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# Highway Microgrid Project Evaluation under Energy Transportation Integration

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**Abstract:** The construction of highway microgrids is evolving into a new highway energy system that integrates "Source-Network-Load-Storage". This paper provides a comprehensive evaluation of expressway microgrids from the perspective of transportation and energy integration. An index model is set up that considers the economy, technology, and environment. The grey evaluation method, on the strength of analytic hierarchy process–entropy weight method, shows that the integrated microgrid of "source-network-load-storage" promotes energy sustainability, supply reliability, and sustainable environmental development. When compared to different evaluation methods for microgrid planning schemes, our method yields the highest score of 0.9127, indicating superior results. This approach is suitable for the multicomponent evaluation system of expressway microgrids and allows for scientifically evaluating microgrid planning schemes.

**Keywords:** integrated energy systems; microgrid; renewable sources; AHP–entropy weight; comprehensive evaluation

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## 1. Introduction

With the continuous growth of carbon emissions, the conflict between transportation, power, and surroundings has become progressively prominent [1]. For the past few years, distributed power generation technology has grown rapidly, providing an effective solution for carbon neutrality. However, it threatens the stability of the traditional power grid. Microgrids overcome the defects and have distinct advantages for system reliability [2]. Therefore, the bond of the transportation system and energy system is an efficient way to accomplish the "carbon peak". China is accelerating the collaborative and complementary development of renewable energy in the field of transportation, and actively promoting the development of highway microgrid projects [3,4].

Because the power market mechanism is not faultless, it is hard to realize the benefits of a highway microgrid. Therefore, it is crucial to research a scientific evaluation method for highway microgrid projects to provide positive guiding significance. Domestic and foreign scholars have recently conducted some research on the benefit evaluation of the highway microgrid project. Poe et al. [5] analyzed the economic, ecological, and political influencing factors of microgrids in highway service areas in the United States. Soullam et al. [6] studied the feasibility of building photovoltaic power stations in some areas along the highway in Korea. Ge et al. [7] conducted an economic evaluation from the aspects of investment and maintenance cost and battery degradation cost in the service area. The above research only considers part of a certain application scenario, and lacks comprehensive evaluation of the whole link of infrastructure construction, transport tools, service facilities, etc.

Thus, it is necessary to study the evaluation method of "Source-Network-Load-Storage" complementary fusion highway microgrid project considering the coupling of all links.

At present, the extensively used weighting methods are subjective and objective weighting methods [8]. These two weights are used dissimilarly. The subjective weighting method depends on specialist experience to judge the significance of indicators. It contains an analytic hierarchy process, Delphi method, and Fuzzy logic method. The objective weighting method is based on actual factual data and quantitative determination of index weights. It mainly includes the entropy weight method, principal component analysis, and so on. In order to determine the optimal energy system under different types of information, Ren et al. [9] used the analytic hierarchy process to calculate and analyze the relationship between factors at different levels. According to the analysis, the priority of indicators and methods has a great impact on the results. Aiming at the problem that the weight of characteristic index and common index is difficult to set, Zhang et al. [10] used the analytic hierarchy process to process indicators and affect the optimal location of photovoltaic power stations. Zou et al. [11] proposed a method of evaluating the importance of experience feedback information based on the analytic hierarchy process, combined with expert judgment. It finally gave a quantitative feedback value score to identify important experience feedback information. Han et al. [12] used the Delphi method to evaluate power grid operation efficiency, and expert opinions accounted for a large proportion in this method. Li et al. [13] consulted experts using the feedback polling method of the Delphi method. This method can effectively gather expert feedback and facilitate the establishment of a comprehensive evaluation model for the consultation and analysis of many experts. Guo et al. [14] established the index system of a distributed power supply system, used a membership degree function to perform fuzzy scoring, and finally calculated the evaluation result with a fuzzy synthesis operator. Yang et al. [15] proposed an enhanced entropy evaluation method for a power system after a lack of success. The method averted the problem of excessive weight of any indicators. Tian et al. [16] adopted a compromise solution between the entropy weight method and the fuzzy best–worst method to evaluate the model, and realized the sustainable development of power grid investment. Qi et al. [17] used the entropy theory based on the principal component analysis method to analyze the thermal power units. The results show that this method is effective at unit comprehensive evaluation for the completion of indicators. Shao et al. [18] refined the principal component analysis to check the correlation between indicators. The results express that the improved principal component analysis method can keep more of the original data's scattered information. Zeng et al. [19] built a multi-stage evaluation index system and proposed an evaluation model combining equilibrium analysis and principal component analysis to achieve the objective evaluation of correlation index information. Based on the fuzzy membership degree hypothesis, He et al. [20] quantifies the risk situation of each stage in the life cycle of the urban power grid, and gives the comprehensive quantitative scores of various risks. However, in the above study, the subjective weighting method shows the subjective opinion and intuition of a specialist, which is arbitrary. The objective weighting method ignores the subjective information necessary for safety evaluation, because it only relies on specific data; the calculation results will be inconsistent with the actual phenomenon. There is a lack of weight evaluation of highway microgrids.

In order to settle the above difficulty, this paper innovatively establishes an index evaluation model for the energy system of a highway microgrid project under the integration of energy and transportation, which provides a new idea for the construction of an integrated highway energy system. In this paper, the AHP–entropy method is employed to compute the comprehensive weight, and then the grey evaluation method is used to realize the scientific evaluation of a microgrid planning scheme. Compared to the above-mentioned literature, this paper has two main contributions.

(1) The first contribution is a new direction for the comprehensive benefit evaluation of a highway energy system, considering the integration of energy and transportation, and the effective evaluation of the complementary highway microgrid, considering the energy coupling characteristics of "Source-Network-Load-Storage". This paper mainly synthesizes three benefit indicators: economic benefit, technical benefit, and environmental benefit. The economic benefit covers the net present value and the internal rate of return. The technical benefit includes energy use efficiency and power supply reliability. The environmental benefit contains carbon emission reduction and emission reduction benefit.
(2) The second contribution is that the AHP–entropy weight method is put forward to ensure the weight between different standards. The AHP–entropy weight method is used to work out the weights, not only considering the experience of the evaluator, but also providing objectivity. Meanwhile, a grey comprehensive evaluation using grey relational degree is presented to achieve the comprehensive evaluation of the efficiency of the highway microgrid project.

By utilizing the proposed method in an empirical analysis, this method is effective in the comprehensive benefit evaluation of highway microgrid projects, and the highest score is 0.9127. Through comparative analysis of disparate planning schemes and methods, the evaluation of "Source-Network-Load-Storage" complementary fusion highway microgrid project using subjective and objective evaluation methods can achieve reliable energy supply, energy synthetical utilization, and maximum environmental benefits within the expected investment range.

The rest of this paper is as follows. the comprehensive evaluation system for expressway microgrid projects is set up in Section 2. The theoretical framework for the grey comprehensive evaluation model based on the AHP–entropy weight method is described in Section 3. The consequences for experimental study are analyzed in Section 4. Finally, the chief conclusions and future research directions are shown in Section 5.

## 2. Highway Microgrid Evaluation System

When evaluating a highway microgrid, it is necessary to establish a reasonable index system first. It is indispensable to build a rational evaluation index system to reflect the comprehensive benefits of expressway microgrid projects and serve as the basis for subsequent evaluation. To build a comprehensive evaluation index system with prominent and differentiated indicators is to lay a solid foundation for the analysis and application of evaluation methods in Sections 3 and 4.

### *2.1. The Composition of the Index Evaluation System*

It is indispensable to divide the evaluation object into several levels that can mirror different perspectives according to the purpose of comprehensive evaluation. Then, each level needs to be divided into multiple elements according to the influencing factors of these levels. In the construction of the benefit index system of the energy fusion microgrid, the selected index should fully reflect the real situation.

The index system is presented in Table 1. Highway microgrid investment operators require the economy of microgrid planning scheme. The index demand of power users is reflected in the security and dependability of power supply in technical aspects. Government departments, as the promoters of microgrid projects, require that microgrids take into account environmental protection and economy. Therefore, the benefit evaluation index system of the expressway microgrid constructed in this paper includes economic benefit [21], technical benefit [22], and environmental benefit [23]. Moreover, the expert panel identified the most important benefit sub-criteria of the economic, technical, and environmental benefit criteria based on their expertise. The economic benefit includes the net present value and the internal rate of return. The technical benefit includes energy use efficiency and power supply reliability. The environmental benefit includes carbon emission reduction and emission reduction benefit.

**Table 1.** Index evaluation hierarchy structure.

| Overall Index | Primary Index | Secondary Index |
|---|---|---|
| comprehensive index evaluation system | Economic index | Net Present Value |
| | | Internal Rate of Return |
| | Technical index | Energy use efficiency |
| | | Power supply reliability |
| | Environmental benefit index | Carbon emission reduction |
| | | Emission reduction benefit |

### *2.2. Index Evaluation Connotation*

#### 2.2.1. Economic Index

The investment cost and maintenance cost should be considered in the highway microgrid project. The investment cost is the purchase and placement cost of the equipment of each unit of the system, and its calculation formula is as follows [24]:

$$C_A = \sum_{i=1}^{4} \frac{P_i c_i r (1+r)^N}{(1+r)^N - 1} \quad (1)$$

where $i$ = 1, 2, 3, and 4 correspond to the wind turbines, photovoltaic arrays, energy storage devices, and charging piles; $P_i$ is the rated installed capacity; $r$ is the discount rate; $N$ is the planning cycle; $c_i$ is the annual unit investment cost.

The operation and maintenance cost of the highway microgrid project involves the costs generated by the routine maintenance of new energy power generation devices, the cleaning of photovoltaic panels, the maintenance of slopes along the highway, and the penalty costs generated by noise [25,26].

1. Routine maintenance cost

After the highway microgrid project is completed and placed in service, it needs to maintain the equipment, which costs routine maintenance. The routine maintenance cost per unit capacity of each piece of equipment determines its annual routine maintenance cost.

$$C_{RM} = \sum_{i=1}^{4} P_i c_i' \quad (2)$$

where $c_i'$ is the annual unit maintenance cost of wind turbines, photovoltaic arrays, energy storage devices, and charging piles.

2. Slope maintenance cost

The purpose of highway slope maintenance is to prevent landslides, collapse, and other dangerous situations on the slope, and ensure the normal operation of highway photovoltaics.

$$C_{SM} = \frac{nh}{\cos\alpha} c_{SM} \quad (3)$$

where $n$ is the slope number; $h$ is single-stage slope height; $\alpha$ is the slope angle; $c_{SM}$ is maintenance cost per unit area.

3. Dust removal maintenance cost

Small particles in the air easily accumulate on the photovoltaic panel to form ash, which reduces the power generation performance, so it is necessary to clean the ash regularly. Dust removal maintenance costs due to ash accumulation and cleaning include power loss cost and cleaning cost.

$$C_{DRM} = (C_d + C_c) \cdot \beta \quad (4)$$

where $C_d$ is the power loss cost generated during a single cleaning interval; $C_c$ is the cleaning maintenance cost generated by a single cleaning; $\beta$ is the cleaning frequency.

4. Noise penalty cost

The operation noise of the equipment is unavoidable. If the noise pollution generated exceeds the national standards for environmental noise, a noise penalty cost shall be paid.

Let the sound pressure level $L_P$ generated by the intensity $L_w$ at the distance noise point $R$ be expressed as:

$$L_P = L_w - 20\lg R - 11 \tag{5}$$

For n noise sources in the new energy power station, the noise of all the receiving points is superimposed, and the equivalent value of noise can be expressed as:

$$L_{PT} = 10\lg\left(\sum_{i=1}^{n} 10^{0.1L_{Pi}}\right) \tag{6}$$

$L_{CN}$ represents the daytime or nighttime environmental noise limits of various functional areas, and the total noise exceeding the standard cost $C_n$ is expressed as:

$$C_n = \sum_{i=1}^{M} (L_{PTi} - L_{CNi})\mu \tag{7}$$

where $\mu$ refers to the collection standard of pollution fee for excessive noise stipulated in the Regulations on the Management of the Collection Standard of Pollution Fee; $M$ stands for the number of months for which noise exceeds the standard.

The income of the highway microgrid project mainly includes the income from the selling of electricity of wind turbines and photovoltaic units and the service income from the service area of the charging station. The power generation income includes the power purchase cost saved when photovoltaic power generation is self-used and the power sale income when the surplus power is online. In addition, while waiting at the charging station in the service area, users can also choose to consume at service facilities such as supermarkets and restaurants to obtain service income [27].

1. Microgrid sale income

$$C_{\text{elec}} = \rho_b(E_{L,t} - E_{b,t}) + \rho_s(E_{PV,t} - E_{L,t} + E_{b,t}) \tag{8}$$

where $\rho_b$, $\rho_s$ are, respectively, the purchase price and the on-grid price of AC fusion microgrid; $E_{L,t}$, $E_{b,t}$ are, respectively, the load power consumption and purchased power of AC fusion microgrid in year $t$.

2. Service income

$$C_{Service} = \sum_{q=1}^{m} w_q \lambda b_{\text{av}} \beta \tag{9}$$

where $m$ is the number of vehicles working for the charging station in the service area during the cycle; $w_q$ is the number of passengers per vehicle; $\lambda$ and $b_{\text{av}}$ are per capita consumption probability and amount, respectively; $\beta$ is the profit factor.

The economic index of the highway microgrid project needs to forecast and analyze the profitability and return on investment of the project. The common financial evaluation index is divided into dynamic and static indices. The static index ignores the influence of time value, while the highway microgrid project has a large investment and a long life cycle, so it is not suitable to use static indicators. Therefore, this paper uses a dynamic index to evaluate the economy of the highway microgrid project [28].

1. NPV

The net present value considers the time value of funds. It can be expressed by the following formula:

$$NPV(i_0) = \sum_{t=0}^{N_S} (CI - CO)_t (1 + i_0)^{-t} \tag{10}$$

where $CI$ is income, $CO$ is cost; $i_0$ is discount rate; $N_S$ is operation cycle.

When $NPV \geq 0$, the project is feasible; when $NPV < 0$, the project is not feasible.

2. IRR

Internal rate of return (IRR) is an important index of financial evaluation, reflecting the investment utilization efficiency of a project. The larger the value of the internal rate of return, the stronger the profitability of the scheme.

$$\sum_{t=0}^{N_S} (CI - CO)_t (1 + IRR)^{-t} = 0 \tag{11}$$

2.2.2. Technical Index

1. Energy use efficiency [29]

$$\alpha = \frac{\sum_{i=1}^{N_W} \sum_{t=1}^{T} [P(t) - P_a(t)]}{\sum_{i=1}^{N_W} \sum_{t=1}^{T} P(t)} \tag{12}$$

where $P(t)$ is the power generation output of the new energy power station; $P_a(t)$ is the new energy abandoned power; $N_W$ is the total number of new energy power stations.

2. Power supply reliability

In this paper, power supply reliability is characterized by system power shortage expectation. It represents the accumulated amount of power lost because the output power is less than the load power requirement in the statistical period.

$$E_{LOE} = \sum_{i=1}^{12} \sum_{j=1}^{n_i} \sum_{t=1}^{24} L_{loss,ijt} \tag{13}$$

where $L_{\text{loss},ijt}$ indicates the loss of load power at hour $t$ on day $j$ of month $i$.

2.2.3. Environmental Benefit Index

1. Carbon emission reduction [30]

$$\beta_{CO_2} = \frac{W_{CO_2} - W'_{CO_2}}{W_{CO_2}} \times 100\% \tag{14}$$

where $W_{CO_2}$ is the carbon emissions generated by the thermal power; $W'_{CO_2}$ is the carbon emissions generated by the highway microgrid.

$$W'_{CO_2} = k_{CO_2} \cdot (E_{\text{All}} - E_{PV} - E_{WP}) \tag{15}$$

where $E_{\text{All}}$ is the total power generation; $E_{PV}$ is the photovoltaic power generation; $E_{WP}$ is the wind power generation; $k_{CO_2}$ is the carbon emission factor.

2. Emission reduction benefit

The emission reduction benefit refers to the reduction in fossil energy power generation by new energy generation, thus reducing the emission of various pollution gases, carbon dioxide, and other wastes, which has certain environmental benefits compared with traditional power generation [31].

$$C_{\text{oal}} = 3.25 \times 10^{-4} \cdot (E_{PV} + E_{WP}) \quad (16)$$

$$C_{\text{emiss}} = \sum_{i=1}^{N} \alpha_i \beta_i C_{\text{oal}} \quad (17)$$

where $\alpha_i$ is the environmental value of emission substance; $\beta_i$ is the emission coefficient of emission substance per ton of standard coal burned.

## 3. Highway Microgrid Comprehensive Evaluation Method

In order to evaluate more scientifically the index system of the microgrid planning scheme in Section 1, this paper avoids the subjective judgment made only depending on the knowledge level of experts, and opts for the grey evaluation method of the AHP–entropy method. This method can not only effectively unite subjective and objective weights to prove the factuality of weight determination, but also realize the comparison of different types of data, so as to ensure the effectiveness of the evaluation system and provide a feasible and strong support for the multi-indicator judgment and decision system. The evaluation flow framework is shown in Figure 1.

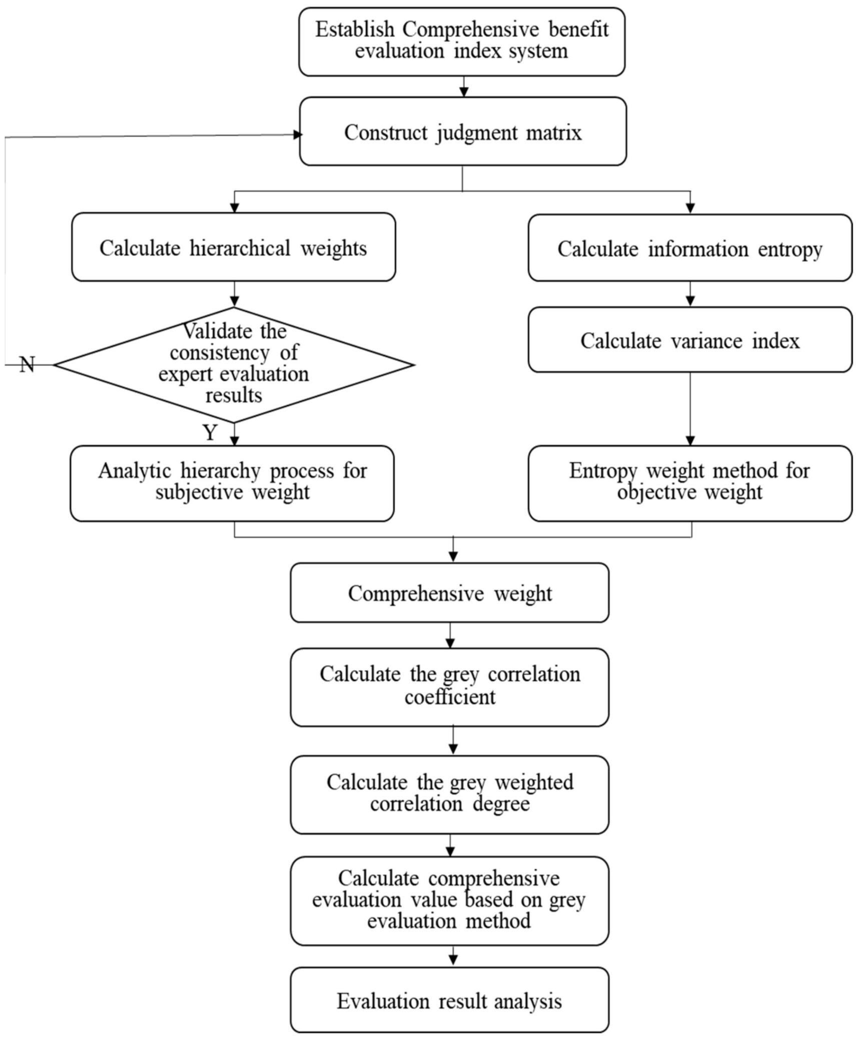


**Figure 1.** The benefit assessment framework.

First, the comprehensive benefit evaluation system is built. Selecting the appropriate evaluation index and constructing the index system is the pivotal requirement for establishing the comprehensive evaluation system. Second, the AHP–entropy weight method is presented to resolve the weight between different criteria. Finally, the grey evaluation method is put forward to compute the comprehensive evaluation value. The grey correlation coefficient and grey weighted correlation degree are calculated based on the grey comprehensive evaluation method. The greater the correlation degree, the better the performance of comprehensive evaluation.

### 3.1. The Calculation Method of Weight

#### 3.1.1. Analytic Hierarchy Process

AHP is a method to determine subjective weights. AHP digitizes and stratifies people's thinking process in complex decision-making problems after deep analysis of the nature of the problem, influencing factors, internal relationships, etc.

AHP is a method of deciding subjective weights. Its basic steps are as follows [32]:

Step 1. The judgment matrix of each level is built by the pairwise comparison method. The pairwise comparison method refers to the comparison of the relative importance between the two indicators when a certain indicator at the upper level is used as the criterion. The comparison scale $a_{ij}$ was used to quantify the judgment results, as shown in Table 2. The judgment matrix $A = (a_{ij})_{n\times n}$ can be set up. The judgment matrix is defined as follows: matrix A satisfies (1) $a_{ij} > 0$; (2) $a_{ji} = 1/a_{ij}$.

**Table 2.** Scale definition of judgment matrix.

| Scale | Value Basis |
|---|---|
| 1 | Both indicators are equally important |
| 3 | The former indicator is slightly more important than the latter indicator |
| 5 | The former indicator is significantly more important than the latter indicator |
| 7 | The former indicator is more important than the latter indicator |
| 9 | The former indicator is extremely more important than the latter indicator |
| 2, 4, 6, 8 | The importance of the two indicators lies between the above |

Step 2. Figure out the maximum eigenvalue of matrix A and its homologous eigenvector.

$$W_i^1 = \frac{\overline{W_i^1}}{\sum\limits_{j=1}^{n} \overline{W_j^1}}, W^1 = [W_1^1, W_2^1, \ldots, W_n^1]^T \tag{18}$$

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(AW^1)_i}{nW_i^1} \tag{19}$$

where $W$ is the eigenvector of the judgment matrix; $\lambda_{\max}$ is the largest eigenvalue of the judgment matrix; $(AW)_i$ is the $i$ element of the vector $AW$.

Step 3. The maximum eigenvalue method is applied to check the consistency of the judgment matrix. If the test passes, the eigenvector is the weight vector.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{20}$$

$$CR = \frac{CI}{RI} \tag{21}$$

When $CR$ is less than 0.1, it indicates that the judgment matrix has passed the consistency test, and the weight of the index can be obtained. Otherwise, it needs to modify the judgment matrix to make it consistent.

3.1.2. Entropy Weight Method

The entropy weight method is an objective weighting method. The entropy weight method is a method to describe the different degrees of evaluation indicators with entropy, and to characterize the weight coefficient according to the difference of evaluation indicators.

For $m$ samples and $n$ evaluation indicators, there is a data matrix $X = (x_{ij})_{m\times n}$. The steps are as follows [33]:

Step 1. Establish a standardized data matrix D, where D = $\{d_{ij}\}_{m\times n}$, and $d_{ij}$ is the characteristic specific gravity.

$$d_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij}, 0 \leq d_{ij} \leq 1 \tag{22}$$

Step 2. Calculate the conditional weight $e(d_j)$ of the $j$ index.

$$H_{\mathrm{j}} = -\frac{1}{\ln m}\sum_{i=1}^{m} d_{ij} \ln d_{ij}, 0 < H_j \leq 1 \tag{23}$$

Step 3. Determine evaluation index entropy weight $W_{Sj}$.

$$W_j^2 = [1 - H_j] / (n - \sum_{j=1}^{n} H_j) \tag{24}$$

3.1.3. Comprehensive Weight Calculation

AHP can effectively use the evaluator's own knowledge and experience, but its evaluation results have some subjective arbitrariness. Although the entropy weight method is supported by specific objective facts and data information, because it only relies on specific data, the calculated results will be inconsistent with the actual phenomenon. Therefore, this paper fully integrates the advantages of the two methods [34].

The comprehensive weight coefficient is gained by combining the subjective weight coefficient obtained by AHP with the objective weight coefficient obtained by the entropy weight method. Its computation formula is as follows:

$$\overline{W}_j = H_j W_j^1 + (1 - H_j) W_j^2 \tag{25}$$

where $W_j^1$ is the weight value determined by AHP; $W_j^2$ is the weight value decided by the entropy weight method.

The method has the following properties [35].

The comprehensive weight coefficient computed by this combination method is between the weight coefficient obtained by the subjective method and the weight coefficient obtained by the objective method.

When $H_j$ is greater than 0.5, the comprehensive weight coefficient is closer to the weight coefficient determined by the subjective method. When $H_j$ is less than 0.5, it is closer to the weight coefficient decided by the objective method.

### *3.2. Grey Comprehensive Evaluation Method*

Grey system theory is a theory to study, analyze, and handle complex systems based on the incompleteness of system data. The grey comprehensive evaluation method has the characteristics of convenient operation and clear theory in the actual calculation process, so it is more and more widely used in the study of evaluation problems. The representative mathematical model calculation formula is as follows [36]:

$$R = E \times W \tag{26}$$

where $R$ is the size of the calculated evaluation results corresponding to $m$ project planning schemes; $W$ is comprehensive weight; $E$ is the evaluation matrix of the evaluation indicators of the project planning scheme, as shown below:

$$E = \begin{bmatrix} \xi_1(1) & \xi_1(2) & \cdots & \xi_1(n) \\ \xi_2(1) & \xi_2(2) & \cdots & \xi_2(n) \\ \vdots & \vdots & \vdots & \vdots \\ \xi_m(1) & \xi_m(2) & \cdots & \xi_m(n) \end{bmatrix} \tag{27}$$

The foundational principles of the grey model based on AHP-EW are as follows [37]:

Step 1. Calculate the evaluation index value and the optimal evaluation index value of the highway microgrid planning schemes.

The series of evaluation indicators of the planning scheme is expressed as:

$$X_i = \{X_i(k)|k = 1, 2, \cdots, n\} i = 1, 2, \cdots, m \tag{28}$$

The series of the optimal index values is expressed as:

$$X_0 = \{X_0(k)|k = 1, 2, \cdots, n\} \tag{29}$$

where $X_0(k)$ is the optimal value of the kth index, which is the best calculated value in each planning scheme. According to the meaning of indicators, the larger the value of some indicators, the more beneficial to the construction of the microgrid. The smaller the value of some indicators, the more beneficial. Therefore, the evaluation index can be split into the benefit index and cost index according to the different attributes. If an indicator belongs to the benefit index, the maximum value calculated by different microgrid planning schemes is taken as the value. If an indicator belongs to the cost index, the minimum value calculated by different microgrid planning schemes will be taken as the value.

Step 2. Calculate the grey correlation coefficient.

$$\xi_i(k) = \frac{\min_i \min_k |X_0(k) - X_i(k)| + \xi \max_i \max_k |X_0(k) - X_i(k)|}{|X_0(k) - X_i(k)| + \xi \max_i \max_k |X_0(k) - X_i(k)|} \tag{30}$$

Step 3. Calculate the grey weighted correlation degree and establish the grey correlation degree.

$$r_i = \sum_{k=1}^{n} W(k) \cdot \xi_i(k) \tag{31}$$

## 4. Case Study

According to the index system and evaluation method of Sections 2 and 3, the example analysis of the highway microgrid project is carried out. Through the analysis of an example, it is verified that the results of the selected method are intuitive and consistent with reality, and the data information utilization rate is higher.

### *4.1. Example Introduction*

In this paper, the microgrid of a highway demonstration project is taken as the research object. With a general length of 178 km, the highway is rich in solar irradiation resources and can use more land. Its installed photovoltaic capacity is 123.99 MW, the installed capacity of the wind power system is 8 kW, there are 32 charging piles of 60 kW, and there is a set of 15 MW/30 MWh battery energy storage systems. On the basis of the above data, three planning schemes are proposed.

Scheme 1 is the scheme to be adopted by the project, which realizes the "Source-Network-Load-Storage" interaction of the highway microgrid.

Scheme 2 reduces the investment in distributed photovoltaics on the basis of Scheme 1 to verify the feasibility of distributed photovoltaics in highway microgrid projects.

Scheme 3 eliminates the configuration of charging piles on the basis of Scheme 1 to verify the comprehensive income of the "Source-Network-Load-Storage" integrated operation mode of the microgrid project.

### *4.2. Comprehensive Benefit Evaluation*

First of all, according to the AHP method, in order to make the scoring scientific and objective, six experts were invited to provide a score. After obtaining the expert's index judgment matrix, the eigenvector of each matrix, that is, the weight of the index, can be gained, and the consistency test can be carried out. The CR of the six matrices is (0.0518, 0.0427, 0.0002, 0.0314, 0.0161, 0.0007), all less than 0.1, conforming to the consistency test. Thus, the weight of each index based on the subjective evaluation of AHP is obtained: $w^1$ = [0.2814 0.1533 0.0911 0.25 0.1361 0.1143 0.1099].

Secondly, the objective assignment of index weights is realized according to the entropy weight method, and the index weight matrix $w^2$ = [0.1929 0.1465 0.1643 0.1561 0.2061 0.1641] can be obtained from Equations (22)–(24).

Based on the linear combination of $w^1$ determined by AHP and $w^2$ determined by the entropy weight method, the index weight matrix can be obtained by Equation (25) as $w^*$ = [0.2562 0.1638 0.1023 0.2077 0.1215 0.1485]. The weights calculated by the three methods are shown in Table 3.

**Table 3.** Weights determined by three methods.

| Method | NPV | IRR | Energy Use Efficiency | Power Supply Reliability | Carbon Emission Reduction | Emission Reduction Benefit |
|---|---|---|---|---|---|---|
| AHP | 0.2814 | 0.1533 | 0.0911 | 0.25 | 0.1143 | 0.1099 |
| Entropy weight | 0.1929 | 0.1465 | 0.1643 | 0.1561 | 0.2061 | 0.1641 |
| AHP-Entropy weight | 0.2562 | 0.1638 | 0.1023 | 0.2077 | 0.1215 | 0.1485 |

The grey correlation coefficient matrix calculated according to the Equation (30).

$$\xi = \begin{pmatrix} 0.8291\ 1.0000\ 1.0000\ 0.7904\ 1.0000\ 1.0000 \\ 0.7592\ 0.7393\ 0.6191\ 1.0000\ \ 0.6908\ 0.7985 \\ 1.0000\ 0.8918\ 0.7074\ 0.8021\ 0.6672\ 0.7011 \end{pmatrix}.$$

Finally, the grey correlation degree $r$ = [0.9127 0.7891 0.8264] is obtained by using Equation (31).

### *4.3. Evaluation Result Analysis*

#### 4.3.1. Comparison of Index Weight Assignment Methods

In order to verify the rationality of the AHP–entropy weighting method, this paper compares the index weights obtained by the three weighting methods, as shown in Figure 2.

It can be seen from the analysis of Figure 2 that the weight value modified by the entropy weight method to the AHP method is between the weights by the AHP method and the entropy method. The calculated result shows that $H_j$ is greater than 0.5, and the comprehensive weight coefficient is closer to the weight coefficient determined by the subjective method. According to the principles to be followed by the method mentioned in Section 3.1.3, properties 1 and 2 are satisfied, showing that the method is feasible.

#### 4.3.2. Comparison of Microgrid Planning Schemes

The results are calculated by using the grey correlation degree, as shown in Figure 3. According to the analysis of Figure 3, the comprehensive evaluation result of Scheme 1 is 0.9127, Scheme 2 is 0.7891, and Scheme 3 is 0.8264. Among the three schemes, the evaluation result of Scheme 1 is the best, indicating that the benefit of Scheme 1 is at a relatively high level, and the integrated operation of "Source-Network-Load-Storage" of the highway microgrid is beneficial to the benefit evaluation of microgrid projects. The evaluation result of Scheme 3 is second only to Scheme 1, indicating that although the charging system will increase the project investment cost, due to its role in promoting the local consumption of new energy, it can achieve friendly interaction with the microgrid under the further improvement of the market mechanism, which is beneficial to the overall benefit evaluation of the highway microgrid project. Scheme 2 ranked last, illustrating the importance of distributed PV for highway microgrid projects, because distributed PV uses solar power generation, lower operating costs than other schemes, and less primary energy consumption, and the PV system produces fewer pollutants, with good environmental benefits. It can be concluded that the highway microgrid project combined with "Source-Network-Load-Storage" considers the cost and investment income of the microgrid project scheme comprehensively. And in terms of energy supply, comprehensive utilization of energy and maximum environmental benefits are achieved within the expected parameters.

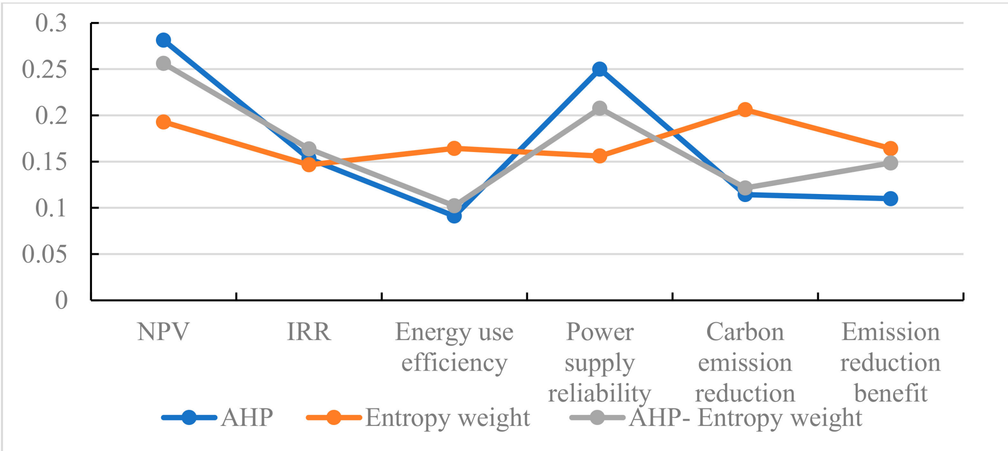


**Figure 2.** Results of the weights by three methods.

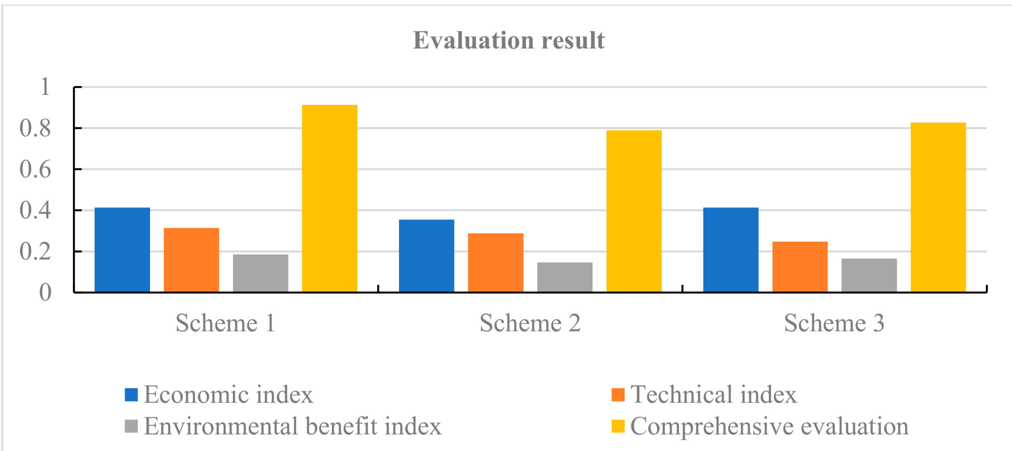


**Figure 3.** Results of scheme evaluations.

4.3.3. Comparison of Evaluation Results under Different Methods

In order to declare the availability of the evaluation method, the evaluation results calculated in this paper are compared with those calculated by the Delphi method and fuzzy comprehensive evaluation method, as shown in Table 4.

**Table 4.** Evaluation results of different evaluation methods.

| Evaluation Method | Scheme 1 | | Scheme 2 | | Scheme 3 | |
|---|---|---|---|---|---|---|
| | Score | Ranking | Score | Ranking | Score | Ranking |
| Textual method | 0.9127 | 1 | 0.7891 | 3 | 0.8264 | 2 |
| Delphi method | 0.7821 | 1 | 0.5743 | 3 | 0.6347 | 2 |
| Fuzzy comprehensiveevaluation method | 0.8443 | 1 | 0.7578 | 2 | 0.6951 | 3 |

Table 4 shows the results obtained by different evaluation methods. As can be seen from Table 4, the score of Scheme 1 is 0.7821, Scheme 2 is 0.5743, and Scheme 3 is 0.6347. The score calculated by the Delphi method is poor. The primary cause is that the Delphi method relies on the evaluator's experience, but ignores some objective factors. However, the comprehensive evaluation index system of the expressway microgrid in this paper involves many attributes and indicators, and the Delphi method cannot truly reflect the performance level of the expressway microgrid planning scheme. The evaluation method proposed in this paper combines the weight determination methods. The calculated comprehensive weight of indicators can reflect not only the knowledge and experience of evaluators, but also the objective information. In addition, it can be seen from Table 4 that the ranking by the fuzzy evaluation method is Scheme 1 > Scheme 2 > Scheme 3, which is different from the ranking results obtained by other methods, because the fuzzy comprehensive evaluation method can only evaluate the system containing model factors, and the evaluation information is repeated due to the correlation between evaluation indicators, which cannot be solved. The grey comprehensive evaluation method is a multi-attribute decision-making method, which can make up for the disadvantages of the fuzzy comprehensive evaluation method and make the evaluation results closer to the actual situation.

## 5. Conclusions

This paper proposes an evaluation index system and comprehensive evaluation method suitable for highway microgrid construction, and takes a practical highway microgrid project as an example to obtain the following conclusions.

(1) In view of the lack of comprehensive evaluation of the "Source-Network-Load-Storage" microgrid scheme, the index system of a highway microgrid is developed in this paper. The index system suitable for the expressway microgrid is constructed from three aspects. The results yield an evaluation value of the planning scheme adopted in this paper of 0.9127, and the highway microgrid has good economic, technical, and environmental benefits, which provides a new idea for the construction of a highway microgrid under the integration of energy and transportation.

(2) The use of the AHP–entropy weight method can not only make use of subjective experience, but also make use of objective facts, so as to avoid the evaluation deviation caused by the imperfect index system. The grey comprehensive evaluation method based on the AHP–entropy weight method is obtained and used to solve the problem that the fuzzy evaluation method can only evaluate the system containing model factors, but not the evaluation indexes with correlation.

A highway microgrid is a new type of microgrid. The evaluation of an expressway microgrid is an evaluation problem involving multiple angles. In terms of indexes, this paper builds an index system from three dimensions: economy, technology, and environment. With the development and operation of this kind of microgrid, more operational data will be accumulated, and the evaluation indicators can be expanded in terms of the impact of the microgrid on traffic, so as to improve the evaluation system.

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## References


1. Ma, J.; Xu, H.L.; Ma, R.C. A review on the development of resilient highway energy system under the integration of energy and transportation. *Power Syst. Technol.* **2022**, *38*, 1–14.
2. Yang, X.F.; Su, J. Overview on micro-grid technology. *Proc. CSEE* **2014**, *34*, 57–70.
3. Jia, L.M.; Shi, R.F.; Ji, L. Road transportation and energy integration strategy in China. *Strateg. Study CAE* **2022**, *24*, 163–172. [CrossRef]
4. Hu, H.T.; Zheng, Z.; He, Z.Y. The framework and key technologies of traffic energy internet. *Proc. CSEE* **2018**, *38*, 12–24.
5. Poe, C.; Filosa, G. Alternative Uses of Highway Rights of Way: Accommodating Renewable Energy Technologies. *Transp. Res. Rec.* **2018**, *2270*, 23–30. [CrossRef]
6. Soullam, K.; Yuhwa, L.; Hak-Ryong, M. Siting criteria and feasibility analysis for PV power generation projects using road facilities. *Renew. Sustain. Energy Rev.* **2018**, *81*, 3061–3069.
7. Ge, S.Y.; Zhu, L.W.; Liu, H. Optimal deployment of electric vehicle charging stations on the highway based on dynamic traffic simulation. *Trans. China Electrotech. Soc.* **2018**, *33*, 2991–3001.
8. Li, C.Z.; Wang, N.L.; Dou, X.X. Review and Prospect on the System Integration of Distributed Energy System With the Complementation of Multiple Energy Sources. *Proc. CSEE* **2023**, *43*, 7127–7150.
9. Ren, H.B.; Gao, W.J.; Zhou, W.S. Multi- criteria evaluation for the optimal adoption of distributed residential energy systems in Japan. *Energy Policy* **2009**, *37*, 5484–5493. [CrossRef]
10. Zhang, X.; Li, H.; Hu, Q.; Zhou, Q.; Shen, B.; Xiang, J. Comprehensive location evaluation of multi-station integration. *Electr. Power Eng. Technol.* **2022**, *41*, 53–59.
11. Zou, X.; Zhang, H.; Lei, L.; Xu, Y.; Zheng, L.; Jiao, F. Research and Application of Significance Determination for Safety-Related Feedback Information Based on Analytic Hierarchy Process in Nuclear Power Plants. *Power Eng.* **2023**, *44*, 189–195.
12. Han, Z.T.; Huang, Z.W.; Ge, S.Y. A comprehensive evaluation system of urban distribution network. *Power Syst. Technol.* **2012**, *36*, 95–99.
13. Li, B.; Liu, Z.F.; Huang, L.J. Comprehensive evaluation benchmark study on line loss management of county power grids. *Power Syst. Technol.* **2016**, *40*, 3871–3879.
14. Guo, H.Y.; Liu, J.S.; Cheng, H.Z. Comprehensive Evaluation of Grid-connected Distributed Generation Based on Fuzzy Mathematics and Combinated Weighting Method. *Mod. Electr. Power* **2017**, *34*, 14–19.
15. Yang, H.; Han, W.; Zeng, T.; Wang, K. Failure Risk Assessment of the Power System transmission Line based on an Improved Entropy Method. *Appl. Mech. Mater.* **2013**, *2490*, 1514–1517. [CrossRef]
16. Tian, H.; Zhao, L.; Guo, S. Comprehensive Benefit Evaluation of Power Grid Investment Considering Renewable Energy Development from the Perspective of Sustainability. *Sustainability* **2023**, *15*, 8299. [CrossRef]
17. Qi, M.F.; Fu, Z.G.; Jing, Y. A comprehensive evaluation method of power plant units based on information entropy and principal component analysis. *Proc. CSEE* **2013**, *33*, 58–64.
18. Shao, B.; Hu, Z.; Liu, D. Using Improved Principal Component Analysis to Explore Construction Accident Situations from the Multi-Dimensional Perspective: A Chinese Study. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3476. [CrossRef]
19. Zeng, B.; Li, Y.Z.; Liu, Z.Q. Comprehensive evaluation method for environmental benefits of smart distribution network based on TO-PCA. *Power Syst. Technol.* **2016**, *40*, 396–404.
20. He, Y.X.; Dai, A.Y.; Yang, W.H. Identification and evaluation of risk in urban network planning based on fuzzy theory. *Power Syst. Technol.* **2010**, *34*, 127–132.
21. Xie, H.; Teng, X.F.; Zhang, Y.J. Analysis of economic influence factors in wind-photovoltaic-storage microgrid. *Autom. Electr. Power Syst.* **2019**, *43*, 70–76.
22. An, M.; Xiao, S.; Liu, B. Reliability evaluation of expressway energy self-reliance system considering time-varying factors. *J. North China Electr. Power Univ.* **2024**, *51*, 39–48.
23. Meng, R.; Zhang, L.; Zang, H.; Jin, S. Evaluation of Environmental and Economic Integrated Benefits of Photovoltaic Poverty Alleviation Technology in the Sanjiangyuan Region of Qinghai Province. *Sustainability* **2021**, *13*, 13236. [CrossRef]
24. Zhang, S.X. Evaluation method of park level integrated energy system for microgrid. *Power Syst. Technol.* **2018**, *42*, 2431–2439.
25. Zhao, B.; Zhang, S.W.; Cao, S.X. Cleaning cycle determination and cost estimation for photovoltaic modules based on dust accumulating condition monitoring. *Proc. CSEE* **2019**, *39*, 4205–4213.
26. Xu, Z.M.; Qu, H.W.; Wang, J.W. Dusty PV modules optimal cleaning cycle. *Proc. CSEE* **2018**, *36*, 1738–1742.

27. Ge, S.Y.; Zhou, H.; Liu, H.; Sun, W.; Zhang, Q.; Chen, B. Considering the impact of vehicle accidents, freeway charging stations and service areas are coordinated planning. *Proc. CSU-EPSA* **2019**, *31*, 1–8.
28. Pan, X.; Liu, K.; Wang, J.; Hu, Y.; Zhao, J. Capacity Allocation Method Based on Historical Data-Driven Search Algorithm for Integrated PV and Energy Storage Charging Station. *Sustainability* **2023**, *15*, 5480.
29. Wang, B.; Zhao, W.W.; Lin, S.J. Integrated energy management of highway service area based on improved multi-objective quantum genetic algorithm. *Power Syst. Technol.* **2022**, *46*, 1742–1751.
30. Tan, Y.; Xie, G.; Xiao, Y.; Luo, Y.; Xie, X.; Wen, M. Comprehensive Benefit Evaluation of Hybrid Pumped-Storage Power Stations Based on Improved Rank Correlation-Entropy Weight Method. *Energies* **2022**, *15*, 8414. [CrossRef]
31. Jiang, L.Z.; Bie, Z.H.; Long, T. Development model and key technology of integrated energy and transportation system. *Proc. CSEE* **2022**, *42*, 1285–1301.
32. Zhou, X.; Chen, C.; Chen, J.; Li, Y.; Lu, X.; Li, J.; Wang, Y. Evaluation Method of Synergy Degree for Comprehensive Benefits System of Hydropower Projects. *Sustainability* **2021**, *13*, 10770. [CrossRef]
33. Zhang, T.; Zhu, T.; Gao, N.P. Optimization design and multi-criteria comprehensive evaluation method of combined cooling heating and power system. *Proc. CSEE* **2015**, *35*, 3706–3713.
34. Pan, X.; Liu, H.; Huan, J.; Sui, Y.; Hong, H. Allocation Model of Carbon Emission Permits for the Electric Power Industry with a Combination Subjective and Objective Weighting Approach. *Energies* **2020**, *13*, 706. [CrossRef]
35. Dong, F.G.; Zhang, Y.; Shang, M.M. Multi-criteria comprehensive evaluation of distributed energy system. *Proc. CSEE* **2016**, *36*, 3214–3223.
36. Malek, A.; Ebrahimnejad, S.; Tavakkoli-Moghaddam, R. An Improved Hybrid Grey Relational Analysis Approach for Green Resilient Supply Chain Network Assessment. *Sustainability* **2017**, *9*, 1433. [CrossRef]
37. Zeng, J.; Xu, D.D.; Guo, H.F. Renewable energy-oriented micro-grid power quality characteristic analysis and comprehensive evaluation. *Power Syst. Prot. Control* **2016**, *44*, 10–16.