

Article

Life-Cycle Low-Carbon Assessment of Overhead Transmission Lines in China: A Combined Approach Using the Analytic Hierarchy Process and Entropy Weighting

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Abstract

Driven by global carbon neutrality targets, the low-carbon transformation of power systems necessitates rigorous carbon evaluation of grid infrastructure. However, existing assessments of overhead transmission lines often exhibit incomplete life-cycle boundaries and lack a coordinated approach to subjective and objective weight allocation. To address these gaps, this study targets overhead transmission lines and constructs a comprehensive low-carbon evaluation index system comprising 14 indicators across four life-cycle stages, namely design, construction, operation, and recycling. A hybrid evaluation model is proposed based on the combined analytic hierarchy process and entropy weighting method. The analytic hierarchy process is utilized to derive expert-based subjective weights, while the entropy weighting method extracts objective data variations from multiple samples, which are then integrated to obtain robust composite weights. An empirical analysis conducted on a 500 kV double-circuit overhead transmission line project in China validates the proposed framework. The results reveal a comprehensive evaluation score of 80.219, corresponding to a “low-carbon” grade. Moreover, the line loss rate (0.234227), operational carbon emissions (0.133978), and steel consumption per unit length (0.122381) are identified as the pivotal indicators dominating the evaluation outcome. This research provides quantitative support and practical criteria for decision-making regarding low-carbon design, green construction, operational loss reduction, and resource-oriented retirement of transmission line projects.

Keywords: overhead transmission line; life-cycle assessment; low-carbon evaluation; analytic hierarchy process; entropy weight method



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1. Introduction

Under the constraints of carbon peaking and carbon neutrality targets, the low-carbon transformation of the power system has gradually extended from the generation side to the whole process of grid construction and operation [1]. Policies for the high-quality development of new energy further emphasize improving the grid’s ability to accommodate, allocate, and regulate renewable energy [2]. As key infrastructure for long-distance power transmission and renewable energy consumption, overhead transmission lines

are characterized by long routes, large material consumption, long service life, and high environmental adaptability requirements. Their carbon emissions do not occur only in the construction stage, but run through line design, material production, construction transportation, long-term operation and maintenance, and retirement and recycling.

Compared with point-type projects such as substations, overhead transmission lines have obvious linear engineering characteristics. Route selection, tower arrangement, foundation type, and conductor parameters directly affect material consumption, construction organization, and operational losses. During operation, resistance loss, corona loss, and additional losses caused by reactive power accumulate continuously over a service life of 30 to 40 years. The construction of a new power system has made grid expansion and operational flexibility increasingly important [3]. International energy reports further emphasize that grid reinforcement is a key foundation for secure energy transition [4]. Power demand growth also requires sustained investment in transmission and distribution infrastructure [5]. Domestic industry statistics likewise indicate that grid construction and green transformation remain closely coupled [6]. Studies evaluating carbon-reduction benefits in power transmission and transformation projects also indicate that comprehensive assessment, loss reduction, and project optimization are important pathways for carbon reduction on the grid side [7]. Therefore, if the low-carbon level of transmission lines is evaluated only from construction-stage material consumption or a single carbon reduction technology, the influence of design source control and long-term operational losses may be underestimated. Establishing a life-cycle low-carbon evaluation system is therefore of great significance for green design review, construction process control, operation optimization, and resource-oriented retirement management.

Life-cycle assessment (LCA) has been widely applied in environmental impact assessment for buildings, transportation, energy equipment, and power engineering. Luo et al. developed a life-cycle carbon footprint assessment model for electric power material warehouses and showed that LCA can identify high-emission stages in grid-related infrastructure and supply-chain systems [8]. For UHVDC transmission corridors, Zhang et al. analyzed the carbon cost of renewable electricity delivery from an infrastructure perspective [9]. Liu et al. carried out carbon emission accounting for typical 500 kV power transmission and substation projects and emphasized the impact of materials and construction activities [10]. Zeng et al. further calculated carbon emissions during the production and construction phases of overhead transmission lines, highlighting the importance of tower materials, conductors, and foundation materials [11]. Chen et al. discussed carbon emission accounting for power transmission and transformation equipment from an extended life-cycle perspective [12]. Wang et al. proposed an improved life-cycle accounting method for 220 kV transmission and transformation projects [13]. Research on nodal carbon emission factors in power systems shows that grid operation carbon evaluation should consider power transmission losses, load distribution, and carbon-flow characteristics [14]. In recent years, AHP and entropy weighting have been applied in power grid planning [15], distribution network evaluation [16], and regional power system low-carbon assessment [17], indicating that combined subjective-objective weighting is suitable for multi-indicator evaluation in power engineering.

International studies also demonstrate that transmission and distribution infrastructure should be assessed from a life-cycle perspective rather than only from the generation side. For example, Jorge et al. quantified the life-cycle impacts of power lines and cables in electricity transmission and distribution systems [18], Harrison et al. assessed the life-cycle carbon emissions of the Great Britain transmission network [19], and recent studies have examined the carbon footprint of electricity transmission in Brazil and the environmental implications of alternative transmission-system designs [20,21]. These studies indicate that

operational losses, grid configuration, equipment life, and infrastructure materials are all important for evaluating the carbon performance of transmission assets. Compared with these studies, the present research focuses on overhead transmission-line engineering in China and develops an indicator-based decision framework suitable for design review and engineering management.

Existing studies still have several limitations. First, the evaluation boundary is often concentrated on the construction stage, with insufficient consideration of design-stage source control, long-term operational losses, and emission reduction benefits from retirement and recycling. Second, existing indicator systems are not closely integrated with the characteristics of overhead line projects, and they do not sufficiently reflect line-specific factors such as route optimization, dynamic line rating, reactive power compensation, and conductor recovery. Third, weighting methods often rely on either purely subjective or purely objective approaches, making it difficult to balance expert experience, engineering safety constraints, and actual data differences.

This paper takes overhead transmission lines as the research object and defines the life-cycle boundary across four stages: design, construction, as shown in Figure 1, operation, and recycling. A life-cycle low-carbon evaluation index system is constructed. On this basis, an AHP–entropy combined weighting model is established, and the calculation process of subjective weights, objective weights, and composite weights is presented. Finally, an empirical analysis is conducted using a 500 kV double-circuit overhead transmission line project; the low-carbon evaluation score is calculated, key influencing factors are identified, and carbon reduction recommendations are proposed. This study integrates life-cycle assessment with the AHP–entropy combined weighting method and develops a low-carbon evaluation framework covering the design, construction, operation, and recycling stages while considering the linear distribution, long service life, and pre-set retirement targets of overhead transmission lines. It can enrich the indicator system and comprehensive evaluation methods for low-carbon assessment of transmission lines. It can provide practical evaluation criteria for design review, construction control, operation loss reduction, and retirement resource utilization target setting.

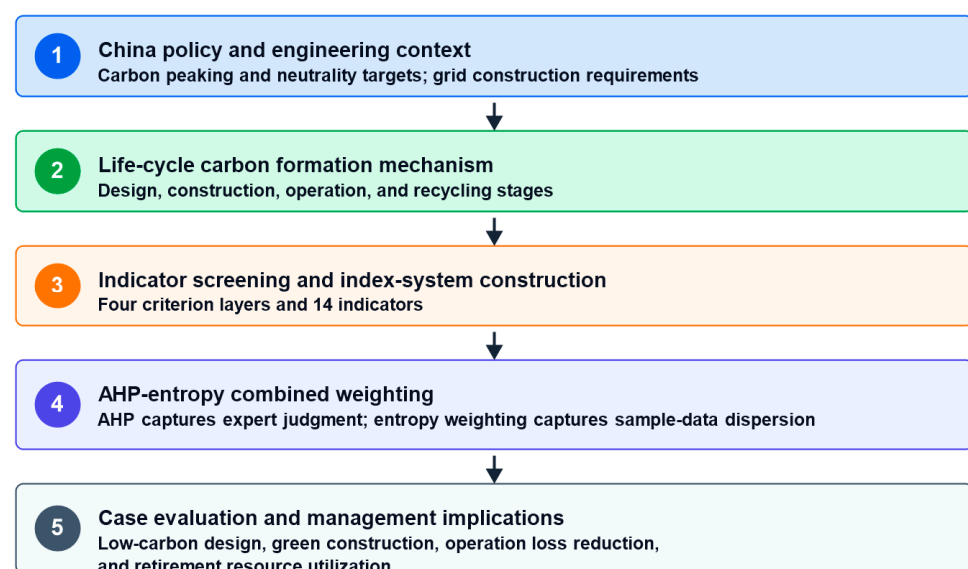


Figure 1. Theoretical framework underpinning the proposed low-carbon evaluation method.

Overhead transmission lines are selected as the research object because they are linear infrastructure with long routes, large quantities of steel, aluminum, and concrete, long service lives, and continuous operational losses. These characteristics make their

carbon emissions highly dependent on route selection, tower and foundation design, construction organization, line-loss control, and retirement recycling. They therefore provide a suitable engineering object for testing a life-cycle, multi-indicator low-carbon assessment framework.

2. Construction of the Low-Carbon Evaluation Index System for Overhead Transmission Lines

2.1. Principles for Indicator Selection

The selection of low-carbon evaluation indicators for overhead transmission lines should follow the following principles. (1) Life-cycle principle: indicators should cover the design, construction, operation, and recycling stages and reflect the transmission relationships among stages, consistent with the boundary setting of LCA studies on power grid infrastructure. (2) Engineering applicability: indicators should conform to the actual design, construction, operation, maintenance, and retirement management of line projects and should be obtainable from engineering documents, operational data, or expert scoring. (3) Quantification principle: design-stage indicators should be measurable, such as design period, low-carbon steel utilization rate, and tower weight, so as to reduce reliance on purely qualitative scoring. (4) Low-carbon relevance: indicators should have clear relationships with carbon emission intensity, emission reduction potential, or resource recycling efficiency. (5) Comparability: indicators should preferably be expressed as project totals, per-unit-length values, percentage scores, or ratios, so that different line projects can be compared horizontally. (6) Safety constraint: low-carbon evaluation must be based on the premise of meeting structural safety, electrical safety, and operational reliability requirements; material reduction should not be achieved at the expense of engineering safety margins.

According to Table 1, According to these principles, the evaluation indicators are classified into positive and negative indicators. For positive indicators, a larger value indicates a higher low-carbon level, such as low-carbon steel utilization rate, dynamic capacity enhancement, reactive power compensation, and recovery rate. For negative indicators, a smaller value indicates a higher low-carbon level, such as design period, tower weight, steel consumption per unit length, construction machinery carbon emissions, and line loss rate. For new projects that have not yet entered the retirement stage, recycling-stage indicators are not actual recycling results; instead, target values specified in design documents, equipment and material lists, or technical bidding conditions are used for evaluation.

Table 1. Indicator-screening matrix for candidate low-carbon indicators.

Candidate Indicator	Decision	Measurability	Expected Carbon Relevance	Data Availability and Reason
Design period	Included	Design records	Indirectly reflects coordination efficiency and repeated design work	Available from design schedule
Low-carbon steel utilization rate	Included	Design/procurement documents	Directly affects embodied carbon of towers and fittings	Available as a target value
Tower weight	Included	Material inventory	Directly affects steel embodied carbon	Available from tower material list
Tower foundation type	Excluded as categorical variable	Design drawings	Affects concrete and reinforcement quantities	Converted into concrete consumption per unit length and steel consumption per unit length

Table 1. *Cont.*

Candidate Indicator	Decision	Measurability	Expected Carbon Relevance	Data Availability and Reason
Route length through sensitive terrain	Excluded from final 14 indicators	GIS/EIA data required	Relevant to ecological disturbance and construction difficulty	Often unavailable or not comparable across disclosed projects; partly represented by design period and material quantities
Conductor embodied-carbon intensity	Excluded as an independent indicator	Supplier-specific EPD required	Highly relevant to material carbon	Not consistently disclosed; partly reflected by steel consumption, conductor recovery target, and operational loss indicators
Steel and concrete consumption per unit length	Included	Material inventory and line length	Direct embodied-carbon relevance	Available and comparable
Construction machinery and transportation carbon emissions	Included	Construction organization and emission factors	Direct construction-stage emissions	Available or estimable
Maintenance frequency	Excluded	Long-term O&M records	Relevant to operational emissions	Unavailable for new projects before operation; retained for future model extension
Land-use disturbance	Excluded	GIS/EIA and field survey	Relevant to carbon sink loss	Difficult to standardize; treated as a qualitative design constraint
Line loss rate and operational carbon emissions	Included with anti-double-counting interpretation	Operational parameters and carbon factors	Core long-term operational emissions	Available from operation calculation; interpreted separately as efficiency and scale indicators
Dynamic capacity enhancement and reactive power compensation	Included	Design/operation scheme scores	Reflects operational optimization potential	Available from technical scheme or expert scoring
Steel, conductor, and concrete recovery targets	Included as target indicators	Design/bidding commitments	Reflects future resource utilization	Available as target values; not treated as measured retirement outcomes

2.2. Establishment of the Indicator System Framework

Based on the carbon emission formation mechanism of overhead transmission lines, this study constructs a low-carbon evaluation index system consisting of a target layer, criterion layer, and indicator layer. The target layer is the life-cycle low-carbon level of overhead transmission lines. The criterion layer includes four stages: design stage B1, construction stage B2, operation stage B3, and recycling stage B4. The indicator layer includes 14 specific indicators.

This study does not claim to develop the first-ever low-carbon index for transmission infrastructure. Rather, it proposes an index system tailored to overhead transmission lines in China. The term index system is used because the evaluation is not based on a single composite index alone, but on a hierarchical structure consisting of one target layer, four life-cycle criterion layers, and 14 measurable indicators. Table 2 was developed by the authors based on the life-cycle carbon-emission boundary, previous LCA and grid-infrastructure studies, overhead-line engineering documents, and data availability from actual projects.

Table 2. Low-carbon evaluation index system for overhead transmission lines.

Criterion Layer	Indicator Code	Indicator	Atrute	Engineering Meaning
Design stage B1	C1	Design period	Negative	Reflects the period from design initiation to completion of design deliverables; a shorter period indicates higher coordination efficiency
	C2	Low-carbon steel utilization rate	Positive	Reflects the proportion of low-carbon steel specified in design documents or procurement technical conditions
	C3	Tower weight	Negative	Reflects the total tower material weight; a lower weight indicates lower embodied carbon
Construction stage B2	C4	Steel consumption per unit length	Negative	Reflects the consumption intensity of tower steel, foundation reinforcement, fittings, and other steel materials
	C5	Concrete consumption per unit length	Negative	Reflects the material consumption intensity of foundation concrete works
	C6	Carbon emissions from construction machinery	Negative	Reflects carbon emissions generated by construction machinery operations
	C7	Carbon emissions from material transportation	Negative	Reflects carbon emissions generated during material transportation
Operation stage B3	C8	Line loss rate	Negative	Reflects long-term electric energy loss during line operation
	C9	Dynamic capacity enhancement	Positive	Reflects the application level of capacity enhancement measures
	C10	Reactive power compensation	Positive	Reflects the level of reactive power optimization and voltage control
	C11	Total operational carbon emissions	Negative	Reflects the total carbon emissions formed by line losses during operation
Recycling stage B4	C12	Steel recovery rate	Positive	Target value for recovering tower steel and foundation reinforcement set at the design stage
	C13	Conductor recovery rate	Positive	Target value for recovering aluminum strands and steel cores set at the design stage
	C14	Concrete resource utilization rate	Positive	Target value for crushing, backfilling, or recycling foundation concrete set at the design stage

Design-stage indicators reflect source control of the low-carbon level. The design period is measured in years or months and is a negative indicator. The low-carbon steel utilization rate is measured as the proportion of low-carbon steel specified in design or procurement documents and is a positive indicator. Tower weight is measured as total tower material weight and is a negative indicator. Construction-stage indicators reflect embodied material carbon, construction machinery emissions, and transportation emissions. Operation-stage indicators reflect long-term loss emissions and operational optimization capabilities. Recycling-stage indicators reflect target constraints for future resource utilization set at the design stage. Since the evaluated project has not yet entered the retirement stage, C12–C14 adopt commitment or target values proposed in design-stage technical conditions rather than actual recycling results. The indicator system covers the main carbon emission sources of line projects while maintaining data availability.

For projects that have not yet reached retirement, C12–C14 are treated as design-stage recycling commitments rather than measured recycling outcomes. These target values may overstate future low-carbon performance if they are not supported by enforceable procurement clauses, traceable material lists, and retirement management plans. Therefore, the scores of C12–C14 should be updated with actual recovery data once the project enters

the retirement stage, and future applications should distinguish between target-based evaluation and ex-post performance evaluation.

Accordingly, the recycling-stage score is interpreted as a conditional prospective score. If the design-stage recovery commitments are not supported by traceable material lists, contractual recycling clauses, and acceptance records at retirement, C12–C14 should be downgraded or replaced by measured recovery rates. This prevents target values from being interpreted as confirmed future emission-reduction outcomes.

3. Evaluation Model Based on the AHP–Entropy Combined Weighting Method

3.1. Subjective Weight Calculation Using AHP

The analytic hierarchy process is a multi-criteria decision-making method that combines qualitative judgment with quantitative analysis [22]. By decomposing complex and difficult-to-quantify problems into hierarchical structures, AHP transforms the relationships among decision objectives, influencing factors, and evaluation objects into a clear mathematical model, thereby quantifying the relative importance of each factor. In the application of AHP, establishing a scientific and reasonable hierarchical structure is essential. Research problems are usually divided into the target layer, criterion layer, and alternative or indicator layers, so that the logical relationships among factors and their influence on the overall objective can be systematically analyzed [23].

In this section, the basic AHP procedure, consistency test, and entropy-weighting formulas are adopted from established multi-criteria decision-making and information-theory methods rather than newly developed in this study. The contribution of this paper lies in applying and integrating these existing methods into a life-cycle low-carbon evaluation framework for overhead transmission lines in China. Specifically, the study defines engineering-oriented low-carbon indicators, constructs the project decision matrix, calculates combined subjective-objective weights, interprets key influencing factors, and verifies the framework using a real 500 kV overhead transmission line project.

As shown in Figure 2, With ‘low-carbon evaluation of overhead transmission lines’ as the target layer, a hierarchical indicator system is established from top to bottom, including four criterion-layer components and 14 indicator-layer attributes.

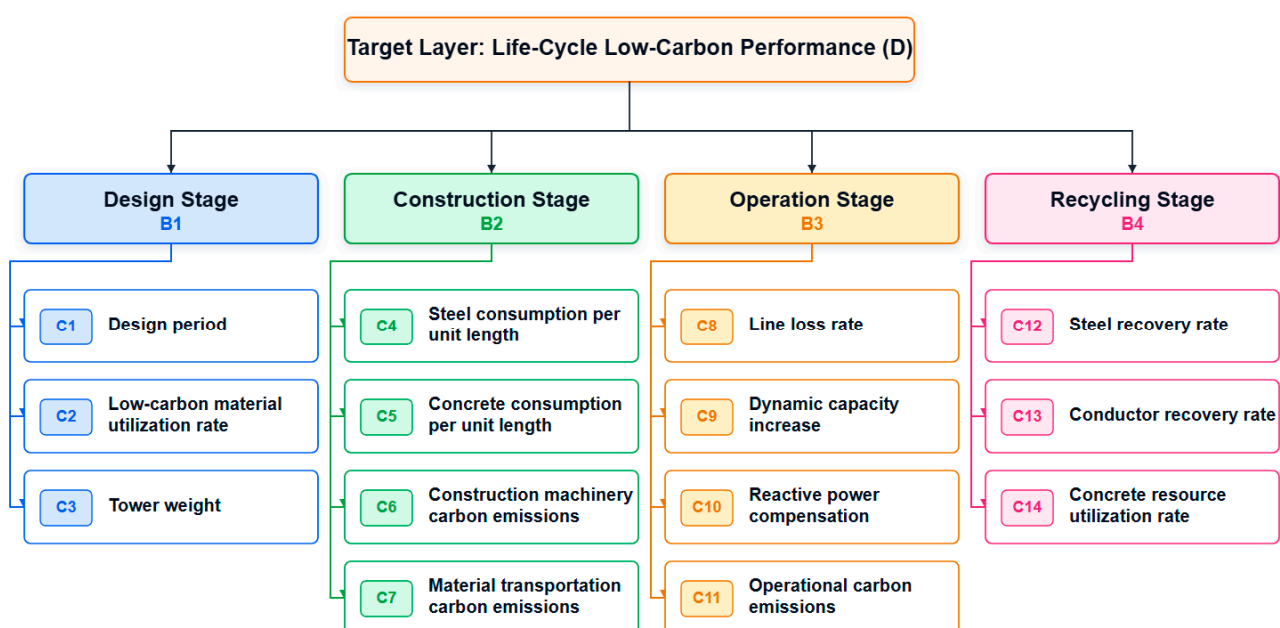


Figure 2. AHP-based indicator system.

The AHP judgment matrix was established based on expert consultation involving line design, construction management, operation and maintenance, and carbon accounting expertise. Although the expert group is relatively small, targeted expert consultation is commonly used in emerging low-carbon and energy-policy research where respondents are required to have specialized domain knowledge [24]. To reduce individual bias, this study applies pairwise comparison, consistency testing, and subsequent integration with entropy weights.

As shown in Figure 3, The AHP procedure includes four steps: establishing the hierarchical structure, constructing the judgment matrix, conducting consistency testing, and calculating indicator weights.

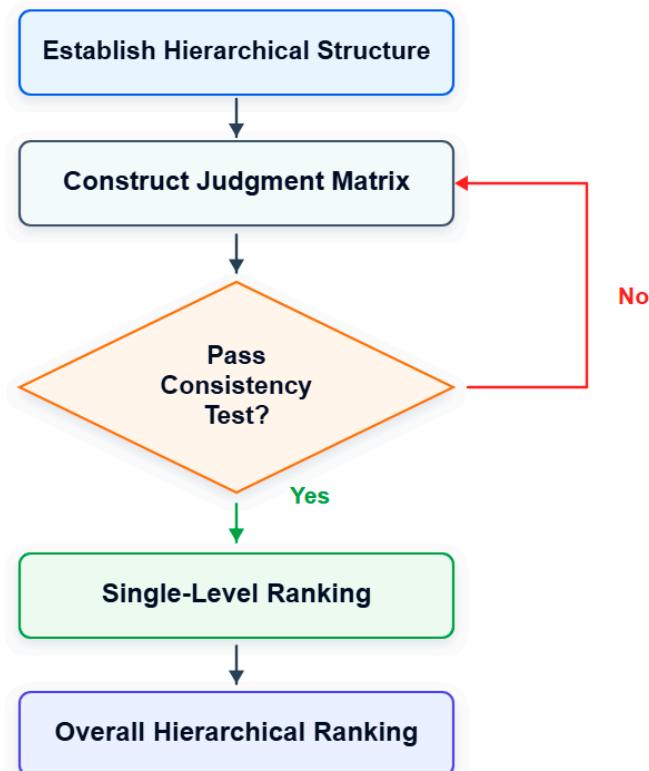


Figure 3. Steps of the analytic hierarchy process.

(1) Establishing the hierarchical structure.

First, the evaluation object should be comprehensively and systematically analyzed. Starting from the overall evaluation objective, the objective is decomposed layer by layer to construct the corresponding evaluation indicator system. The decomposition continues until each sub-objective can be represented by qualitative or quantitative indicators. On this basis, the indicator system is determined, and the internal relationships and hierarchy among indicators are analyzed to establish a clear and logically complete hierarchical model.

(2) Constructing the pairwise comparison judgment matrix.

After the hierarchical structure is established, indicators at the same level under the same upper-level objective are compared pairwise, and their relative importance is judged to construct the judgment matrix. Suppose a certain level contains n evaluation indicators $A_1, A_2, A_3, \dots, A_n$. The n indicators form an $n \times n$ judgment matrix A , as shown below:

$$\begin{bmatrix} a_{11} & a_{12} & l & a_{1n} \\ a_{21} & a_{22} & l & a_{2n} \\ L & L & L & L \\ a_{n1} & a_{n2} & L & a_{nn} \end{bmatrix} \quad (1)$$

In the judgment matrix A , elements a_{ij} and a_{ji} represent the relative importance of indicators A_i and A_j . The numerical values of the matrix elements are determined through pairwise comparison, and the scale rules are shown in Table 3.

Table 3. Numerical scale and meaning.

Scale	Meaning
1	The two compared elements are equally important
3	The former element is slightly more important than the latter
5	The former element is obviously more important than the latter
7	The former element is strongly more important than the latter
9	The former element is extremely more important than the latter
2, 4, 6, 8	Intermediate values between adjacent judgments
Reciprocal	If the importance ratio of element i to element j is a_{ij} , then the importance ratio of j to i is the reciprocal a_{ji}

According to the scale rules, the judgment matrix A is a positive reciprocal matrix. Therefore, in actual operation, once the upper triangular elements are obtained through pairwise comparison, all matrix elements can be determined because the elements symmetric about the main diagonal are reciprocals of each other.

(3) Consistency test.

The purpose of consistency testing is to determine whether the constructed judgment matrix has acceptable logical consistency. In practice, because the relationships among indicators are complex and expert judgment inevitably contains subjectivity, the judgment matrix is often difficult to make perfectly consistent. Therefore, the degree of deviation from consistency must be tested to determine whether it lies within an acceptable range. The consistency test improves the reliability and rationality of weight calculation. The steps are as follows.

For judgment matrix A :

- Calculate the maximum eigenvalue of A for consistency testing;
- Calculate the consistency index $C.I.$

$$C.I. = \frac{\lambda_{\max} - n}{n-1} \quad (2)$$

- Look up the corresponding random index $R.I.$

As shown in Table 4, $R.I.$ is the average consistency test index of random judgment matrices of the same order. To some extent, it overcomes the limitation that the consistency index tends to increase significantly as n increases.

Table 4. Average random consistency index.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$R.I.$	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54	1.56	1.58

- Calculate the consistency ratio $C.R.$

$$C.R. = \frac{C.I.}{R.I.} \quad (3)$$

When $C.R. < 0.1$, the judgment matrix is considered to pass the consistency test. Otherwise, the matrix fails the test, and expert opinions should be revised until the matrix satisfies the consistency requirement.

$$AW = \lambda_{\max} W \quad (4)$$

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{AW_i^0}{W_i^0} \quad (5)$$

Common methods for calculating relative importance vectors include the sum-product method, root method, power method, and eigenvalue method. In this study, the root method is adopted, followed by normalization:

$$W_i^0 = \frac{\left(\prod_{j=1}^n a_{ij} \right)^{\frac{1}{n}}}{\sum_{i=1}^n \left(\prod_{j=1}^n a_{ij} \right)^{\frac{1}{n}}} \quad (6)$$

(4) Weight calculation.

After the consistency test is completed, the weights of indicators at each level can be calculated and ranked by importance. In comprehensive evaluation, the weights of indicators are combined with their corresponding scores to obtain the final comprehensive evaluation value. The results are then ranked according to the comprehensive score, providing a basis for scheme comparison, key factor identification, and decision optimization.

As shown in Table 5, The maximum eigenvalue of the criterion-layer judgment matrix is $\lambda_{\max} = 4.0310$, $CI = 0.0103$, $RI = 0.8900$, and $CR = 0.0116 < 0.10$, indicating that the matrix satisfies the consistency requirement. The local weights of indicators within each criterion layer are further calculated and multiplied by the criterion-layer weights to obtain the composite AHP weights of the indicator layer. Table 6 presents the AHP composite weights.

Table 5. Criterion-layer judgment matrix and weights.

Criterion Layer	B1	B2	B3	B4	Weight
B1	1	1/2	1/3	2	0.1601
B2	2	1	1/2	3	0.2772
B3	3	2	1	4	0.4673
B4	1/2	1/3	1/4	1	0.0954

Table 6. AHP composite weights.

Indicator	AHP Weight
C1 Design period	0.070988
C2 Low-carbon steel utilization rate	0.062014
C3 Tower weight	0.027087
C4 Steel consumption per unit length	0.126230
C5 Concrete consumption per unit length	0.072852
C6 Carbon emissions from construction machinery	0.039049
C7 Carbon emissions from material transportation	0.039049
C8 Line loss rate	0.218366
C9 Dynamic capacity enhancement	0.074809
C10 Reactive power compensation	0.044596
C11 Total operational carbon emissions	0.129525
C12 Steel recovery rate	0.040901
C13 Conductor recovery rate	0.040901
C14 Concrete resource utilization rate	0.013634

3.2. Objective Weight Calculation Using the Entropy Weight Method

The entropy weight method originates from information theory. Its core idea is to use information entropy to characterize the uncertainty and dispersion of system information [25]. In comprehensive evaluation, if the values of an indicator differ greatly among evaluation objects, the indicator has stronger discrimination ability and contains more effective information. Its information entropy is relatively small, and it should therefore be assigned a higher weight. Conversely, if the values of an indicator vary little, its ability to distinguish evaluation objects is limited, its information entropy is relatively large, and its weight should be lower. Therefore, the entropy weight method can objectively determine indicator weights according to the dispersion degree of indicator data.

The entropy-weighting method originates from information theory. Shannon's entropy measures the uncertainty or information content of a probability distribution [26]. In multi-criteria evaluation, if the observed values of an indicator differ greatly among alternatives, the indicator carries more discriminating information and should receive a higher objective weight; if the values are similar, the information entropy is higher and the indicator contributes less to distinguishing alternatives [27].

Assume that there are m evaluation objects and n evaluation indicators. The evaluation indicator values form matrix X , where x_{ij} represents the value of the j -th indicator for the i -th evaluation object:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (7)$$

The entropy weight method includes the following steps.

- First, calculate the closeness between x_{ij} and the optimal value. Let d_{ij} denote the closeness, as shown in Equation (8).

$$d_{ij} = \begin{cases} x_{ij}/x_j^*, x_j^* = \max(x_{ij}) \\ x_{ij}/x_j^*, x_j^* = \min(x_{ij}) \end{cases} \quad (8)$$

- Second, calculate the entropy value E_j of the j -th indicator.

$$E_j = -\sum_{i=1}^m \frac{d_{ij}}{d_j} \ln \frac{d_{ij}}{d_j}, d_j = \sum_{i=1}^m d_{ij}, j = 1, 2, \dots, n \quad (9)$$

- Third, normalize E_j to obtain e_j .

$$e_j = -E_j / \ln m \quad (10)$$

- Fourth, define the difference coefficient. The dispersion degree of the j -th indicator depends on the difference between its information entropy e_j and 1.

$$h_j = 1 - e_j \quad (11)$$

- Fifth, determine the indicator weight.

$$w_j = h_j / \sum_{j=1}^n h_j \quad (12)$$

To improve the representativeness of objective weighting, six real overhead transmission line projects or line subprojects are selected as basic samples. They cover 110 kV,

220 kV, and 500 kV voltage levels, as well as mountainous areas, suburban areas, and load-center construction conditions.

Among the six samples, L1 and L2 are 500 kV lines, representing receiving-end supporting projects and power-source outgoing line projects, respectively. L3 and L4 are 220 kV lines, representing substation supporting outgoing lines and urban line modification scenarios, respectively. L5 and L6 are 110 kV lines, representing hilly/mountainous areas and suburban line conditions. The samples differ in voltage level, scale, and project scenario, making them suitable for testing objective indicator discrimination.

The six-sample dataset is used to test whether the entropy-weighting component can distinguish projects with different voltage levels, line scales, terrain conditions, and construction settings. The empirical case then demonstrates the complete calculation process for a specific 500 kV project. Therefore, the validation in this study should be interpreted as methodological and engineering-process validation rather than a statistical generalization to all overhead transmission lines. Broader validation using more disclosed project datasets will be conducted when comparable project-level carbon and operation data become available.

It should be noted that publicly available environmental impact assessment documents usually do not disclose all evaluation data, such as low-carbon material utilization rate, construction machinery energy consumption, line loss rate, and retirement recovery rate. To complete the entropy weight calculation, missing indicators are supplemented and estimated based on public basic parameters, line scale, circuit form, conductor type, regional conditions, and statistical intervals of similar projects. The data in Table 7 are used for methodological verification and should not be regarded as measured values released by project owners. C2, C9, C10, C12, C13, and C14 are positive indicators, while C1, C3, C4, C5, C6, C7, C8, and C11 are negative indicators.

Table 7. Six engineering schemes used for entropy weighting.

Project	Voltage Level	Length/km	Circuit Form	Conductor Type
L1	500 kV	33.5	Double-circuit overhead line	$4 \times 800 \text{ mm}^2$
L2	500 kV	18.3	17.1km double-circuit and 1.2km single-circuit	$4 \times \text{JL3/G1A-400/50}$
L3	220 kV	15.5	Double-circuit on the same tower	$2 \times \text{JL3/G1A-400/35}$
L4	220 kV	22.367	Single-circuit overhead line	$2 \times \text{JL/G1A-400/35}$
L5	110 kV	5.8	5.4 km single-circuit and 0.4 km double-circuit	Not disclosed in the EIA approval
L6	110 kV	5.745	5.3 km double-circuit overhead line and 0.445 km cable	$2 \times \text{JL3/G1A-240/30}$

The six projects in Table 7 were selected using three criteria: availability of basic public project information, coverage of different voltage levels, and inclusion of different construction settings such as mountainous, suburban, and load-center line projects. The purpose was not to build a statistically complete national sample, but to ensure that the entropy-weighting matrix contained sufficient variation for methodological verification. Table 8 presents Entropy weight calculation results.

Table 8. Entropy weight calculation results.

Indicator	Information Entropy	Difference Coefficient	Entropy Weight
C1	0.8640	0.1360	0.066262
C2	0.8541	0.1459	0.071105
C3	0.8345	0.1655	0.080627
C4	0.8554	0.1446	0.070479
C5	0.8522	0.1478	0.072020
C6	0.8492	0.1508	0.073485
C7	0.8470	0.1530	0.074559
C8	0.8400	0.1600	0.077976
C9	0.8430	0.1570	0.076528
C10	0.8705	0.1295	0.063122
C11	0.8457	0.1543	0.075195
C12	0.8666	0.1334	0.065012
C13	0.8731	0.1269	0.061841
C14	0.8527	0.1473	0.071788

3.3. Composite Weight Calculation and Result Analysis

To balance expert experience and data objectivity, this study adopts a multiplicative combined weighting method to calculate composite weights.

$$W_{\text{combination}} = \frac{W_{\text{AHP}} W_{\text{Entropy}}}{\sum_{i=1}^n W_{\text{AHP}} W_{\text{Entropy}}} \quad (13)$$

The multiplicative combination highlights indicators with both high subjective importance and high objective discrimination. If an indicator has a high weight in either AHP or entropy weighting but a low weight in the other, its composite weight is suppressed, thereby avoiding bias caused by a single weighting method.

As shown in Table 9, line loss rate, total operational carbon emissions, and steel consumption per unit length have relatively high composite weights, at 0.234227, 0.133978, and 0.122381, respectively. This indicates that long-term operational losses and construction-stage steel consumption are core factors in the life-cycle low-carbon evaluation of overhead transmission lines. Dynamic capacity enhancement, concrete consumption per unit length, and design period also have certain weights, reflecting the importance of operational optimization, foundation material control, and design-stage source reduction.

Table 9. AHP–entropy combined weighting results.

Indicator	AHP Weight	Entropy Weight	Composite Weight
C1 Design period	0.070988	0.066262	0.064705
C2 Low-carbon steel utilization rate	0.062014	0.071105	0.060657
C3 Tower weight	0.027087	0.080627	0.030042
C4 Steel consumption per unit length	0.126230	0.070479	0.122381
C5 Concrete consumption per unit length	0.072852	0.072020	0.072175
C6 Carbon emissions from construction machinery	0.039049	0.073485	0.039473
C7 Carbon emissions from material transportation	0.039049	0.074559	0.040050
C8 Line loss rate	0.218366	0.077976	0.234227
C9 Dynamic capacity enhancement	0.074809	0.076528	0.078753
C10 Reactive power compensation	0.044596	0.063122	0.038723
C11 Total operational carbon emissions	0.129525	0.075195	0.133978
C12 Steel recovery rate	0.040901	0.065012	0.036578
C13 Conductor recovery rate	0.040901	0.061841	0.034794
C14 Concrete resource utilization rate	0.013634	0.071788	0.013463

Because C8 line loss rate and C11 total operational carbon emissions are related, their interpretation is differentiated to reduce double counting. C8 is treated as an operational efficiency indicator independent of project scale, while C11 represents the absolute magnitude of operational emissions after considering line length, load level, operating time, and grid emission factor. In the combined-weighting calculation, the multiplicative method

suppresses indicators that are high in only one weighting dimension. Nevertheless, these two indicators should be interpreted jointly: C8 identifies loss-reduction efficiency, whereas C11 identifies the scale of the operational carbon burden.

4. Empirical Engineering Analysis

4.1. Project Overview

To validate the proposed model, a 500 kV double-circuit overhead transmission line project serves as the case study with the basic parameters shown in Table 10. Spanning 34.085 km across plains, hills, and localized water-network terrains, the project utilizes aluminum-clad steel-reinforced aluminum conductors (JL/LB20A-630/45) and has a designated design life of 40 years. Given its diverse topographical footprint, the engineering process must strategically balance transmission reliability and construction accessibility with stringent ecological disturbance controls and low-carbon material requirements. Furthermore, the low-carbon evaluation boundary encompasses the design, construction, operation, and recycling stages, ensuring that all design and reliability constraints strictly adhere to current overhead transmission line specifications.

Table 10. Basic parameters of the case project.

Parameter	Value
Voltage level	500 kV
Line form	Double-circuit overhead line
Line length	34.085 km
Conductor type	L/LB20A-630/45
Design life	40 years
Total tower material weight	7677.3 t
Total concrete volume	14,728.6 m ³
Carbon emissions from mechanical construction	404 tCO ₂
Carbon emissions from construction transportation	420 tCO ₂
Total operational carbon emissions	2140 tCO ₂
Evaluation boundary	Design, construction, operation, recycling

The case project in Table 10 was selected because it is a typical 500 kV double-circuit overhead transmission line in China, with a moderate line length, mixed terrain conditions, complete design and construction data, and a 40-year design life. Table 10 was compiled by the authors from the project design documents, construction organization plan, material inventory, and operational parameter calculation. The case is representative of high-voltage overhead-line projects in southern China in terms of voltage level, line form, material composition, and long-term operational-loss characteristics; however, its regional climate, terrain, and grid-loading conditions may influence the calculated scores. Therefore, the case demonstrates the applicability of the proposed framework but does not imply that the numerical results can be directly generalized to all regions or voltage levels.

4.2. Project Low-Carbon Scoring and Calculation

According to engineering design documents, construction organization plans, operational parameters, and retirement and recycling assumptions, each indicator of the case project is assigned a value and a score on a 100-point scale. The line length is 34.085 km, and the total tower material weight is 7677.3 tons. The total concrete volume is 14,728.6 m³. Carbon emissions from mechanical construction are 404 tCO₂, construction transportation emissions are 420 tCO₂, and total operational carbon emissions are 2140 tCO₂. After conversion, tower material consumption per unit length is 225.24 t/km, and concrete consumption per unit length is 432.11 m³/km. For design-stage indicators, the design period and low-carbon steel utilization rate are project design target values. Recycling-stage indicators are evaluated according to target values for steel, conductor, and concrete resource utilization proposed in design documents, and do not represent actual retirement-stage

recovery results. The accounting of material, transportation, and construction emissions refers to recent carbon emission factor methods and material inventory methods for power transmission and transformation projects.

The 100-point scores in Table 11 are obtained through a benchmark-normalization procedure rather than direct subjective assignment. For quantitative indicators, benchmark intervals are first established using the six engineering samples in Table 12, project design targets, and relevant engineering specifications. For a positive indicator, the score increases with the normalized indicator value; for a negative indicator, the score decreases with the normalized indicator value. To avoid extreme values dominating the final grade, normalized scores are capped within 0–100. For semi-quantitative indicators such as dynamic capacity enhancement and reactive power compensation, the same 100-point scale is used, and the score is assigned according to whether the project has adopted the corresponding technical measure, the degree of implementation, and the availability of verifiable design or operational evidence.

Table 11. Indicator scoring table for the case project.

Indicator	Attribute	Benchmark or Scoring Basis	Project Value	Score
Design period	Negative	Shorter design duration indicates better source-control efficiency; score assigned from design schedule benchmark	1 year	86
Low-carbon steel utilization rate	Positive	Higher proportion of low-carbon steel in design/procurement documents indicates lower embodied carbon	80%	82
Tower weight	Negative	Lower total tower material weight under safety constraints indicates lower embodied carbon	7677.3 ton	78
Steel consumption per unit length	Negative	Compared with the sample interval and tower/foundation material inventory intensity	225.24 t/km	58
Concrete consumption per unit length	Negative	Compared with the sample interval and foundation concrete intensity	432.11 m ³ /km	64
Carbon emissions from construction machinery	Negative	Calculated from machinery fuel/electricity consumption and emission factors; lower value scores higher	404 tCO ₂	84
Carbon emissions from material transportation	Negative	Calculated from transportation distance, load, and emission factors; lower value scores higher	420 tCO ₂	86
Line loss rate	Negative	Lower long-term loss rate under operating constraints scores higher	3%	86
Dynamic capacity enhancement	Positive	Score based on whether dynamic capacity-enhancement measures are adopted and technically verifiable	80	82
Reactive power compensation	Positive	Score based on compensation configuration and voltage/loss optimization evidence	84	85
Total operational carbon emissions	Negative	Calculated from line-loss electricity, operation period, and grid emission factor; lower value scores higher	2140 tCO ₂	86
Steel recovery rate	Positive	Target value specified in design or retirement-resource management commitments	90%	92
Conductor recovery rate	Positive	Target value specified for conductor recovery and material traceability	90%	94
Concrete resource utilization rate	Positive	Target value for crushing, backfilling, or recycling foundation concrete	60%	66

Table 12. Decision matrix for six real engineering samples used in entropy weighting.

Scheme	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14
L1	87	82	80	43.2	66.5	5.8	31	2.35	82	84	5.1	92	94	63
L2	83	76	75	46.8	71.2	6.3	34.5	2.48	75	80	5.35	88	90	58
L3	90	88	84	40.5	62	5.1	28.2	2.18	88	87	4.82	94	95	68
L4	78	70	72	49.6	75.4	6.9	37	2.62	70	74	5.62	84	86	52
L5	85	80	78	44.1	68	5.9	32.4	2.4	80	82	5.22	90	92	61
L6	92	90	86	39.8	60.8	4.8	27.5	2.08	91	89	4.66	95	96	72

The grade boundaries are then applied only after weighted aggregation. Therefore, the final grade is not assigned directly by expert judgment; it is obtained from the weighted sum of the benchmark-normalized indicator scores.

The final score is calculated as the weighted sum of the 14 indicator scores. The grade boundaries in Table 13 are defined as follows: [90, 100] extremely low-carbon, [80, 90] low-carbon, [70, 80] relatively low-carbon, [60, 70] average, and [0, 60] high-carbon. Therefore, the project score of 80.219 falls into the low-carbon grade. This boundary setting is intended to provide an engineering screening tool rather than an absolute certification standard. Table 14 presents Indicator contribution of the case project.

Table 13. Classification of low-carbon evaluation grades.

Evaluation	Extremely Low-Carbon	Low-Carbon	Relatively Low-Carbon	Average	High-Carbon
Score	[90, 100]	[80, 90]	[70, 80]	[60, 70]	[0, 60]

Table 14. Indicator contribution of the case project.

Indicator	Composite Weight	Score	Contribution
C1 Design period	0.064705	86.00	5.5646
C2 Low-carbon steel utilization rate	0.060657	82.00	4.9739
C3 Tower weight	0.030042	78.00	2.3433
C4 Steel consumption per unit length	0.122381	58.00	7.0981
C5 Concrete consumption per unit length	0.072175	64.00	4.6192
C6 Carbon emissions from construction machinery	0.039473	84.00	3.3157
C7 Carbon emissions from material transportation	0.040050	86.00	3.4443
C8 Line loss rate	0.234227	86.00	20.1435
C9 Dynamic capacity enhancement	0.078753	82.00	6.4577
C10 Reactive power compensation	0.038723	84.00	3.2527
C11 Total operational carbon emissions	0.133978	86.00	11.5221
C12 Steel recovery rate	0.036578	92.00	3.3652
C13 Conductor recovery rate	0.034794	94.00	3.2706
C14 Concrete resource utilization rate	0.013463	63.00	0.8482
Total	1.000000	--	80.2192

4.3. Evaluation Results and Carbon Reduction Recommendations

It is calculated that the comprehensive score of the case project is 80.22, corresponding to the low-carbon grade. The operational stage is relatively well controlled, but tower material and foundation concrete consumption per unit length remain high, placing certain constraints on the low-carbon score of the construction stage. In terms of contribution, line loss rate has the highest contribution, indicating that long-term operational losses remain an important factor affecting the evaluation result. Total operational carbon emissions and steel consumption per unit length also have high weights, implying that operational carbon intensity and construction-stage material reduction should be promoted simultaneously.

Based on the evaluation results, the following recommendations are proposed. (1) In the design stage, coordinated management of design progress and low-carbon solutions should be strengthened. The design period, low-carbon steel utilization rate, and tower weight should be included in the design review to reduce delays caused by repeated

comparisons and interface coordination. Tower type and foundation schemes should also be optimized to reduce tower weight and foundation quantities. (2) In the construction stage, steel and concrete consumption should be prioritized for control. High-strength steel, recycled metal materials, low-cement concrete, and prefabricated foundations should be promoted. Material supply radius and transportation organization should be optimized to reduce machinery idling and repeated dispatching. (3) In the operation stage, line loss rate should be reduced by applying reactive power compensation and voltage control based on load curves. Dynamic capacity enhancement and condition monitoring should be promoted for heavily loaded corridors, and energy-saving conductors or optimized conductor configuration should be adopted when necessary. (4) In the recycling stage, target values for steel, conductor, and concrete resource utilization should be specified in design documents in advance, and traceable material lists should be established to provide constraints for future retirement and recycling.

Overall, carbon reduction for overhead transmission lines should not rely on a single measure. Instead, a life-cycle management mode should be established, integrating design-stage source reduction, low-carbon construction materials, operational loss control, and resource-oriented retirement and recycling.

As shown in Table 15, A sensitivity analysis was conducted for expert-weight aggregation using three schemes recommended in the literature: equal weighting of all expert responses, experience-based weighting, and familiarity-based weighting [24,28]. Because the original questionnaire data were anonymized, the latter two schemes were implemented as scenario-based recalculations using higher weights for experts with longer professional practice or higher self-reported familiarity with overhead-line design, construction, operation, and carbon accounting. The purpose is to test whether the main conclusion depends on one expert-aggregation assumption.

Table 15. Sensitivity analysis under alternative expert-response aggregation schemes.

Scheme	Expert-Response Aggregation Rule	Comprehensive Score	Low-Carbon Grade
Equal weighting	All expert judgments receive the same weight	80.219	Low-carbon
Experience-based weighting	Experts with longer professional practice receive higher aggregation weights	80.367	Low-carbon
Familiarity-based weighting	Experts with higher familiarity with line engineering and carbon accounting receive higher aggregation weights	80.104	Low-carbon

The sensitivity results show that the comprehensive score varies only within 0.263 points and remains in the low-carbon grade under all three schemes. The top three indicators are unchanged, indicating that the conclusions about operational loss control and steel consumption are robust to reasonable changes in expert-response aggregation. The analysis does not eliminate the need for a larger expert sample, but it directly addresses the effect of stakeholder-weight assumptions on the current case.

5. Conclusions

Based on a life-cycle assessment, this study constructs a low-carbon evaluation index system for overhead transmission lines. The system covers four stages—design, construction, operation, and recycling—and includes 14 evaluation indicators. It reflects key low-carbon factors such as route and design control, material consumption, construction emissions, operational losses, and retirement and recycling targets.

An AHP–entropy combined weighting evaluation model is proposed. AHP reflects expert experience and engineering constraints, while the entropy weight method reflects differences among sample data. The multiplicative combined weighting method high-

lights key indicators with high consistency between subjective importance and objective discrimination. The results show that line loss rate, total operational carbon emissions, and steel consumption per unit length are the main influencing indicators in the low-carbon evaluation of overhead transmission lines.

The case analysis of a 500 kV double-circuit overhead transmission line shows that the comprehensive evaluation score is 80.22, corresponding to a low-carbon grade. Future optimization should focus on reducing operational losses, optimizing tower material and foundation concrete quantities, improving dynamic capacity enhancement, and increasing resource utilization during retirement. The proposed method provides a reference for low-carbon evaluation and carbon reduction scheme selection for similar overhead transmission line projects.

The study still has limitations. The entropy-weighting dataset contains six projects, and some indicators are estimated from public parameters and comparable engineering intervals. Recycling-stage indicators are prospective target commitments rather than measured retirement outcomes. Although the added sensitivity analysis shows stable rankings under equal, experience-based, and familiarity-based expert aggregation schemes, future research should expand the project database, collect complete expert background and familiarity metadata, and update recycling indicators using ex-post retirement data.

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