Article

Power Generation Performance Indicators of Wind Farms Including the Influence of Wind Energy Resource Differences

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Abstract: The accurate evaluation and fair comparison of wind farms power generation performance is of great significance to the technical transformation and operation and maintenance management of wind farms. However, problems exist in the evaluation indicator systems such as confusion, coupling and broadness, and the influence of wind energy resource differences not being able to be effectively eliminated, which makes it difficult to achieve the fair comparison of power generation performance among different wind farms. Thus, the evaluation indicator system and comprehensive evaluation method of wind farm power generation performance, including the influence of wind energy resource differences, are proposed in this paper to address the problems above, to which some new concepts such as resource conditions, ideal performance, reachable performance, actual performance, and performance loss are introduced in the proposed indicator system; the combination of statistical and comparative indicators are adopted to realize the quantitative evaluation, indicator decoupling, fair comparison, and loss attribution of wind farm power generation performance. The proposed comprehensive evaluation method is based on improved CRITIC (Criteria Importance through InterCriteria Correlation) weighting method, in which the uneven situation of different evaluation indicators and the comprehensive comparison of power generation performance among different wind farms shall be overcome and realized. Several sets of data from Chinese wind farms in service are used to validate the effectiveness and applicability of the proposed method by taking the comprehensive evaluation models based on CRITIC weighting method and entropy weighting method as the benchmarks. The results demonstrated that the proposed evaluation indicator system works in the quantitative evaluation and fair comparison of wind farm design, operation, and maintenance and traces the source of power generation performance loss. In addition, the results of the proposed comprehensive evaluation model are more in line with the actual power generation performance of wind farms and can be applied to the comprehensive evaluation and comparison of power generation performance of different wind farms.

Keywords: wind farms; power generation performance; wind energy resource differences; comprehensive evaluation; improved CRITIC weighting method

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1. Introduction

Under the strategic goal of building a new power system with new energy as the main body, China's wind power industry will enter a new era of rapid development [1]. The simultaneous development of incremental and stock wind power installation will be an important development feature in the future. The stock wind farms have the advantages of large installed scale and excellent wind energy resources. However, due to the lack of experience in early wind turbine manufacturing, wind turbine selection, and wind farm operation and maintenance management, some in-service wind farms do not fully exploit the advantages of wind energy resources with high quality and have a great space for

performance improvement. Moreover, some wind turbines with a long service time have experienced the problems of declining equipment health and increased failure frequency, and it is urgent to improve power generation performance through technical transformation. Therefore, how to improve the quality and efficiency of huge stock wind power assets has become a new challenge to be solved by practitioners in the field of wind power. Wind farm power generation performance evaluation is used to quantitatively evaluate the actual power generation performance and its deviation from the ideal power generation performance of wind farms, tracing the source of power generation performance loss and determining the performance improvement space through technical transformation and operation and maintenance management, which can provide reliable data support for technical transformation and operation and maintenance management of wind farms. In addition, the comparison of the power generation performance among different wind farms can lead the production and operation activities of the wind power industry to the way of low cost and high efficiency and comprehensively improve the operation and management level of the wind power industry.

Many scholars have conducted corresponding studies on wind farm power generation performance evaluation, which are mainly divided into two fields: indicators method optimization and indicators system establishment. For indicators method optimization, Guo et al. [2] proposed the concept of theoretical power generation completion rate and the corresponding calculation method for the evaluation of offshore wind farms performance. Dong et al. [3,4] constructed the efficiency cloud and performance cloud models of wind turbines and used cloud characteristic parameters to quantitatively evaluate the operation efficiency and performance of wind turbines. Aldersey et al. [5] used the capacity factor to measure the power generation performance of offshore wind farm and analyzed the inter-year and intra-year variability of capacity factor. Lo et al. [6] used capacity factor to measure the operation performance of wind farms and discussed the relationship between the operation performance of wind farms and key factors such as resource area, regional location, and scale. Niu et al. [7] made a comparative analysis of the correlation, consistency, and representation of three efficiency measurement indicators such as wind farm availability, power generation efficiency, and power coefficient from the aspects of probability distribution, pairwise difference, and linear correlation.

The above improved indicators have different emphases and application scenarios, which can only reflect partial characteristics of wind farms and cannot comprehensively evaluate the performance of wind power generation. For indicators system establishment, wind farm operation indicator system stipulated in the industry standard “Guide for wind farm operation index evaluation” issued by the National Energy Administration of China involves four aspects: electricity indexes, equipment operation indexes, operation and maintenance indexes, and electric power consumption indexes [8]. Yan et al. [9] constructed a wind turbine operation performance evaluation indicator system from three aspects of wind turbine power curve, availability, and reliability and constructed a wind farm operation performance evaluation indicator system from three aspects of wind farm optimization operation capacity, maintenance efficiency, and other evaluation indicators. Luo et al. [10] constructed a wind farm operation performance indicator system with inherent characteristics, network related characteristics, and operation characteristics as the core. Meng et al. [11] established a multi-level evaluation indicator system for wind farm operation from three aspects of wind energy resource, wind farm operation, and wind farm equipment operation. Pfaffel et al. [12] defined capacity factor, time-based availability, technical availability, energetic availability, failure rate, and mean down time to evaluate the performance and reliability of wind turbines. Zhang et al. [13] established four indicators: energy consumption intensity, energy payback time, energy payback ratio, and energy return intensity to measure the energy performance of inland, coastal, and offshore wind farms. Kulkarni et al. [14] proposed four kinds of evaluation indicators: technical performance, environmental performance, economic performance, and social performance

to evaluate the performance of wind farms. In order to make the summary of the literature review clearer, the summary of the existing indicators is shown in Table 1.

Table 1. The summary of the existing indicators.

Article	Category	Indicators
Guo et al. [2]	Performance indicators	Theoretical completion rate of power output
Dong et al. [3,4]	Performance and efficiency indicators	Performance cloud parameters, efficiency cloud parameters
Niu et al. [7]	Power production efficiency indicators	Availability, power generation efficiency, power coefficient
NB/T 31045-2013. [8]	Electricity indicators	Energy production, on-grid energy, off-grid energy, transformer substation electric power consumption, equivalent full load hours, capacity factor [5,6]
	Equipment operation indicators	Real availability rate, mean time between failure
	Operation and maintenance indicators	Mean time to recovery, mean routine maintenance time, operation and maintenance cost per unit capacity, operation and maintenance cost per kilowatt-hour
	Power consumption indicators	Comprehensive wind farm electric power consumption rate, transformer substation electric power consumption rate, transmission line loss rate, electric power consumption rate for wind farm
Yan et al. [9]	Wind turbine operation performance indicators	Power curve deviation, reachable performance factor of power curve, time-based availability, energetic availability, electricity loss factor, mean time of repair failures
	Wind farm operation performance indicators	Wind farm wake effect control ability, wind turbine life optimization control ability, mean time to repair, comprehensive wind farm electric power consumption rate, transmission line loss rate, spare parts management ability
Luo et al. [10]	Inherent characteristics indicators	Turbulence intensity, effective wind power density, effective wind hour rate, wind turbine distribution coefficient
	Grid-connection characteristics indicators	Active power control ability, reactive power control ability, low voltage ride through ability, power prediction ability, Power quality
	Operation characteristic indicators	Capacity factor, equivalent full load hours, real availability rate, mean time between failure, mean time to repair, mean routine maintenance time, comprehensive wind farm electric power consumption rate, transmission line loss rate
Meng et al. [11]	Wind resource indicators	Mean wind speed, effective wind hour rate, mean effective wind power density (MEWPD),
	Operation indicators	Capacity factor, grid-connection hours, comprehensive wind farm electric power consumption rate
	Equipment operation indicators	Equipment availability, power generation ability, volatility
Pfaffel et al. [12]	Performance and reliability indicators	Capacity factor, time-based availability, technical availability, energetic availability, failure rate and mean down time
Zhang et al. [13]	Energy performance indicators	Energy consumption intensity, energy payback time, energy payback ratio, energy return intensity
Kulkarni et al. [14]	Technical performance indicators	Energy production capacity, feasibility, risk, duration of preparation and implementation phase, technological maturity, reliability, safety, local technical knowhow
	Environmental performance indicators	Investment cost, implementation cost, operation and maintenance cost, service life, economic value, availability of funds
	Economic performance indicators	Pollutant emission (CO ₂), need of waste disposal, land requirements
	Social performance indicators	Social acceptability, policy objectives, labor impact, political acceptance, compatibility with national energy

In summary, many scholars have studied the improved indicators and indicator system related to wind farm power generation performance evaluation, but there are still some problems remaining unsolved:

- (1) The existing improved indicators have different emphases and application scenarios, which can only reflect partial characteristics of wind farms and fail in the comprehensive evaluation of power generation performance of wind farms.
- (2) The existing evaluation indicator systems have problems such as confusion, coupling and broadness, and the influence of wind energy resource differences could not be effectively eliminated, which makes it difficult to achieve the fair comparison of power generation performance among different wind farms.
- (3) The existing evaluation indicator systems cannot trace the causes of wind farm power generation performance loss, which is difficult to effectively guide the technical transformation and operation and maintenance management of wind farms.

To solve the aforementioned problems, the evaluation indicator system and comprehensive evaluation method of wind farm power generation performance, including the influence of wind energy resource differences, are proposed in this paper. The major contributions of this paper are as follows:

- (1) The indicator system including new concepts such as resource conditions, ideal performance, reachable performance, actual performance, and performance loss is constructed, which are not cross coupled in functional characteristics and can maintain the independence, hence realize the quantitative evaluation of wind farm design, operation, and maintenance.
- (2) The comparative indicators based on the wind energy resource and design level of wind farms are proposed, which can effectively eliminate the influence of wind energy resource and design levels differences and achieve the fair comparison of power generation performance among different wind farms.
- (3) The refined performance loss indicators are proposed in a targeted manner to trace the source of power generation performance loss and guide the technical transformation and operation and maintenance management of wind farms.
- (4) The comprehensive evaluation method of wind farm power generation performance based on improved CRITIC weighting method is proposed to overcome the uneven situation of different evaluation indicators and realize the comprehensive comparison of power generation performance among different wind farms.

The remainder of this paper is organized as follows. Section 2 elaborates wind farm power generation performance evaluation indicator system. Section 3 describes the comprehensive evaluation method of wind farm power generation performance based on improved CRITIC weighting method. Section 4 elaborates the case study. Section 5 concludes this paper.

2. Wind Farm Power Generation Performance Evaluation Indicator System

2.1. The Design Principle of Indicator System

Wind farm power generation performance evaluation indicator system is the foundation for the quantitative evaluation and fair comparison of power generation performance among different wind farms. In order to objectively, truly, and effectively evaluate wind farm power generation performance, the constructed indicator system should meet the following basic design principles:

- (1) Purpose. The design purpose of indicator system is the prerequisite and foundation for the existence of indicator system. The construction of any indicator system must have a clear design purpose, and the selected evaluation indicators and the constructed indicator system must meet the purpose of wind farm power generation performance evaluation.
- (2) Science. The design of the indicator system must follow the actual situation of wind farms, which can not only objectively and effectively reflect the power generation

- performance level and development trend of wind farms but also conform to the scientific theory and objective facts that have been proved by practice.
- (3) Independence. The selected indicators should comprehensively reflect the power generation performance level of wind farms. The logical relationship among various indicators shall be ensured. Besides, they should be independent of each other to avoid cross coupling of information.
 - (4) Operability. The definitions and calculation methods of indicators should be simple and easy to understand and quantify. The basic data used for indicators calculation should be easy to obtain in order to make a definite quantitative evaluation of wind farms power generation performance.
 - (5) Comparability. The impact of external conditions shall be considered in the comparison of power generation performance among different wind farms due to the difference in wind energy resource, terrain, and wind turbine type of different wind farms. Therefore, the selected comparative indicators should be reasonable, fair, and comparable to facilitate the fair comparison of power generation performance among different wind farms.

2.2. The Structure Design of Indicator System

The whole life cycle of wind farms can be divided into four stages: planning and design, construction, operation and maintenance management, and decommissioning [15]. The inherent characteristics of wind farms are determined by the planning and design stage, including the macro and micro site selection, wind turbine selection, and optimal layout, etc. Construction mainly includes wind farms road construction, wind turbines hoisting, substation installation, and collecting power lines laying, etc. Operation and maintenance management is the decisive factor affecting the evolution of actual power generation performance, operation life, and economic benefits of wind farms. Decommissioning refers to the dismantlement of wind turbines at one time after wind farms reach their service life, and the dismantlement of all wind farm facilities and the ecological restoration of the site, mainly including the dismantlement, transfer, and recycling of wind farms related equipment.

For in-service wind farms, operation and maintenance management is the dominant factor to affecting wind farm power generation performance, which determines the degree to which the power generation performance is close to the optimal performance under the actual wind energy resource. Therefore, the operation and maintenance management stage is selected as the research stage of wind farm power generation performance evaluation in this paper where the actual power generation performance of wind farms and its deviation from the ideal performance are quantitatively evaluated and the source of power generation performance loss and potential for improvement are determined. Following the five design principles of indicator system and taking energy as the clue and adopting five categories of evaluation indicators, including resource conditions, ideal performance, reachable performance, actual performance, and performance loss, the evaluation indicator system of wind farm power generation performance based on statistical and comparative indicators is constructed, as shown in Figure 1.

As shown in Figure 1, the constructed wind farm power generation performance evaluation indicator system is mainly divided into five categories of evaluation indicators: resource conditions, ideal performance, reachable performance, actual performance, and performance loss. The indicator of resource conditions is mainly used to measure the abundance of available wind energy resource in wind farms, which is the main source of energy conversion in wind farms. Ideal performance, reachable performance, and actual performance are mainly used to measure the power generation performance that all wind turbines of the wind farm can achieve under the design level, the current normal operation state, and the current actual operation state under the condition of actual wind energy resource. The three kinds of evaluation indicators are under the parallel relationship in functional characteristics and correspond to the power generation performance of wind

farms equipment under different health conditions and operating conditions. The operation and maintenance ability of wind farms can be measured by the gap between the three categories of evaluation indicators. The gap between reachable performance and ideal performance mainly measures the maintenance ability of wind farms maintenance staffs, and the gap between actual performance and reachable performance mainly measures the operation and management ability of wind farms. The proposed indicators of performance loss are mainly used to refine the specific reasons for the gap between actual performance and reachable performance, which is complementary to the actual performance, and can be used to guide the technical transformation and operation and maintenance management of wind farms. It should be noted that the wind energy resources of different wind farms are different. It is necessary to eliminate the impact of wind energy resource difference to realize the fair comparison of power generation performance among different wind farms. Therefore, six comparative indicators are proposed to compare the power generation performance of different wind farms by the relative changes of statistical indicators.

Figure 1. Wind farm power generation performance evaluation indicator system.

To sum up, the constructed wind farm power generation performance evaluation indicator system has the following characteristics: (1) The categories of evaluation indicators are not cross coupled in functional characteristics, and their independence can be maintained. (2) The proposed comparative indicators are based on the wind energy resource and design level of wind farms, which can eliminate the influence of wind energy resource and design-level differences and achieve the fair comparison of power generation performance among different wind farms. (3) The proposed indicators of performance loss can refine the specific reasons of performance loss and can effectively guide the technical transformation and operation and maintenance management of wind farms.

2.3. Definitions and Calculation Methods of Indicator

2.3.1. The Indicators of Resource Conditions

The indicators of resource conditions are mainly used to measure the abundance and exploitable utilization of wind energy resource in wind farm area. The available wind energy resource is the most fundamental factor affecting the power generation performance of wind farms. The MEWPD is used to measure the availability of wind energy resource in wind farms.

MEWPD refers to the power of the effective wind speed (between cut-in wind speed and cut-out wind speed, usually 3–25 m/s) in the unit area perpendicular to the wind direction within the statistical period. With the increase of rotor diameter and tower height, the spatial fluctuation of wind speed in the wind wheel sweeping plane is becoming more and more obvious due to the influence of wind shear and tower shadow effect [16]. Hence, the influence of wind shear and tower shadow effect should be considered in the calculation of MEWPD in which wind shear is the main cause of power loss, while tower shadow effect is the main cause of power fluctuation, so the power loss caused by tower shadow can be ignored [17]. Therefore, the rotor equivalent wind speed considering wind shear effect is used to replace the hub height wind speed to simplify the calculation. The specific calculation method is shown in Formulas (1)–(3).

$$W = \frac{1}{N} \sum_{i=1}^N W_i \quad (1)$$

$$W_i = \frac{1}{2T} \sum_{t=1}^T \rho(t) V_i(t)^3 \quad (2)$$

$$\begin{cases} V_i(t) = V_i^H(t) \left[1 + \frac{\alpha(t)(\alpha(t)-1)}{8} \left(\frac{R_i}{H_i} \right)^2 \right] \\ V_i^H(t) = \begin{cases} 0 & V_i^H(t) < V_i^{cut-in}, V_i^H(t) > V_i^{cut-out} \\ V_i^H(t) & V_i^{cut-in} \leq V_i^H(t) \leq V_i^{cut-out} \end{cases} \end{cases} \quad (3)$$

where W is the MEWPD of wind farm within the statistical period; W_i is the MEWPD of the i -th wind turbine within the statistical period; N is the number of wind turbines; T is the number of wind speed data within the statistical period (the statistical period refers to the evaluation period of wind farm power generation performance, which is usually month or year); $\rho(t)$ is the air density at time t , which is calculated by ambient temperature and atmospheric pressure [10]; $V_i(t)$ is the rotor equivalent wind speed of the i -th wind turbine at time t ; $V_i^H(t)$ is the hub height wind speed of the i -th wind turbine at time t , the nacelle transfer function is usually used to correct the nacelle wind speed to hub height wind speed [18]; $\alpha(t)$ is the wind shear coefficient at time t ; R_i and H_i are the rotor radius and hub height of the i -th wind turbine respectively; V_i^{cut-in} and $V_i^{cut-out}$ are the cut-in wind speed and cut-out wind speed of the i -th wind turbine respectively.

2.3.2. The Indicators of Ideal Performance

The indicators of ideal performance are mainly used to measure the maximum power generation performance that all wind turbines of wind farm can achieve according to the design requirements under the actual wind energy resource conditions, which mainly reflects the design, manufacturing, and installation level of wind turbines and the adaptability of wind turbines selection. The designed energy production (DEP) and designed wind energy utilization coefficient (DWEUC) are used to measure the ideal performance of wind farms.

(1) DEP

The DEP refers to the power output of all wind turbines operating at the design level within the statistical period under the actual wind energy resources conditions, which mainly reflects the maximum power generation performance that wind farm can achieve under the actual wind energy resource conditions. The calculation method is shown in Formula (4).

$$E_0 = \sum_{i=1}^N \sum_{t=1}^T f_0(V_i(t)) \Delta t \quad (4)$$

where E_0 is the DEP of wind farm within the statistical period; Δt is the time resolution of wind speed data, and the measurement unit needs to be converted to hour; $f_0(\cdot)$ is the modified dynamic power curve of wind turbine based on actual wind energy resource conditions and wind turbine manufacturer power curve [19,20], which mainly includes air

density correction and turbulence intensity correction, the specific correction methods can be found in [9,21].

(2) DWEUC

The DWEUC refers to the proportion of the DEP to the effective wind energy of wind farm within the statistical period, which mainly reflects the effective wind energy capture capacity of the wind farm and can indirectly measure the adaptability between wind turbines selection and actual wind resource conditions. The calculation method is shown in Formulas (5) and (6).

$$\eta_0 = \frac{E_0}{E} \quad (5)$$

$$E = \sum_{i=1}^N \sum_{t=1}^T \frac{1}{2} \rho_i(t) A_i V_i(t)^3 \Delta t \quad (6)$$

where η_0 is the DWEUC of wind farm within the statistical period; E is the effective wind energy of wind farm within the statistical period, that is, the sum of available wind energy in the sweeping plane of all wind turbines within the statistical period; A_i is the rotor swept area of the i -th wind turbine.

2.3.3. The Indicators of Reachable Performance

The indicators of reachable performance are mainly used to measure the theoretical power generation performance of all wind turbines in the wind farm under actual wind energy resource conditions and current equipment health status. With the increase of wind turbines operation time, their health status and power generation performance will gradually deteriorate, and the power generation performance of wind turbines can achieve complete or partial recovery after overhaul and components replacement. The indicators of reachable performance mainly reflect the reachable power generation performance and maintenance level of wind farms. The reachable energy production (REP) and maintenance performance coefficient (MPC) are used to measure the reachable performance of wind farms.

(1) REP

The REP refers to the theoretical energy production that can be achieved by all wind turbines of the wind farm under the actual wind energy resource conditions and current equipment health status within the statistical period, which mainly reflect the theoretical reachable performance of the wind farm in actual operation. The calculation method is shown in Formula (7).

$$E_1 = \sum_{i=1}^N \sum_{t=1}^T f_1(V_i^N(t)) \Delta t \quad (7)$$

where E_1 is the REP of wind farm within the statistical period; $f_1(\cdot)$ is the wind turbine power curve model based on nacelle wind speed and theoretical power [19]; $V_i^N(t)$ is the nacelle wind speed of the i -th wind turbine at time t .

(2) MPC

The MPC refers to the proportion of the REP to the DEP of wind farm within the statistical period, which mainly measures the maintenance ability of wind farms maintenance staffs and can provide decision-making support for wind turbines renovation and maintenance plan. The calculation method is shown in Formula (8).

$$\eta_1 = \frac{E_1}{E_0} \quad (8)$$

where η_1 is the MPC of wind farm within the statistical period.

2.3.4. The Indicators of Actual Performance

The indicators of actual performance are mainly used to measure the actual power generation performance of all wind turbines of wind farm, which mainly reflect the operation and management ability of wind farms. The actual energy production (AEP) and operation performance coefficient (OPC) are used to measure the actual performance of wind farms.

(1) AEP

The AEP refers to the sum of the actual power generation of all wind turbines of wind farm within the statistical period, which mainly reflect the actual power generation benefits of wind farm. The calculation method is shown in Formula (9).

$$E_2 = \sum_{i=1}^N \sum_{t=1}^T P_i(t) \Delta t \quad (9)$$

where E_2 is the AEP of wind farm within the statistical period; $P_i(t)$ is the actual power of the i -th wind turbine at time t , which is generally obtained from wind turbine supervisory control and data acquisition (SCADA) system.

(2) OPC

The OPC refers to the proportion of the AEP to the REP of wind farm within the statistical period, which mainly measures the operation management ability of wind farms and the potential for power generation performance improvement by improving the operation management ability. This indicator measures the actual power generation level based on the wind energy resource and design level of wind farms, and it can eliminate the influence of wind energy resource and design levels differences. The calculation method is shown in Formula (10).

$$\eta_2 = \frac{E_2}{E_1} \quad (10)$$

where η_2 is the OPC of wind farm within the statistical period.

2.3.5. The Indicators of Performance Loss

In order to realize the power loss attribution and effectively guide the technical transformation and operation and maintenance management of wind farms, the evaluation indicators of performance loss of wind farm power generation are proposed, which mainly include failure loss, regular inspection loss, power limitation loss, and other losses.

(1) Failure loss

The energy production loss due to failure (EPLF) refers to the energy production loss of wind farm due to the shutdown of the on-site equipment failure within the statistical period, mainly including wind turbines failure, substation equipment failure, and collecting power lines failure, etc. For wind turbine, only its own fault is considered. The failure loss coefficient (FLC) refers to the proportion of the EPLF to the REP of the wind farm within the statistical period, which mainly reflects the fault repair ability and spare parts management ability of wind farms. The calculation method of FLC is shown in Formula (11).

$$\eta_f = \frac{E_f}{E_1} \quad (11)$$

where η_f is the FLC of wind farm within the statistical period. E_f is the EPLF of wind farm within the statistical period, which is equal to the sum of the REP in all fault shutdown periods within the statistical period. The start and end time of fault shutdown of each wind turbine can be determined according to the fault statistics reports of wind farms production and operation management system.

(2) Regular inspection loss

The energy production loss due to regular inspection (EPLRI) refers to the energy production loss of wind farm due to the shutdown of the on-site equipment regular inspection within the statistical period, mainly including wind turbines regular inspection, substation equipment regular inspection, and collecting power lines regular inspection, etc. For wind turbine, only its own regular inspection loss is considered. The regular inspection loss coefficient (RILC) refers to the proportion of the EPLRI to the REP of wind farm within the statistical period, which mainly reflects the rationality and execution efficiency of regular inspection arrangement of wind farms. The calculation method of RILC is shown in Formula (12).

$$\eta_i = \frac{E_i}{E_1} \quad (12)$$

where η_i is the RILC of wind farm within the statistical period. E_i is the EPLRI of wind farm within the statistical period, which is equal to the sum of the REP in all regular inspection shutdown periods within the statistical period. The start and end time of regular inspection shutdown of each wind turbine can be determined according to the fault statistics reports of wind farms production and operation management system.

(3) Power limitation loss

The energy production loss due to power limitation (EPLPL) refers to the energy production loss of wind farm due to the dispatching power limitation of power grid within the statistical period. The power limitation loss coefficient (PLLC) refers to the proportion of the EPLPI to the AEP of wind farm within the statistical period, which mainly reflects wind power consumption capacity of the grid dispatching section where the wind farm is located. The calculation method of PLLC is shown in Formula (13).

$$\eta_l = \frac{E_l}{E_1} \quad (13)$$

where η_l is the PLLC of wind farm within the statistical period. E_l is the EPLPL of wind farm within the statistical period, which is equal to the sum of the difference between the REP and the AEP in all power limit periods within the statistical period. In general, each wind farm will send corresponding signals by wind farm automatic generation control (AGC) system during power limiting operation, including specific power limiting time, duration, and power. The power limiting data can be marked with the record of power limiting instructions to directly identify the power limiting data [22]. For wind farms with missing power limiting records, they need to be identified according to the characteristics of operation data after power limiting as an auxiliary method, such as clustering analysis [20,23] and time series analysis [22,24].

(4) Other losses

The energy production loss due to other factors (EPLOF) refers to the energy production loss caused by other off-site factors within the statistical period, such as off-site transmission lines fault, power system fault, bad weather (thunderbolt, freezing, typhoon), and other complex conditions. The other losses coefficient (OLC) refers to the proportion of the EPLOF to the AEP of wind farm within the statistical period. The calculation methods of EPLOF and OLC are shown in Formulas (14) and (15).

$$E_{other} = E_1 - E_f - E_i - E_l \quad (14)$$

$$\eta_{other} = \frac{E_{other}}{E_1} = 1 - \eta_2 - \eta_f - \eta_i - \eta_l \quad (15)$$

where E_{other} and η_{other} are the EPLOF and OLC of the wind farm within the statistical period respectively.

3. Comprehensive Evaluation Method of Wind Farm Power Generation Performance Based on Improved CRITIC Weighting Method

Seven comparative indicators are proposed to compare the power generation performance among different wind farms. However, it is likely that different evaluation indicators are uneven in the practical evaluation process, and it is impossible to quantitatively compare the comprehensive power generation performance levels among different wind farms. Therefore, a comprehensive evaluation method of wind farm power generation performance based on the improved CRITIC weighting method is proposed. It is worth noting that there is a complementary relationship between the OPC and the four performance loss coefficients. In order to eliminate information redundancy, only six comparative indicators except the OPC are selected to evaluate wind farm power generation performance.

3.1. Improved CRITIC Weighting Method

The weight determination methods are mainly divided into subjective and objective weighting method and it is difficult to subjectively determine the importance of the six comparative indicators in the comprehensive evaluation process of power generation performance. Therefore, the objective weighting method is adopted to determine the weight of different comparative indicators. The objective weighting approaches mainly include the entropy weight method [25], principal component analysis method [26], and CRITIC weighting method [27], etc. The entropy weight method mainly takes the discreteness of indicators in data samples to determine the importance of the indicators, ignoring the correlation between different indicators. The principal component analysis method adopts dimension reduction to maintain the independence between variables, but it cannot measure the discreteness of indicators in data samples. However, the CRITIC weighting method takes both the discreteness of indicators and the conflict among different indicators into consideration, and it determines the weight of indicators based on the contrast strength and the conflict among indexes. The strength of contrast is reflected by standard deviation where the larger the standard deviation is, the more information the indicator reflects and the greater the weight. The conflict is reflected by the correlation between indicators where the larger the correlation coefficient, the lower the mutual exclusivity and the lower the weight of the indicator.

The CRITIC weighting method is adopted to calculate the weight of the evaluation indicators after being compared with other methods above in the aspect of applicability and shortcoming. However, the weight determined only by the CRITIC weighting method belongs to the static constant weight evaluation matrix, ignoring the influence of the internal differences of each indicator on the evaluation object, and the phenomenon of state imbalance is prone to occur. When a certain indicator turns into poor or extremely poor, the weight of the indicator is too weak to be reasonably presented, thus the evaluation results are inconsistent with the practical situation and the comprehensive power generation performance level of the wind farm cannot be evaluated effectively. The variable weight theory can maintain the balance of each indicator in the comprehensive evaluation by revising the constant weight on the basis of the deterioration degree of the indicators, which avoids the problems of one-sided and unreasonable evaluation results caused by the constant weight [28]. Therefore, the variable weight theory is applied to improve the CRITIC weighting approach. The specific calculation steps are as follows.

- (1) Establishment of the initial evaluation matrix

Assuming that the numbers of wind farms and indicator to be evaluated are m and n , respectively, the j -th index of the i -th wind farm to be evaluated shall be described as x_{ij} , and the initial evaluation matrix is shown in Formula (16).

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (16)$$

(2) Normalization of the initial evaluation matrix by relative deterioration degree

The initial evaluation matrix is normalized by relative deterioration degree to eliminate the influence of indicators dimension. The relative deterioration degree of an evaluation indicator of the power generation performance reflects the degree of deviation from its optimal state whose range is $[0, 1]$. The larger the indicator value is, the smaller the relative deterioration degree value is.

The calculation method of the relative deterioration degree is shown in Formula (17) for the high-superior evaluation indicators, such as the DWEUC and MPC.

$$x_{ij}^* = \begin{cases} 0 & x_{ij} < \alpha \\ \frac{\beta - x_{ij}}{\beta - \alpha} & \alpha \leq x_{ij} \leq \beta \\ 1 & x_{ij} > \beta \end{cases} \quad (17)$$

where x_{ij}^* is the relative deterioration degree value of the i -th wind farm and the j -th indicator to be evaluated. The range of the corresponding indicator is $[\alpha, \beta]$, which is commonly taken as $[0, 1]$ except for the DWEUC, where the range is $[0, 0.593]$.

For the low-superior evaluation indicators, such as the FLC, RILC, PLLC, and OLC, the calculation method of the relative deterioration degree is shown in Formula (18).

$$x_{ij}^* = \begin{cases} 0 & x_{ij} < \alpha \\ \frac{x_{ij} - \alpha}{\beta - \alpha} & \alpha \leq x_{ij} \leq \beta \\ 1 & x_{ij} > \beta \end{cases} \quad (18)$$

(3) Calculation of the contrast strength of each evaluation indicator

The standard deviation of each evaluation indicator is applied to reflect the contrast strength in the CRITIC weighting method which can be illustrated by Formula (19).

$$S_j = \sqrt{\frac{1}{m} \sum_{i=1}^m (x_{ij}^* - \bar{x}_j^*)^2} \quad (19)$$

where S_j and $\bar{x}_j^*$ are the normalized standard deviation and mean value of the j -th evaluation indicator respectively.

(4) Calculation of the correlation coefficient and quantitative conflict index between the evaluation indicators

The conflict is reflected in CRITIC weighting method by the correlation between the evaluation indicators. The correlation coefficient among the n evaluation indexes shall be calculated firstly to obtain the value of the quantification conflict index. The correlation coefficient between the p -th and the j -th evaluation indicator is shown in Formula (20).

$$\rho_{pj} = \frac{\sum_{i=1}^m (x_{ip}^* - \bar{x}_p^*)(x_{ij}^* - \bar{x}_j^*)}{\sqrt{\sum_{i=1}^m (x_{ip}^* - \bar{x}_p^*)^2} \sqrt{\sum_{i=1}^m (x_{ij}^* - \bar{x}_j^*)^2}} \quad (20)$$

where ρ_{pj} is the correlation coefficient between the p -th and the j -th evaluation indicator; $\bar{x}_p^*$ is the mean value of the p -th evaluation indicator.

The quantitative conflict index of the j -th evaluation indicator and other evaluation indicators can be derived from Formula (21).

$$\lambda_j = \sum_{p=1}^n (1 - \rho_{pj}) \quad (21)$$

(5) Calculation of the constant weight values of the evaluation indicators

Firstly, the comprehensive information coefficient C_j of the j -th evaluation indicator is derived from the standard deviation and quantitative conflict index obtained respectively according to steps (3) and (4), shown in Formula (22). Then, the constant weight value w_j^0 of the j -th evaluation indicator is obtained according to the comprehensive information coefficient C_j , shown in Formula (23).

$$C_j = S_j \lambda_j = S_j \sum_{p=1}^n (1 - \rho_{pj}) \quad (22)$$

$$w_j^0 = \frac{C_j}{\sum_{j=1}^n C_j} \quad (23)$$

(6) Calculation of the variable weight values of the evaluation indicators by variable weight theory

The variable weight theory is adopted to revise the constant weight values, and the calculation method is shown in Formula (24).

$$w_{ij} = w_j^0 (1 - x_{ij}^*)^{T-1} / \sum_{k=1}^n w_k^0 (1 - x_{ik}^*)^{T-1} \quad (24)$$

where w_{ij} is the variable weight value of the i -th wind farm and the j -th indicator to be evaluated; T is the variable weight coefficient, which is taken as 0.5 in this paper; w_k^0 is the constant weight value of the k -th evaluation indicator; x_{ik}^* is the relative deterioration degree value of the i -th wind farm and k -th indicator to be evaluated.

3.2. Modeling Process

The modeling process of the comprehensive evaluation model of wind farm power generation performance based on the improved CRITIC weighting approach is shown in Figure 2, and the specific steps are as follows.

- (1) Collecting the operating data of the wind farm to be evaluated, which mainly includes wind farm operation management system data, wind farm AGC system data (if any), wind turbine SCADA system data, anemometer tower data, wind turbine nacelle transfer function or lidar wind data, wind turbine design parameters (such as designed wind turbine power curve, hub height, rotor radius, etc.).
- (2) Calculating the power generation performance evaluation indicators matrix of the wind farm, which mainly includes six comparative indicators such as the DWEUC, MPC, FLC, RILC, PLLC, and OLC.
- (3) Determining the comprehensive fuzzy evaluation level of the wind farm power generation performance, which is mainly divided as $L = \{L_1, L_2, \dots, L_n\}$. Among which, the larger the value n is, the more detailed the evaluation object is, and the more it can reflect the fuzziness and gradual change of the fuzzy evaluation. However, the greater the complexity and calculation of the model, it is necessary to consider the accuracy of the evaluation results and the complexity of the evaluation process. According to

the practical needs of wind farm power generation performance evaluation, four evaluation levels are selected in this paper, namely $L = \{Excellent, Good, Medium, Poor\}$.

- (4) Calculating the relative degradation degree matrix g of the wind farm power generation performance evaluation indicators. Each evaluation indicator is normalized to obtain the deterioration degree matrix based on the concept of relative deterioration degree and the differences of indexes. The calculation steps are the same as those of the improved CRITIC weighting method in step (2) and the relative deterioration degree matrix g is shown in Formula (25).

$$g = \begin{bmatrix} x_{11}^* & x_{12}^* & \cdots & x_{1n}^* \\ x_{21}^* & x_{22}^* & \cdots & x_{2n}^* \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1}^* & x_{m2}^* & \cdots & x_{mn}^* \end{bmatrix} \quad (25)$$

where x_{mn}^* is the relative deterioration degree value of the m -th wind farm and the n -th indicator to be evaluated.

- (5) Determining the membership function. The triangular and semi-trapezoidal functions are adopted as the membership functions [29] in this paper, and the fuzzy decomposition interval of membership function is determined according to relevant criteria and expertise. The membership degree matrix corresponding to each evaluation level is obtained according to the relative deterioration degree of each indicator, and the membership matrix of the i -th wind farm to be evaluated is shown in Formula (26).

$$v_i = \begin{bmatrix} v_1^{i,1} & v_1^{i,2} & \cdots & v_1^{i,k} \\ v_2^{i,1} & v_2^{i,2} & \cdots & v_2^{i,k} \\ \vdots & \vdots & \ddots & \vdots \\ v_n^{i,1} & v_n^{i,2} & \cdots & v_n^{i,k} \end{bmatrix} \quad (26)$$

where $v_n^{i,k}$ is the membership degree of the i -th wind farm and the n -th indicator belongs to the rank L_k , and k was taken as 1, 2, 3, 4 in this paper.

- (6) Determining the variable weight values of the evaluation indicators by the improved CRITIC weighting method, of which the calculation steps are illustrated in Section 3.1, as shown in Formula (27).

$$w = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_{m1} & w_{m2} & \cdots & w_{mn} \end{bmatrix} \quad (27)$$

- (7) Calculating the fuzzy comprehensive evaluation grade matrix of the wind farm power generation performance and the fuzzy comprehensive evaluation grade matrix of the i -th wind farm to be evaluated is shown in Formula (28).

$$B_i = w(:,1) \cdot v_i \quad (28)$$

- (8) Determining the fuzzy comprehensive evaluation results of power generation performance of wind farm by adopting the maximum membership principle.

Figure 2. Modeling process of wind farm power generation performance comprehensive evaluation model.

4. Case Study

4.1. Data

The effectiveness and applicability of the proposed approach are verified based on the measured data from 14 wind turbines of wind farm in Northwest China and six wind farms in Northeast China. The data types mainly include the fault statistics reports of wind farms production and operation management system, wind turbine SCADA system data, anemometer tower data, lidar wind data, wind turbine design parameters (such as wind turbine design power curve, hub height, rotor radius, etc.). The time length of wind turbine SCADA system data, anemometer tower data, and lidar wind data is 1 year, and the time resolution is 10 min. Based on the nacelle wind speed and hub-height wind speed measured by lidar of some wind turbines, the nacelle transfer function models are constructed, which are applied to other wind turbines of the same model.

4.2. Wind Turbines Power Generation Performance Evaluation Results

The power generation performance of different wind turbines is quantitatively evaluated based on the measured data from 14 wind turbines of wind farm in Northwest China. The calculation results of MEWPD of wind turbines are shown in Figure 3.

As shown in Figure 3, the MEWPD of the 14 wind turbines in the wind farm is 75–150 W/m², which belongs to the third category of wind resource area. The wind farm terrain is complex, and the wind resources of different wind turbines are significantly different. Among them, WT #7 has the highest MEWPD (143.88 W/m²), and WT #10 has the lowest MEWPD (87.63 W/m²), with the difference of 56.25 W/m². Therefore, the influence of the wind energy resource differences should not be ignored in the evaluation process of power generation performance of different wind turbines.

Figure 4 shows the calculation results of the DEP, REP, and AEP of wind turbines. As shown in Figure 4, different wind turbines have different DEP, REP, AEP. The DEP of WT #7 is the highest (3108 MWh) and WT #10 is the lowest (2150 MWh), with a difference of 958 MWh, which is related to the wind energy resource conditions where the wind turbine is located. The gap between the REP and DEP is mainly related to the maintenance level of wind turbines, which will gradually increase with the deterioration of health

status and power generation performance, and this gap can be narrowed by improving the maintenance level of wind turbines. The gap between the AEP and REP is mainly related to the operation and management ability of wind farms, which needs to further refine the causes of power generation loss of wind turbines and tap the power generation potential of wind turbines by formulating effective operation and management measures.

Figure 3. The calculation results of MEWPD of wind turbines.

(a)

Figure 4. Cont.

Figure 4. The calculation results of DEP/REP/AEP of wind turbines. (a) WT #1–7; (b) WT #8–14.

The energy production losses of wind turbines are mainly divided into the EPLF, EPLRI, EPLPL, and EPLOF, etc. The calculation results are shown in Table 2. It can be seen from Table 2 that there are considerable differences in the EPLF of different wind turbines: the EPLF of WT #14 is the highest (102.95 MWh), indicating that the reliability of WT #14 is relatively low; the EPLF of WT #1 is the lowest (59.66 MWh), indicating that the reliability of WT #1 is relatively high. It is worth noting that WT #7 has the optimal wind energy resource conditions, but the AEP is not the highest (its power generation loss is mainly caused by the fault shutdown being large, and its good wind resource conditions are not well utilized). Therefore, troubleshooting must be strengthened to improve the reliability of WT #7. There is little difference between the EPLRI of different wind turbines, which is basically maintained near 7 MWh of which the small proportion in total loss indicates that the regular inspection plan of the wind farm is relatively reasonable. There are some differences in the EPLPL of different wind turbines since the optimal allocation of active power to reduce the fatigue load of different wind turbines under power limiting conditions. The EPLOF of different wind turbines vary greatly, and it is necessary to further trace the root causes of other energy production losses of different wind turbines with the help of more data information and more advanced big data mining technology.

Because of the differences of wind energy resources in different wind turbine locations, it is unfair to use statistical evaluation indicators for comparison. Therefore, the comparative indicators are adopted to compare the power generation performance of different wind turbines, and the calculation results are shown in Table 3. It can be seen from Table 3 that the MEWPD of wind turbines are basically above 0.45, indicating that the wind turbines selection is relatively reasonable and can take full advantage of wind energy resources. It should be noted that the MEWPD of some wind turbines may be

higher than its maximum design utilization coefficient. The main reason is the measuring error of nacelle anemometer, which requires wind farms maintenance staffs to check the installation and measurement accuracy of wind measuring devices. Except for WT #7, the MPC of other wind turbines are all above 0.9, hence the maintenance level of WT #7 should be further improved. The OPC of wind turbines are all above 0.92, indicating that all wind turbines have good operating performance and relatively low power generation losses.

Table 2. The calculation results of energy production losses of wind turbines.

Wind Turbine Number	EPLF (MWh)	EPLRI (MWh)	EPLPL (MWh)	EPLOF (MWh)
WT #1	59.66	9.03	39.47	14.25
WT #2	68.40	5.30	44.28	19.46
WT #3	83.80	7.95	34.86	26.06
WT #4	60.10	6.39	39.60	26.60
WT #5	66.80	6.77	31.49	21.30
WT #6	64.95	7.75	35.62	21.33
WT #7	94.86	8.33	53.80	19.90
WT #8	66.66	5.95	63.80	33.12
WT #9	73.54	6.25	38.76	19.37
WT #10	67.08	9.21	50.76	19.91
WT #11	94.79	6.80	30.37	19.23
WT #12	92.52	5.53	26.84	7.52
WT #13	98.35	6.43	39.54	10.45
WT #14	102.95	6.70	47.30	15.47

Table 3. The calculation results of comparative indicators of wind turbines.

Wind Turbine Number	DWEUC	MPC	OPC	FLC	RILC	PLLC	OLC
WT #1	0.5263	0.9360	0.9419	2.83%	0.43%	1.87%	0.68%
WT #2	0.4743	0.9325	0.9522	2.38%	0.18%	1.54%	0.68%
WT #3	0.4992	0.9316	0.9339	3.63%	0.34%	1.51%	1.13%
WT #4	0.4812	0.9078	0.9531	2.12%	0.23%	1.40%	0.94%
WT #5	0.5046	0.9309	0.9521	2.53%	0.26%	1.19%	0.81%
WT #6	0.5256	0.9457	0.9389	3.06%	0.37%	1.68%	1.00%
WT #7	0.4656	0.8937	0.9363	3.42%	0.30%	1.94%	0.72%
WT #8	0.4904	0.9329	0.9327	2.65%	0.24%	2.53%	1.32%
WT #9	0.4988	0.9139	0.9398	3.21%	0.27%	1.69%	0.85%
WT #10	0.5288	0.9169	0.9254	3.40%	0.47%	2.58%	1.01%
WT #11	0.5095	0.9158	0.9344	4.11%	0.29%	1.32%	0.83%
WT #12	0.4863	0.9341	0.9525	3.32%	0.20%	0.96%	0.27%
WT #13	0.4821	0.9114	0.9420	3.69%	0.24%	1.48%	0.39%
WT #14	0.4828	0.9494	0.9395	3.61%	0.24%	1.66%	0.54%

Based on six comparative indicators, such as the DWEUC, MPC, FLC, RILC, PLLC, and OLC, the comprehensive evaluation method based on improved CRITIC weighting approach is adopted to comprehensively evaluate the power generation performance among different wind turbines. The calculation results compared with the comprehensive evaluation methods based on CRITIC weighting method and entropy weighting method are shown in Tables 4–6.

Table 4. The comprehensive evaluation results of wind turbines power generation performance (entropy weighting method).

Wind Turbine Number	Entropy Weighting Method				Result
	Excellent	Good	Medium	Poor	
WT #1	0.6683	0.0436	0.1512	0.1368	Excellent
WT #2	0.5987	0.1973	0.0223	0.1818	Excellent
WT #3	0.1549	0.3817	0.3177	0.1458	Good
WT #4	0.4912	0.0594	0.3349	0.1145	Excellent
WT #5	0.4796	0.5178	0.0026	0.0000	Good
WT #6	0.4230	0.2339	0.3307	0.0123	Excellent
WT #7	0.1171	0.2387	0.2919	0.3523	Poor
WT #8	0.3800	0.2270	0.0662	0.3268	Excellent
WT #9	0.0524	0.7362	0.2114	0.0000	Good
WT #10	0.2040	0.1457	0.3376	0.3127	Medium
WT #11	0.2822	0.3644	0.1730	0.1804	Good
WT #12	0.5709	0.2733	0.1558	0.0000	Excellent
WT #13	0.4167	0.0646	0.3893	0.1294	Excellent
WT #14	0.4490	0.1605	0.3905	0.0000	Excellent

Table 5. The comprehensive evaluation results of wind turbines power generation performance (CRITIC weighting method).

Wind Turbine Number	CRITIC Weighting Method				Result
	Excellent	Good	Medium	Poor	
WT #1	0.6770	0.0385	0.1273	0.1571	Excellent
WT #2	0.5871	0.1838	0.0250	0.2041	Excellent
WT #3	0.1410	0.4000	0.3247	0.1343	Good
WT #4	0.4741	0.0546	0.3523	0.1190	Excellent
WT #5	0.4554	0.5419	0.0027	0.0000	Good
WT #6	0.4490	0.2062	0.3306	0.0142	Excellent
WT #7	0.1078	0.2431	0.2677	0.3815	Poor
WT #8	0.3935	0.2473	0.0740	0.2852	Excellent
WT #9	0.0554	0.7370	0.2077	0.0000	Good
WT #10	0.2291	0.1410	0.3249	0.3049	Medium
WT #11	0.2675	0.3788	0.1829	0.1708	Good
WT #12	0.5538	0.2759	0.1703	0.0000	Excellent
WT #13	0.3976	0.0644	0.4138	0.1242	Medium
WT #14	0.4625	0.1392	0.3983	0.0000	Excellent

Table 6. The comprehensive evaluation results of wind turbines power generation performance (improved CRITIC weighting method).

Wind Turbine Number	Improved CRITIC Weighting Method				Result
	Excellent	Good	Medium	Poor	
WT #1	0.5350	0.0363	0.1388	0.2898	Excellent
WT #2	0.4454	0.1504	0.0441	0.3601	Excellent
WT #3	0.1113	0.3257	0.3679	0.1952	Medium
WT #4	0.3387	0.0603	0.4446	0.1564	Medium
WT #5	0.4304	0.5669	0.0027	0.0000	Good
WT #6	0.3598	0.2073	0.4155	0.0174	Medium
WT #7	0.0206	0.0513	0.0600	0.8681	Poor
WT #8	0.0861	0.0682	0.0233	0.8223	Poor
WT #9	0.0550	0.7184	0.2266	0.0000	Good
WT #10	0.0274	0.0276	0.0662	0.8789	Poor
WT #11	0.0603	0.0991	0.0527	0.7879	Poor
WT #12	0.4435	0.3315	0.2250	0.0000	Excellent
WT #13	0.2819	0.0521	0.5019	0.1641	Medium
WT #14	0.3446	0.1374	0.5180	0.0000	Medium

As shown in Tables 4 and 5, there is no obvious difference in the results of the comprehensive evaluation method based on entropy weight method and CRITIC weight method, which is possibly because there is little correlation difference between indicators. The only difference is that the evaluation results of WT #13 are different, which are excellent and medium, respectively. From the analysis in Table 3, it can be seen that WT #13 has the second largest FLC, and the result of the comprehensive evaluation method based on entropy weight method is excellent, which is obviously not in line with the actual power generation performance. As shown in Tables 5 and 6, the proportion of excellent, good, medium, and poor in the comprehensive evaluation results based on CRITIC weighting method is 50%, 29%, 14%, and 7% respectively, while the proportion in the comprehensive evaluation results based on the improved CRITIC weighting method is 21%, 14%, 36%, and 29% respectively, which has a great difference. Taking WT #8, WT #10, and WT #11 with larger differences in evaluation results as examples, as shown in Table 3, the OLC of WT #8, PLLC of WT #10, and FLC of WT #11 are the highest, indicating that the power generation loss of the three wind turbines is relatively large and the power generation performance is relatively low. However, the evaluation results based on CRITIC weighting method are excellent, medium, and good respectively, which are obviously inconsistent with the actual conditions. The evaluation results based on improved CRITIC weighting method are poor, which are more aligned with the actual power generation performance level of the wind turbines and can effectively measure the comprehensive level of power generation performance of different wind turbines.

4.3. Wind Farms Power Generation Performance Evaluation Results

In order to further verify the effectiveness and applicability of the proposed approach, the measured data from six wind farms in Northeast China are adopted to quantitatively evaluate the power generation performance of different wind farms. The calculation results of the MEWPD of wind farms are shown in Figure 5.

Figure 5. The calculation results of MEWPD of wind farms.

As shown in Figure 5, the MEWPD of the six wind farms are all higher than 300 W/m^2 , which belongs to the first category of wind resource area, and the wind energy resource is excellent. Among them, the MEWPD of WF #1 is the highest (554 W/m^2), and the MEWPD of WF #2 is the lowest (321 W/m^2), with a difference of 233 W/m^2 . The specific reason for this discrepancy may be the difference in wind energy resource endowments of the wind

farm itself or the influence of wake effect of large wind power base, which needs to be further verified. Therefore, the difference in wind energy resources should be eliminated to achieve a fair comparison of the power generation performance among different wind farms, so as to prevent some wind farms from remaining invincible due to its inherent advantages of wind resources.

Figure 6 shows the calculation results of the DEP, REP, and AEP of wind farms. As shown in Figure 6, there is a great difference between the REP and DEP of WF #2, WF #5, and WF #6, indicating that the maintenance ability of these three wind farms is relatively poor, and the health status and power generation performance are greatly degraded. In order to improve the overall power generation performance of wind farm, it is necessary to carry out necessary technical transformation for wind turbines with low power generation performance while improving the maintenance ability of wind farm maintenance staffs. There is a large difference between the AEP and REP of WF #1, WF #4, and WF #6, indicating that the operation and management ability of these three wind farms is relatively poor. Therefore, it must deeply explore the causes of power generation loss and improve the operation and management ability of the wind farm, so as to maximize the power generation potential of wind farm.

Figure 6. The calculation results of DEP/REP/AEP of wind farms.

The calculation results of energy production loss of wind farms are shown in Table 7. The EPLOF of wind farms is the highest except for WF #6, and it is necessary to further trace the root causes of other energy production losses of different wind turbines with the help of more specific data information and more advanced big data mining technology. It is worth noting that the EPLOF of WF #6 are relatively small, but the EPLF, EPLRI, and EPLPF are the highest, indicating that the fault repair ability and timeliness, the rationality of regular inspection plan, and the consumption capacity of the power grid are undesirable. Therefore, it is necessary to optimize the regular inspection work plan, improve the business skills of operation and maintenance staffs, and explore the wind power consumption scheme, so as to reduce the power generation loss of WF #6 as much as possible.

Table 7. The calculation results of energy production loss of wind farms.

Wind Farm Number	EPLF (MWh)	EPLRI (MWh)	EPLPL (MWh)	EPLOF (MWh)
WF #1	1958	731	404	11144
WF #2	139	64	489	2915
WF #3	176	116	768	2924
WF #4	2007	647	2983	17384
WF #5	3850	98	3292	13173
WF #6	5459	1773	11159	1514

The comparative indicators are used to evaluate the power generation performance of different wind farms. The comparative indicators are based on the wind energy resource and design level of wind farms themselves, which can eliminate the influence of wind energy resource and design levels differences; the calculation results are shown in Table 8. The DWEUC of different wind farms is between 0.23 and 0.33, which is relatively low compared with Table 3. The main reason is that the six wind farms are located in the first category of wind resource area with excellent wind resources, but the wind turbines are all early small capacity units, which cannot make full use of excellent wind energy resources. Therefore, the power generation performance of wind farms could be improved by lengthening blades, adding power amplifiers, or replacing small capacity with large capacity to avoid wasting excellent wind energy resource. The MPC of WF #2 and WF #6 is low (lower than 0.85), and the maintenance level of the wind farm must be improved. The OPC of WF #4 and WF #6 is low (lower than 0.86), and it is necessary to improve the operation and management ability of wind farms to reduce energy production losses. Significantly, the OLC of WF #4 is 14.03%, which is the most important factor causing energy production losses and it needs more specific data information to locate the root causes.

Table 8. The calculation results of comparative indicators of wind farms.

Wind Farm Number	DWEUC	MPC	OPC	FLC	RILC	PLLC	OLC
WF #1	0.2352	0.9299	0.8842	1.59%	0.59%	0.33%	9.06%
WF #2	0.3296	0.8098	0.9373	0.24%	0.11%	0.85%	5.07%
WF #3	0.3047	0.9656	0.9338	0.29%	0.19%	1.28%	4.86%
WF #4	0.2521	0.9701	0.8141	1.62%	0.52%	2.41%	14.03%
WF #5	0.2701	0.9246	0.9398	1.14%	0.03%	0.97%	3.88%
WF #6	0.2598	0.8070	0.8550	3.98%	1.29%	8.13%	1.10%

Based on the above six comparative indicators, the comprehensive evaluation method based on improved CRITIC weighting method is adopted to comprehensively evaluate the power generation performance of different wind farms. The calculation results compared with the comprehensive evaluation methods based on CRITIC weighting method and entropy weighting method are shown in Tables 9–11.

Table 9. The comprehensive evaluation results of wind farms power generation performance (entropy weighting method).

Wind Farm Number	Entropy Weighting Method				Result
	Excellent	Good	Medium	Poor	
WF #1	0.1364	0.4341	0.2067	0.2228	Good
WF #2	0.6063	0.1419	0.2518	0.0000	Excellent
WF #3	0.6786	0.3153	0.0061	0.0000	Excellent
WF #4	0.2509	0.3116	0.2947	0.1428	Good
WF #5	0.4144	0.5800	0.0056	0.0000	Good
WF #6	0.1428	0.1585	0.0644	0.6344	Poor

Table 10. The comprehensive evaluation results of wind farms power generation performance (CRITIC weighting method).

Wind Farm Number	CRITIC Weighting Method				Result
	Excellent	Good	Medium	Poor	
WF #1	0.1459	0.4316	0.2662	0.1563	Good
WF #2	0.4959	0.2494	0.2547	0.0000	Excellent
WF #3	0.5921	0.4014	0.0066	0.0000	Excellent
WF #4	0.2516	0.2618	0.2341	0.2524	Good
WF #5	0.4878	0.5065	0.0056	0.0000	Good
WF #6	0.2524	0.1111	0.0452	0.5913	Poor

Table 11. The comprehensive evaluation results of wind farms power generation performance (improved CRITIC weighting method).

Wind Farm Number	Improved CRITIC Weighting Method				Result
	Excellent	Good	Medium	Poor	
WF #1	0.0528	0.1939	0.1438	0.6095	Poor
WF #2	0.1924	0.1183	0.6893	0.0000	Medium
WF #3	0.5763	0.4173	0.0064	0.0000	Excellent
WF #4	0.0362	0.0535	0.0590	0.8513	Poor
WF #5	0.4500	0.5445	0.0055	0.0000	Good
WF #6	0.0174	0.0149	0.0060	0.9617	Poor

As shown in Tables 9 and 10, the results of the comprehensive evaluation model based on CRITIC weighting method and entropy weighting method are the same, and the possible reasons have been explained in the evaluation process of wind turbine power generation performance. As shown in Tables 10 and 11, the evaluation results of the two methods have both similarities and differences. The evaluation results of WF #1, WF #2, and WF #4 are different among them. The DWEUC of WF #1 is the lowest, the MPC of WF #2 is the second lowest, and the OLC of WF #4 is the highest, indicating that the effective wind energy capture capacity of WF #1 is relatively low, the maintenance ability of WF #2 is relatively low, and the energy production losses of WF #4 are relatively high. However, the evaluation results based on CRITIC weighting method are good, excellent, and good respectively, while the evaluation results based on improved CRITIC weighting method are poor, medium, and poor respectively. The evaluation results of the proposed model are more aligned with the actual power generation performance level of the wind farms, which further verifies the effectiveness and applicability of the proposed approach.

5. Conclusions

The evaluation indicator system and comprehensive evaluation method of wind farm power generation performance, including the influence of wind energy resource differences, are proposed in this paper. Firstly, taking energy as the clue, using five categories of evaluation indicators, including resource conditions, ideal performance, reachable performance, actual performance, and performance loss, the evaluation indicator system of wind farm power generation performance based on statistical and comparative indicators is constructed. Then, aiming at the comprehensive comparison of power generation performance among different wind farms, the comprehensive evaluation method of wind farm power generation performance based on improved CRITIC weighting method is proposed. Finally, actual data from Chinese wind farms are used to validate the effectiveness and applicability of the proposed method by taking the comprehensive evaluation models based on CRITIC weighting method and entropy weighting method as the benchmarks. The conclusions are as follows:

- (1) The proposed statistical indicators can realize the quantitative evaluation of different aspects, such as resource conditions, ideal performance, achievable performance, actual performance, and performance loss of wind farms, trace the root causes of

power generation performance loss, and effectively guide the technical transformation and operation and maintenance management of wind farms.

- (2) The proposed comparative indicators are based on the wind energy resource and design level of wind farms themselves, which can effectively eliminate the influence of wind energy resource and design levels differences and achieve the fair comparison of power generation performance among different wind farms.
- (3) The proposed comprehensive evaluation model based on improved CRITIC weighting method can avoid the problems of one-sided and unreasonable evaluation results caused by the models based on CRITIC weighting method and entropy weighting method, and the results are more aligned with the actual power generation performance of wind farms, which can effectively realize the comprehensive evaluation and fair comparison of power generation performance of different wind farms.

There are several possible directions to further the present work. The evaluation indicator system of wind farm operation performance including evaluation aspects such as power generation performance, energy consumption level, grid connection characteristics, and power market transaction can be further studied. In addition, wind farm operation performance improvement schemes can be further studied to form a benign closed-loop management mode to maximize the potential of wind farm power generation and economic benefits.

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