evaluation Study of Source-Grid-Load-Storage Based on AHP-Entropy Weighting

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Abstract

With the development of the power system, the ability to present a comprehensive and reasonable evaluation of its coordination level has become important for the collaborative optimization of source-grid-load-storage. By identifying uncertain risk factors fully, the present work develops a multi-level coordination-level evaluation of source-grid-load-storage based on AHP-entropy weighting. Building on previous studies, the present work reflects interactive characteristics of the collaborative optimization of source-grid-load-storage. Meanwhile, to determine the indicator weighting more reasonably, AHP-entropy weighting is adopted; this method combines the advantages of subjective AHP weighting and objective entropy weighting. Firstly, the multi-level coordination-level evaluation of source-grid-load-storage is introduced and includes both direct factors and indirect factors. Next, based on AHP-entropy weighting, the indicator weighting of the multi-level coordination-level evaluation is determined. Lastly, a case study is conducted that involves evaluating the coordination levels of the power systems of three regions. Additionally, the effectiveness of the multi-level coordination-level evaluation of source-grid-load-storage is validated.

Keywords: AHP-entropy weighting; coordination-level evaluation; power system; source-grid-load-storage

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1. Introduction

With the development of the power system, energy flow and information flow have become deeply integrated and include the operation and regulation of energy sources, power grids, load resources, and energy storage [1–6]. To address the growing integration of renewable energy sources and storage systems into distribution networks, Simonic et al. [4] investigated the impact of integrating residential rooftop photovoltaic (PV) systems and battery energy-storage systems (BESSs) into low-voltage (LV) distribution networks. To enhance the fault ride-through (FRT) ability of large-scale wind farms (WFs) while reducing wind-power losses during the fault conditions, Wei et al. [6] proposed an optimal-coordinated post-event voltage-control (OPVC) scheme with energy storage boundary analysis. However, the integration of a number of renewable energy sources into power grids, the participation of flexible load resources, and the application of new energy storage technologies bring a series of uncertain risk factors, which affect the coordination level of the power system significantly [7–12]. Therefore, it is important to develop the capacity for a comprehensive coordination-level evaluation of the power system.

Given the aim of collaborative optimization of source-grid-load-storage, the comprehensive coordination-level evaluation of the power system is studied widely [13–20]. To address the effects of large-scale intermittent consumption of renewable energy and power-load instability on power-grid dispatching, Huang et al. [13] developed an optimal dispatching strategy for a multi-source complementary power-generation system that takes source–load uncertainty into account. To cope with the efficient consumption and flexible regulation of resource scarcity that arises due to grid integration of renewable energy sources, Mi et al. [14] presented a scheduling strategy that takes into account the coordinated interaction of source, grid, load, and storage. Considering the complementary nature of flexible carbon-capture systems (FCCS) and hydrogen-storage systems (HSS) in terms of rotating standby and time-shift characteristics, Zhao et al. [15] developed a source–storage–load flexible scheduling strategy. Considering wind and photovoltaic power-generation systems, Wang et al. [16] presented a new method for power-system planning, the collaborative planning of source–grid–load–storage. To improve the system's ability to absorb large-scale renewable energy such as light and wind, Che et al. [17] developed a source-grid-load-storage power system coordinated expansion-planning model that considers demand-response services. To coordinate and control the complementary interactions between the power side and the flexible load side, Qi et al. [18] established a cooperative operation optimization model for the power system source-grid-load-storage based on Gurobi mathematical programming under the dual carbon objective. Based on large-scale system theory, Liu et al. [19] studied the planning method used for distribution-network structures in the centralized-distributed form and the regional source–load coordination planning method, considering the power-probability balance. To realize the better utilization of energy-storage technology for renewable-energy-dominated power systems, Wang et al. [20] proposed a method for planning energy storage that is adapted to the development of renewable-energy-dominated power systems.

The previous comprehensive coordination-level evaluation of the power system was developed based on economy and technology, making it less likely to reflect the interactive characteristics of collaborative optimization among source, grid, load, and storage. By identifying uncertain risk factors fully, the present work develops a multi-level coordination-level evaluation of source-grid-load-storage, which reflects interactive characteristics of the collaborative optimization of source-grid-load-storage. Meanwhile, in developing the multi-level coordination-level evaluation of source-grid-load-storage, indicator weighting is important. Though a series of methods to determine the indicator weighting are presented, including fuzzy analytic hierarchy process, gray relation analysis, inverse entropy weight method, principal component clustering analysis [21–24], the results are unlikely to reflect subjective indicator weighting and objective indicator weighting.

To determine the indicator weighting more reasonably, the AHP-entropy weighting is adopted; this method combines advantages of subjective AHP weighting and objective entropy weighting. The present work develops a multi-level coordination-level evaluation of source-grid-load-storage based on AHP-entropy weighting and is organized as follows. Firstly, the multi-level coordination-level evaluation of source-grid-load-storage is introduced, including direct factors and indirect factors. Next, based on AHP-entropy weighting, the indicator weighting of the multi-level coordination-level evaluation is determined. Then, to validate the effectiveness of the multi-level coordination-level evaluation of source-grid-load-storage, a case study is conducted and the coordination level of the power system of three regions is evaluated. Lastly, the present work is concluded.

2. Multi-Level Coordination-Level Evaluation of Source-Grid-Load-Storage

With the increase in the rate of renewable energy penetration, the energy supply is becoming more diversified [25,26]. Zhan et al. [25] proposed a strategy that aggregated multiple distributed resources, such as distributed photovoltaics, energy storage, and controllable load, emphasizing the coordination and optimization between distributed resources. Li et al. [26] established a new day-ahead optimal dispatching model for a power system with a high proportion of photovoltaic energy sources Firstly, the consumption of the renewable energy is promoted by the development of the energy-storage technology. Secondly, in the demand-response strategy, the user is willing to actively adjust the load based on the power output. Therefore, as the structure of the power system becomes more complex, the coordination level of the power system is significantly affected by a series of uncertain risk factors, including direct factors and indirect factors. The direct factors are divided into single-link and link-interaction factors, where single-link factors include power sources, power grids, load resources and energy storage, link interaction includes source-grid interaction, source-load interaction, source-storage interaction, grid-load interaction, grid-storage interaction, and load-storage interaction. The indirect factors are divided into greenhouse gas emission-reduction benefits and disasters. The power sources are responsible for generating electricity, which is transported to the power grids. To keep the balance between power sources and power grids, the amount of electricity generated by power sources should be equal to the amount of electricity absorbed by power grids. However, different types of power sources are used to generate electricity, including traditional thermal-power plants, water-power plants, and renewable wind or solar power plants. The fluctuation of renewable wind and solar power plants is strong and is affected by environment factors . The balance between power sources and power grids affects the coordination level. Meanwhile, the load resources are not constant, but vary significantly with time. To improve the economy and stability of the power system, achieving balance between power grids and load resources is important. If power generation exceeds load demand, wind and solar energy may be wasted, negatively affecting economic efficiency. Conversely, if load demand exceeds power generation, system stability decreases, impairing the power system's level of coordination.

With the development of energy-storage technology [27,28], the imbalance between power generation and load demand is managed by utilizing the fast charging and discharging capabilities of energy-storage devices. When power generation exceeds load demand, surplus electricity is stored in energy-storage devices; when load demand exceeds power generation, stored electricity is discharged to cover the deficit, thereby improving the power system's level of coordination. To evaluate the economy and stability of the power system, it is necessary to develop the capacity for comprehensive coordination-level evaluation that reflects the level of coordination among power sources, power grids, load resources, and energy storage. To evaluate the economy and stability of the power system, it is necessary to develop a comprehensive coordination-level evaluation method that accurately reflects the interplay among power sources, power grids, load resources, and energy storage. In conducting a comprehensive coordination-level evaluation of the power system, the effects of single-link, link-interaction and indirect indicators on the power system are evaluated quantitatively, providing guidance for planning and optimization decisions and enhancing the coordination of source-grid-load-storage. To conduct the comprehensive coordination-level evaluation of the power system, firstly, the direct and indirect indicators are defined; secondly, the direct and indirect indicators are calculated quantitatively. Meanwhile, in the development of a multi-level coordination-level evaluation of source-grid-load-storage, indicator weighting is important. To determine the

indicator weights more reasonably, the AHP-entropy weighting is adopted; this approach combines advantages of subjective AHP weighting and objective entropy weighting. Lastly, the comprehensive indicator score of the power system is calculated; this score reflects the level of coordination among power sources, power grids, load resources, and energy storage, providing a reference for planning optimization decisions and promoting coordination of source-grid-load-storage. According to the decomposition of direct factors and indirect factors, a multi-level coordination-level evaluation of source-grid-load-storage is developed, as shown in Figure 1.

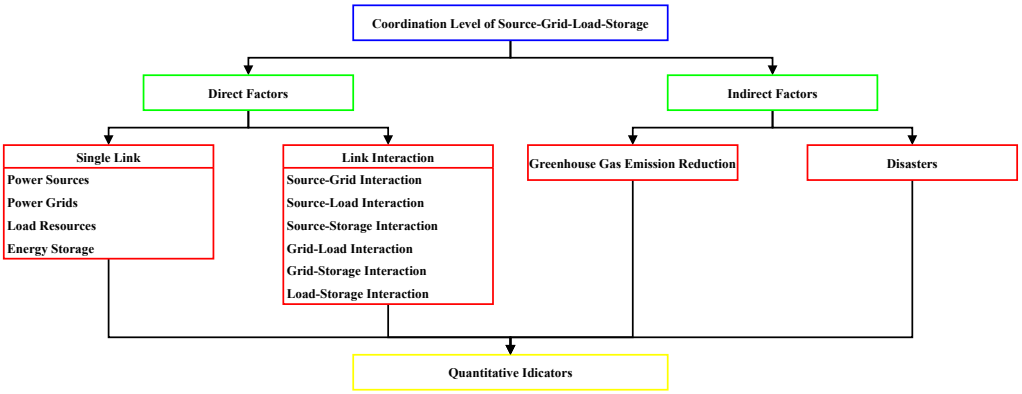


Figure 1. A multi-level coordination-level evaluation of source-grid-load-storage.

Firstly, the direct factors are calculated. Single links include power sources, power grids, load resources, and energy storage. Link interactions include source–grid, source–load, source–storage, grid–load, grid–storage, and load–storage interactions. The indicators of power sources are effect of new energy development F^1_{source}, new energy output fluctuation F^2_{source}, and new energy utilization efficiency F^3_{source}; these are defined as follows:

$$F^1_{\text{source}} = \frac{I^{\text{new}}_{\text{source}}}{I^{\text{total}}_{\text{source}}} \tag{1a}$$

$$F^2_{\text{source}} = \frac{E^{\text{max}}_{\text{source}} - E^{\text{min}}_{\text{source}}}{E^{\text{max}}_{\text{source}}} \tag{1b}$$

$$F^3_{\text{source}} = \frac{E^{\text{actual}}_{\text{source}}}{E^{\text{theoretical}}_{\text{source}}} \tag{1c}$$

where $I^{\text{new}}_{\text{source}}$ is the benefit of new energy development during the evaluation period, $I^{\text{total}}_{\text{source}}$ is the total benefit of the power system, $E^{\text{max}}_{\text{source}}$ is the maximum output of new energy on typical days, $E^{\text{min}}_{\text{source}}$ is the minimum output of new energy on typical days, $E^{\text{actual}}_{\text{source}}$ is the actual output of new energy on typical days, $E^{\text{theoretical}}_{\text{source}}$ is the theoretical output of new energy on typical days. In the present work, the new energy sources mainly include wind and photovoltaic energy, which are characterized by strong randomness. The capacity of wind and photovoltaic constitute the main portion of developed new energy. To calculate the effect of new energy development, we should measure the benefit of new energy development and the total benefit. The benefits of new energy development and the total benefit include economic and environmental benefits. The economic benefit refers to the value of power generated by new energy plants, while the environmental benefit corresponds to the reduction in equivalent carbon emissions, offset by thermal power plants. The indicators for power grids are the ratio of transformer capacity to load F^1_{grid},

fault self-healing rate F^2_{grid}, and cost of grid-structure differentiated planning F^3_{grid}, which are defined as follows:

$$F^1_{\text{grid}} = \frac{E^{\text{total}}_{\text{grid}}}{E^{\text{max}}_{\text{grid}}} \tag{2a}$$

$$F^2_{\text{grid}} = \frac{N^{\text{fault}}_{\text{grid}}}{N^{\text{total}}_{\text{grid}}} \tag{2b}$$

$$F^3_{\text{grid}} = C^{\text{line}}_{\text{grid}} + C^{\text{metal}}_{\text{grid}} + C^{\text{tower}}_{\text{grid}} + C^{\text{trans}}_{\text{grid}} \tag{2c}$$

where $E^{\text{total}}_{\text{grid}}$ is the total transformer capacity of the maximum load, $E^{\text{max}}_{\text{grid}}$ is the maximum load, $N^{\text{fault}}_{\text{grid}}$ is the number of fault self-healing events, $N^{\text{total}}_{\text{grid}}$ is the total fault number, $C^{\text{line}}_{\text{grid}}$ is the construction cost of the lines, $C^{\text{metal}}_{\text{grid}}$ is the cost of the metal and insulators, $C^{\text{tower}}_{\text{grid}}$ is the construction cost of the towers, and $C^{\text{trans}}_{\text{grid}}$ is the construction cost of the transformers. The indicators of load resources are demand-response load rate F^1_{load}, load prediction accuracy F^2_{load}, and load reliability rate F^3_{load}, which are defined as follows:

$$F^1_{\text{load}} = \frac{L^{\text{res}}_{\text{load}}}{L^{\text{total}}_{\text{load}}} \tag{3a}$$

$$F^2_{\text{load}} = \frac{L^{\text{pre}}_{\text{load}}}{L^{\text{pos}}_{\text{load}}} \tag{3b}$$

$$F^3_{\text{load}} = \sum_{i=1}^{n} \omega_i \left(1 - \frac{T_i}{T}\right) \tag{3c}$$

where $L^{\text{res}}_{\text{load}}$ is the demand-response load at the peak load period, $L^{\text{total}}_{\text{load}}$ is the total load, $L^{\text{pre}}_{\text{load}}$ is the predicted load that is consistent with the actual load, $L^{\text{pos}}_{\text{load}}$ is the posterior actual load, n is the number of important loads, ω_i is the ratio of important loads to total loads, T_i is the fault duration time for important loads, and T is the total time. The energy storage indicators are energy storage unit investment F^1_{storage} and energy storage unit operation cost F^2_{storage}, which are defined as follows:

$$F^1_{\text{storage}} = C_{\text{kW}} E_{\text{ES}} C(l, r) \tag{4a}$$

$$F^2_{\text{storage}} = \mu C_{\text{kW}} E_{\text{ES}} \tag{4b}$$

where C_{kW} is the energy storage cost of 1 kW, E_{ES} is the capacity of the energy-storage system, $C(l, r)$ is the coefficient of the investment, l is the service life of the devices, r is the depreciation rate of the devices, and $\mu \approx 0.5\%$ is the daily decay rate. Besides the single-link indicators, the link-interaction indicators are calculated, including source-grid interaction, source-load interaction, source-storage interaction, grid-load interaction, grid-storage interaction, and load-storage interaction. The source-grid interaction indicators are new energy abandonment loss rate $F^1_{\text{source-grid}}$, grid-connected investment rate $F^2_{\text{source-grid}}$, and grid-connected accident loss rate $F^3_{\text{source-grid}}$, which are defined as follows:

$$F^1_{\text{source-grid}} = \frac{E_{\text{abandoned}}}{E_{\text{capacity}}} \tag{5a}$$

$$F^2_{\text{source-grid}} = \frac{C_{\text{con}}}{C_{\text{total}}} \tag{5b}$$

$$F^3_{\text{source-grid}} = \frac{C_{\text{accident}}}{C^{\text{total}}_{\text{accident}}} \tag{5c}$$

where $E_{\text{abandoned}}$ is the abandoned new energy power output, E_{capacity} is the capacity of new energy power output, C_{con} is the investment cost to connect new energy to the grid, C_{total} is the total investment in the grid, C_{accident} is the accident loss caused by the new energy being connected to the grid, and $C_{\text{accident}}^{\text{total}}$ is the total accident loss of the grid. The source-load interaction indicators include the contribution rate of new energy to power interruptions $F_{\text{source-load}}^{1}$, which are defined as follows:

$$F_{\text{source-load}}^{1} = \frac{E_{\text{shortage}}^{\text{before}} - E_{\text{shortage}}^{\text{after}}}{P_{\text{NE}}} \tag{6}$$

where $E_{\text{shortage}}^{\text{before}}$ is the electricity shortage before the new energy is connected to the grid, $E_{\text{shortage}}^{\text{after}}$ is the electricity shortage after the new energy is connected to the grid, and P_{NE} is the capacity of the new energy. The source-storage interaction indicators are new energy fluctuation $F_{\text{source-storage}}^{1}$ and transmission-line overload loss $F_{\text{source-storage}}^{2}$, which are defined as follows:

$$F_{\text{source-storage}}^{1} = \frac{E_{\text{storage}}}{E_{\text{NE}}} \tag{7a}$$

$$F_{\text{source-storage}}^{2} = (C_1 - C_0)E_{\text{G}}h + I_{\text{S}} \tag{7b}$$

where E_{storage} is the regulation capacity of the energy-storage system in the low-load periods, E_{NE} is the capacity of the new energy, C_1 is the on-grid electricity price, C_0 is the unit cost of power generation, E_{G} is the reduced electricity generation caused by the generator faults, h is the duration of the power interruption, and I_{S} is the increased cost of device operation and maintenance. The grid-load interaction indicators are fluctuation in load resources $F_{\text{grid-load}}^{1}$, load difference rate $F_{\text{grid-load}}^{2}$, and cost of a new line $F_{\text{grid-load}}^{3}$, which are defined as follows:

$$F_{\text{grid-load}}^{1} = \frac{L_{\max} - L_{\min}}{L_{\max}} \tag{8a}$$

$$F_{\text{grid-load}}^{2} = \frac{\sigma_{\text{T}}}{\eta_{\text{ave}}} \tag{8b}$$

$$F_{\text{grid-load}}^{3} = \sum_{i \in \Omega_{\text{L}}} L_i n_i m_0 N_i \epsilon \tag{8c}$$

where $L_{\max}$ is the maximum load of the grid, $L_{\min}$ is the minimum load of the grid, σ_{T} is the standard error of the load rate, η_{ave} is the average of the main transformer, L_i is the length of the i-th line, n_i is the number of split lines, m_0 is the weight of the line, N_i is the number of line circuits, ϵ is the price of the line, and Ω_{L} is the set of transmission lines. The grid–storage interaction indicator is the load-shedding loss $F_{\text{grid-storage}}^{1}$, which is defined as follows:

$$F_{\text{grid-storage}}^{1} = \sum (C_i - C_1)E_i h + \sum r_i E_i h + I_{\text{shedding}} \tag{9}$$

where C_i is the price of the i-th type electricity, C_1 is the on-grid electricity price, E_i is the capacity of load shedding, h is the duration of the power interruption, r_i is the power-outage compensation price, and I_{shedding} is the cost of load shedding. The load-storage interaction indicators are load rate $F_{\text{load-storage}}^{1}$ and contribution rate of energy storage to power interruption $F_{\text{load-storage}}^{2}$, which are defined as follows:

$$F_{\text{load-storage}}^{1} = \frac{L_{\text{ave}}}{L_{\max}} \tag{10a}$$

$$F^2_{\text{load-storage}} = \frac{E^{\text{before}}_{\text{shortage}} - E^{\text{after}}_{\text{shortage}}}{E_{\text{ES}}} \tag{10b}$$

where L_{ave} is the average load, $L_{\max}$ is the maximum load, $E^{\text{before}}_{\text{shortage}}$ is the electricity shortage before the new energy is connected to the grid, $E^{\text{after}}_{\text{shortage}}$ is the electricity shortage after the new energy is connected to the grid, and E_{ES} is the capacity of the energy-storage system.

Secondly, the indirect factors are calculated, including greenhouse gas emission-reduction benefits and disaster impacts, which are defined as follows:

$$F^1_{\text{env}} = \frac{\Delta Q_{\text{emi}}}{Q^{\text{initial}}_{\text{emi}}} \tag{11a}$$

$$F^2_{\text{env}} = \frac{\Delta Q_{\text{CO}_2}}{Q^{\text{initial}}_{\text{CO}_2}} \tag{11b}$$

$$F^1_{\text{dis}} = \frac{C_{\text{resist}}}{C_{\text{sys}}} \tag{11c}$$

$$F^2_{\text{dis}} = C_{\text{cut}} + C_{\text{repair}} \tag{11d}$$

where F^1_{env} is the pollutant reduction, F^2_{env} is the cost of the CO_2 emissions penalty, $Q^{\text{initial}}_{\text{emi}}$ is the initial pollutant emissions, ΔQ_{emi} is the reduced pollutant emissions, $Q^{\text{initial}}_{\text{CO}_2}$ is the initial CO_2 emission, ΔQ_{CO_2} is the reduced CO_2 emissions, F^1_{dis} is the investment in disaster resistance, F^2_{dis} is the cost imposed by disasters, C_{resist} is the cost of disaster resistance, C_{sys} is the construction cost of the system, C_{cut} is the power-outage compensation cost, C_{repair} is the cost of repairs after disasters.

3. Ahp-Entropy Weighting Method

After calculating the values of various evaluation indicators, we choose to determine the weights of the indicators, which are the quantitative reflections of the importance of the indicators relative to the evaluation objectives [29–32]. We should point out that use of the reference-point method is unnecessary to determine the weights of the indicators [33,34]. For example, Chintala et al. [33] proposed a new inverse-model-based multiobjective evolutionary algorithm for meter placement in active distribution system state estimation, employing an adaptive reference-point method. However, developing a comprehensive coordination-level evaluation of source-grid-load-storage depends on expert recommendations. To incorporate expert experience, AHP-entropy weighting is adopted, combining the advantages of subjective expert judgment and objective entropy weighting, with indicator weights requiring determination. In developing a comprehensive coordination-level evaluation of source-grid-load-storage, indicator weighting is important; given that need, the analytic hierarchy process (AHP) has been adopted widely.

However, the indicator weighting determined by AHP is significantly influenced by the evaluator's understanding of the evaluation problem, making it a subjective method. To overcome the subjectivity in the indicator weighting of AHP, the entropy weighting method is adopted, as it is more objective. To combine the advantages of AHP and the entropy weighting method, the AHP-entropy weighting method is adopted to determine the indicator weighting to be used in comprehensive coordination-level evaluation. Figure 2 shows the flowchart of the AHP-entropy weighting method. Firstly, construct the hierarchy model of the evaluation object, including the target layer, principle layer, and indicator layer. Secondly, calculate the judgment matrix, where every two indicators are compared. If the importance of the indicator i is equal to that of the indicator j, the value of the judgment matrix $r_{ij} = 1$; if the indicator i is slightly more important than the indicator j, the value of the judgment matrix $r_{ij} = 3$; if the indicator i is clearly important compared to the indicator

j, the value of the judgment matrix $r_{ij} = 5$; if the indicator i is very important compared to the indicator j, the value of the judgment matrix $r_{ij} = 7$; if the indicator i is extremely important compared to the indicator j, the value of the judgment matrix $r_{ij} = 9$. We should point out that the value of the indicator j relative to that of the indicator i is the reciprocal of the value of the indicator i to the indicator j. These are defined as follows: $r_{ji} = 1/r_{ij}$. Thirdly, conduct the consistency test, which is defined as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{12}$$

where CR is the consistency ratio. If $\mathrm{CR} < 0.1$, the consistency of the judgment matrix is accepted; otherwise, the judgment matrix should be corrected.

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{13}$$

is the consistency index, $\lambda_{\max}$ is the maximum characteristic value of the judgment matrix, n is the order of the judgment matrix, and RI is the average random consistency index, which is listed in Table 1.

Table 1. Average random consistency index.

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.52	0.89	1.12	1.26	1.36	1.41	1.46

After the consistency test, calculate the maximum characteristic root $\lambda_{\max}$, which is the indicator weighting, defined as follows:

$$\omega_i^{\mathrm{AHP}} = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i} \tag{14}$$

where ω_i^{AHP} is the indicator weighting of the i-th evaluation indicator determined with AHP. Furthermore, calculate the indicator weighting with the entropy weighting method. First, select the original data matrix, which is defined as follows:

$$\begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \tag{15}$$

where r_{ij} is the j-th evaluation value of the i-th evaluation indicator. Secondly, calculate the characteristic proportion of the evaluation object, as follows:

$$p_{ij} = r_{ij} / \sum_{i=1}^{n} r_{ij} \tag{16}$$

where p_{ij} is the characteristic proportion of the j-th evaluation indicator of the i-th evaluation object. Thirdly, calculate the entropy of the j-th evaluation indicator, which is defined as follows:

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{17}$$

After the calculation of the entropy, the difference coefficient is calculated as follows:

$$\alpha_j = 1 - e_j \tag{18}$$

where α_j is the difference coefficient of the j-th evaluation indicator. Lastly, the entropy weighting is calculated as follows:

$$\omega_j^{\text{entropy}} = \frac{\alpha_j}{\sum_{j=1}^{n} \alpha_j} \tag{19}$$

where $\omega_j^{\text{entropy}}$ is the indicator weighting of the j-th evaluation indicator determined with the entropy weighting method. After the indicator weighting is determined with AHP and entropy weighting, respectively, the AHP-entropy weighting method takes advantage of AHP and entropy weighting, where the complementary indicator weighting is

$$\omega_j^{\text{com}} = \frac{\omega_j^{\text{AHP}} \omega_j^{\text{entropy}}}{\sum_{j=1}^{n} \omega_j^{\text{AHP}} \omega_j^{\text{entropy}}} \tag{20}$$

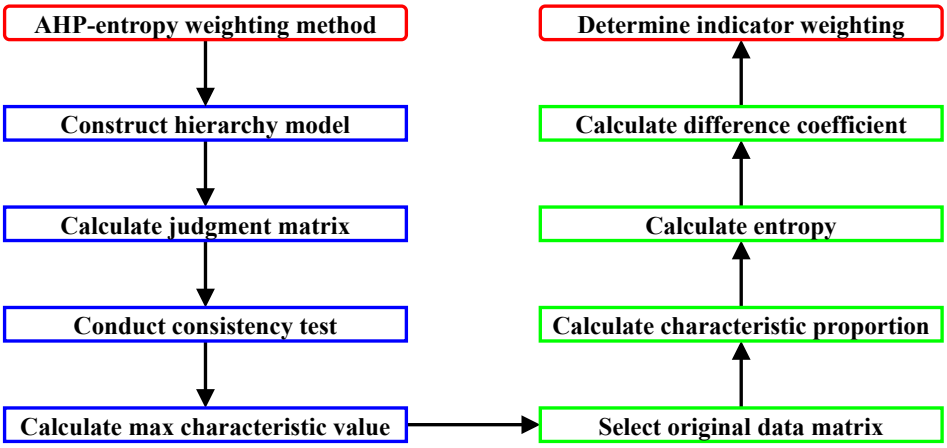


Figure 2. Flowchart of AHP-entropy weighting method.

4. Case Study

To validate the multi-level coordination-level evaluation of source-grid-load-storage, the case study is conducted. With the rapid development of artificial intelligence technologies, data centers have become strategic resources in relation to economic and social development. To promote the green and high-quality development of data centers, developing green power direct supply for data centers is a promising approach. The western region of China is vast, with abundant renewable resources, making it a convenient region in which to conduct the coordination-level evaluation of source-grid-load-storage.

Figure 3 shows wind and photovoltaic output and data-center load on a typical day in Xining City, Qinghai Province. The randomness of wind and photovoltaic output and the fluctuation in the data-center load require balancing; therefore, the fast charging and discharging capabilities of energy-storage devices are useful. As shown in Figure 4, energy-storage devices discharge to compensate for insufficient wind and photovoltaic output during peak load periods; energy-storage devices charge to reduce the amount of abandoned wind and photovoltaic output during low-load periods; where charging power is negative, discharging power is positive.

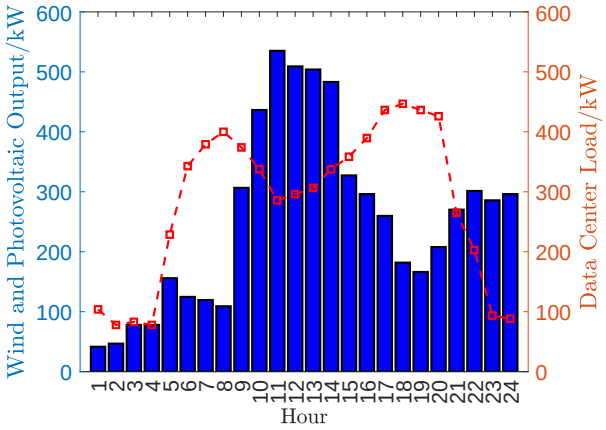


Figure 3. Wind and photovoltaic output and data-center load on a typical day in Xining City, Qinghai Province.

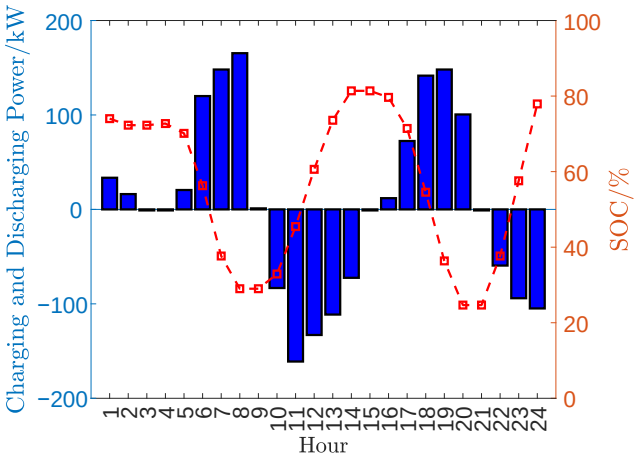


Figure 4. Charging and discharging power and SOC of energy-storage devices on a typical day in Xining City, Qinghai Province.

To conduct the coordination-level evaluation of source-grid-load-storage, three regions were selected. The temperature of region A is low; there, ice-related disasters are prone to occur. The temperature of region B is mild; there, wildfires are the main disaster. The temperature of region C is high; there, the heavy rainfall contributes to landslides. To decrease the subjectivity of the expert input, ten experts from the relevant field are invited to evaluate the coordination level of the three regions, and the values of indicator i relative to indicator j are averaged. Considering the inconsistent dimensions of indicators and the coexistence of cost and benefit indicators in the indicator system, the indicators are nondimensionalized. For cost indicators $x_j^- \geq 0$, the lower the value, the lower the coordination level of the evaluation object. For benefit indicators $x_j^+ \geq 0$, the higher the value, the higher the coordination level of the evaluation object. Use the min-max method to nondimensionalize the indicators, which are defined as follows:

$$X_j^- = \frac{\max(x_j^-) - x_j^-}{\max(x_j^-) - \min(x_j^-)} \tag{21a}$$

$$X_j^+ = \frac{\max(x_j^+) - x_j^+}{\max(x_j^+) - \min(x_j^+)} \tag{21b}$$

where X_j^- is the nondimensionalized cost indicators and X_j^+ is the nondimensionalized benefit indicators. The indicator weightings for single links and link interactions among

direct factors are listed in Tables 2 and 3. Based on the data in Tables 2 and 3, the indicator weightings for both single links and link interactions passed the consistency test.

Table 2. Indicator weightings of single links for direct factors.

Single Link	Characteristic Vector	Indicator Weighting	Maximum Characteristic Value	CI
power sources	0.415	8.296%	5.114	0.029
power grids	2.613	52.26%		
load resources	1.154	23.07%		
energy storage	0.253	5.057%		

Table 3. Indicator weightings of link interactions for direct factors.

Link Interaction	Characteristic Vector	Indicator Weighting	Maximum Characteristic Value	CI
source-grid	0.429	7.140%	3.000	0.000
source-load	0.857	14.28%		
source-storage	1.714	28.57%		
grid-load	1.000	14.28%		
grid-storage	0.500	7.140%		
load-storage	2.000	28.57%		

Adopting the AHP-entropy weighting method, the complementary indicator weightings for these three regions, including single link, link interaction, and indirect indicators, are calculated and listed in Table 4. According to Table 4, the scores of single-link and link-interaction indicators for region C are relatively low, mainly due to the unreasonable location and capacity of new energy grid connections under the district's planning scheme. The association of the highest indirect indicator score with region B is due to this region's having the largest proportion of new energy installed capacity, a high environmental indicator score, and relatively lower impact from natural disasters, which results in a high disaster indicator score. Due to climate factors, natural disasters occur more frequently in regions A and C, leading to higher disaster-loss indicators and greater investment in disaster prevention, which affect overall safety and the economy. The final evaluation results, as per the weight calculation of the comprehensive coordination-level quantification value, are listed in Table 5. Overall, under the planning scheme, the system coordination in regions A, B, and C is at a general level, with the schemes for regions A and B being relatively reasonable. The comprehensive index score of region B is the highest, which means that under the planning scheme of region B, the level of coordination and interaction among sources, grids, loads, and storage is relatively the highest due to the low frequency of natural disasters and relatively safe operating environment in the region. The relatively low score of the planning scheme of region C is due to the high weights of indicators, such as fluctuations in new energy output, rate of investment in grid-connected technology, fluctuation in the power-supply load, and the contribution of energy storage to power interruption, which contribute significantly to the overall score. However, these values for region C are relatively small, resulting in a low comprehensive indicator score. To improve the coordination level of the power system, these indicators should be given special attention in planning and corresponding improvement measures should be proposed and implemented. For example, investment in grid-connection technology can reduce the impact of power electronic devices on the grid, lower the impact on power quality, improve the response mechanisms of controllable loads to effectively track new energy output, and add energy-storage devices of appropriate capacity to stabilize the uncertainty of sources and loads.

Table 4. Calculation of the coordination-level evaluation indicators.

Region	Single Link	Link Interaction	Indirect Indicators
A	0.585	0.593	0.773
B	0.606	0.595	0.783
C	0.542	0.530	0.765

Table 5. Final evaluation results of three regions.

Region	Comprehensive Indicator Score	Coordination Level Evaluation
A	0.627	slightly high
B	0.631	slightly high
C	0.582	medium

5. Conclusions

A comprehensive and reasonable coordination-level evaluation of source-grid-load-storage is developed to guide the optimization planning of the new energy power system. The present work integrates various factors that affect the coordination level of the power system and constructs a hierarchical evaluation index system with multiple interactions. Through the establishment of mathematical models of various indicators, a source-grid-load-storage coordination-level evaluation based on AHP-entropy weighting is presented. The coordination-level evaluation is validated by comprehensively assessing the reasonableness of the actual planning schemes from three regions, providing a reference for planning optimization decisions and promoting the coordination level of source-grid-load-storage.

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