A Hybrid AHP-CRITIC Framework for Green Quality Evaluation of Power Cables

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Abstract: This paper presented a green quality evaluation method for power cable. It analyzed the carbon emissions during the cable production process, and a green indicator system has been established according to the quality testing standards of China State Grid. Focusing on production energy consumption, quality inspection results, and raw material carbon costs, it developed a "goal-criterion-indicator" framework to construct a low-carbon evaluation system. Specifically, the Analytic Hierarchy Process (AHP) was utilized to determine the weights of production energy consumption and emission indicators, whereas the Criteria Importance Through Intercriteria Correlation (CRITIC) method was employed to calculate the weights of quality and criterion-layer indicators, thereby a comprehensive green evaluation model has been formed.

Keywords: Power Cables; AHP; CRITIC; Carbon Footprint

1. Introduction

As one of the world's most populous developing countries, China faces challenges in balancing high-quality development with security [1]. Traditional industries suffer from high energy use and emissions, with transformation pressures ongoing [2]. Energy and electricity demand grows, complicating grid operations, while environmental issues persist with high pollutant and carbon emissions. With the implementation of the "carbon peak" plan, it is necessary to control carbon emissions from the source [3]. Power grid materials like cables affect operational reliability and lifespan [4]. Currently, many studies have been focused on green quality evaluation of transformer [5,6], but the cable green quality evaluation needs improvement [7]. The current quality assessment standards for power materials only focus on quality indicators and ignore carbon footprint indicators, and the low-carbon indices may conflict with quality ones [8,9]. So, a balanced green index system is urgently needed for grid materials evaluation [10]. This paper proposes a green evaluation method for cables based on analyzing production carbon footprints and aligning with State Grid standards. It builds a goal-criterion-indicator framework by weighting energy and emissions via AHP and quality via CRITIC.

2. Indicator Set Construction

The ZC-YJV22-8.7/15-3*400 type cable is a typical high-voltage cross-linked polyethylene insulated PVC power cable with excellent electrical, mechanical, and thermal properties, which is widely used in power transmission and distribution systems. Therefore, it has been selected as our study object. Its production process is shown in Figure 1.

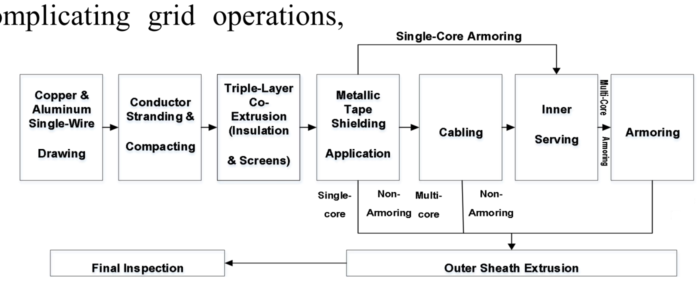

Figure 1. Production Process

Our goal is to establish a scientific comprehensive evaluation index system that takes into account various factors, such as environmental impact, resource consumption, energy efficiency, and quality throughout the entire production life cycle of power cable, and quantify the green quality levels of cable. The suggested cable quality index system is shown in Figure 2.

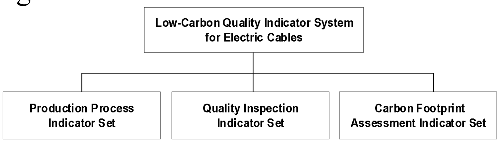

Figure 2. Low-Carbon Quality Indicator System for Power Cables

2.1 Construction of Production Energy Consumption Indicator Set

The production process of power cable consists of nine stages (can be seen as nine indicators): wire drawing, stranding, insulation extrusion, copper tape shielding, three-core cabling, inner sheath extrusion, steel tape armoring, outer sheath extrusion, and performance testing. Energy consumption during these stages primarily comes from electricity consumed by powers machinery, heating systems, cooling mechanisms, and control devices, with considerable variation across different stages.

Indicator selection involves a two-step screening to ensure relevance and distinctiveness. Firstly, it uses Pearson correlation analysis to examine the inter-stage relationships of the above indicators, yielding coefficients near 0 (e.g., 0.420 for wire drawing and stranding) and p-values greater than 0.05, which indicated that there are no significant correlations among these indicators. Secondly, it uses a one-dimensional K-means clustering algorithm to categorize these stages by standard deviation into two groups: a high variability and a low variability group, using iterative threshold calculations (initial T from mean standard deviation, updated via group means until convergence).

According to the above steps, five indicators have been selected as production energy consumption indicator set: insulation extrusion, wire drawing, outer sheath extrusion, inner sheath extrusion, and stranding, as shown in Figure 3. These indicators capture the majority of energy use and fluctuations, enabling focused low-carbon optimization.

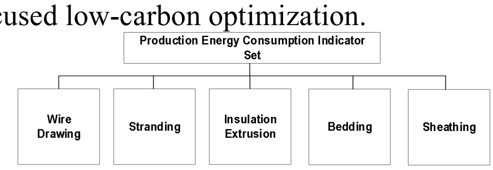

Figure 3. Production Energy Consumption Indicator Set

2.2 Construction of Quality Inspection Indicator Set

The quality inspection of cables must comply with the relevant standards of the State Grid of China. The testing process includes over 20 tests, which include structural and dimensional verification, conductor resistance, mechanical properties pre- and post-aging, thermal extension, shrinkage, insulation resistance, partial discharge, voltage endurance and flame retardancy. Here a test can be seen as an indicator.

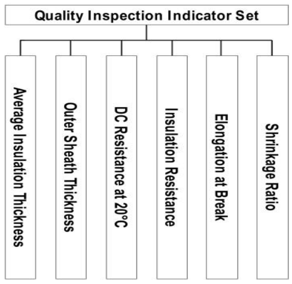

Figure 4. Quality Inspection Indicator Set

To streamline and eliminate redundancy of these indicators, they are screened based on their critical impact on performance, reliability, and energy efficiency. Finally, five indicators are selected: (1) structural and dimensional checks, which was chosen for ensuring installation compatibility and minimizing energy losses from mismatches; (2) conductor DC resistance with 20°C temperature, which is selected to evaluate conductivity and reduce transmission inefficiencies; (3) insulation resistance measurement, which is prioritized to prevent leakage and enhance long-term stability; (4) thermal extension of insulation and elastomeric sheath, which is selected to assess thermal adaptability and fault prevention; and (5) XLPE insulation shrinkage test, which is picked to verify material stability under temperature variations, avoiding deformation-related energy waste. The selected indicators can directly influence the green quality of cable. The quality inspection indicator set is depicted in Figure 4.

2.3 Construction of Carbon Footprint Characteristic Indicator Set

Considering the magnitude of carbon emissions, five indicators are selected for their direct quantification of environmental impact: (1) major raw material consumption (e.g., copper, aluminum, insulation); (2) raw material transportation distances; (3) transportation mode; (4) proportion of clean energy in production; (5) waste recycling rate. The carbon footprint characteristic indicator set is shown in Figure 5.

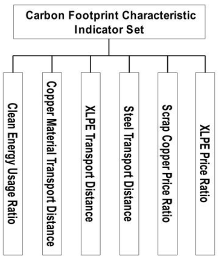

Figure 5. Carbon Footprint Characteristic Indicator Set

3. Indicator Weighting

The weighting methodology is used for the green quality evaluation indicators of power cables for ensuring a robust and balanced assessment. The AHP is employed as the primary structural framework, it organizes the indicators hierarchically into goal, criterion, and indicator layers, facilitating a systematic evaluation of the low-carbon quality for the cable. Additionally, the CRITIC method is applied to derive weights for the production energy consumption and carbon footprint characteristic indicator sets, leveraging objective measures of data variability and inter-indicator conflicts. In parallel, AHP is used for weighting the quality inspection indicator set and the criterion layer, incorporating subjective insights from expert judgments. This integrated hybrid strategy results in comprehensive weights for the entire system, promoting an equitable low-carbon quality appraisal.

(1) CRITIC method

The CRITIC method was employed to assign weights to the indicator sets for energy consumption and carbon emissions in production processes. It determines weights by comprehensively considering both the standard deviation (dispersion) of data under each indicator and the correlation coefficients (similarity) between indicators. The details are elaborated below:

Let C_j denotes the information content contained in the j-th indicator (dimension or component). Then C_j can be expressed ass Formula 1. The Pearson correlation coefficient R_{ij} is given by Formula 2.

$$C_j = \delta_j \sum_{i=1}^{n} (1 - r_{ij}) \tag{1}$$

$$r_{ij} = \frac{n\sum xy - \sum x \sum y}{\sqrt{n\sum x^2 - (\sum x)^2}\sqrt{n\sum y^2 - (\sum y)^2}} \tag{2}$$

The proportion of the i-th sample value relative to the j-th indicator is calculated using Formula 3.

$$\rho_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, (i = 1,2,3,...,n; j = 1,2,3,...,m) \tag{3}$$

The entropy value of the j-th indicator (column) is calculated using Formula 4, where k is determined by Formula 5.

$$e_j = -k\sum_{i=1}^{n} \rho_{ij} \times \ln(\rho_{ij}), (j = 1,2,3,...,m) \tag{4}$$

$$k = \frac{1}{ln\,(n)}, \left(0 \le e_j \le 1\right) \tag{5}$$

The divergence coefficient of the j-th indicator (column) is calculated using Formula 6.

$$d_{ij} = 1 - e_j \tag{6}$$

The weight of the j-th indicator (column) is calculated using Formula 7.

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j}, (j = 1,2,3,...,m) \tag{7}$$

(2) AHP method

The AHP method is a method of subjectively scoring indicators to determine weights. It provides a consistency testing mechanism to ensure the transitivity of indicator preferences, effectively avoiding scoring errors and reducing evaluation bias caused by subjective judgments. It is employed to establish the weight vectors for individual indicators within the quality inspection indicator set and the criterion-layer weight vector of the indicator system. The specific steps are as follows:

1) Analyzing the relationships between various factors in the system and establishing a hierarchical structure for the system.

2) Starting from the top layer, based on the elements of the previous layer from top to bottom, compare the elements of the next layer pairwise and construct a judgment matrix. For example, with research object A as the target, b_i and b_j (i, j = 1, 2, 3, . n) represent each indicator factor. b_{ij} represents the relative importance of b_i to b_j The judgment matrix A-B is composed of b_{ij}.

$$A - B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \tag{8}$$

Here, b_{ij} represents the relative importance degree of the i-th element compared to the j-th element within the same hierarchy. According to the 1~9 scale method in the table, this value quantifies importance levels such as "equal", "moderate", "strong", "very strong", or "extreme".

3) Using the geometric mean method to calculate the maximum eigenvalue and corresponding eigenvector, and then using the maximum eigenvalue λ_{max} for consistency testing. For the n-order judgment matrix, the specific calculation process is as follows:

Calculating the product of each element in each row of the judgment matrix according to Formula 9.

$$m_i = \prod_{i=1}^{n} a_{ij}, (i = 1,2,3,...,n) \quad (9)$$

Calculating the n-th root according to Formula10.

$$\overline{W_i} = \sqrt[n]{m_i} \quad (10)$$

Normalizing the vector in accordance with Formula 11. This vector represents the desired eigenvector. The normalization process is as follows:

$$\widehat{W}_i = \frac{\overline{W_i}}{\sum_{i=1}^{n} \overline{W_i}} \quad (11)$$

Calculating the maximum eigenvalue of the judgment matrix according to Formula 12.

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{A\widehat{W}_i}{\widehat{W}_i} (i = 1,2,3, ..., n) \quad (12)$$

Calculating the consistency index according to Formula 13.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (13)$$

Calculating the consistency ratio according to Formula 14.

$$CR = \frac{CI}{RI} \quad (14)$$

Among them, RI refers to the random consistency index, which is obtained by looking up the table.

3.1 Weighting Approach

The weighting method adopts balances subjectivity and objectivity to improve the reliability of the low-carbon quality assessment framework.

Specifically, AHP establishes the hierarchical architecture, wherein the goal layer encapsulates the overarching green quality objective; the criterion layer encompasses production energy consumption, quality inspection, and carbon footprint characteristics; and the indicator layer delineates precise metrics within each criterion. The empirical foundation stems from surveys involving 20 production batches at various manufacturers, which yielded detailed datasets including energy consumption metrics, quality inspection outcomes, and carbon footprint parameters.

CRITIC is applied on the production energy consumption set, which includes five indicators, and is also used for the carbon footprint set, which comprises six indicators. In contrast, AHP is applied to the quality inspection set, which consists of six indicators. It is also applied to the criterion layer, using pairwise comparisons obtained from 10 experts. The resulting composite weights are calculated by multiplying the criterion-level weights by the corresponding sub-indicator weights and normalizing the sum to one, thus providing a unified weighting scheme.

3.2 Weighting Results

The weights are meticulously calculated using our survey data from cable manufacturers, which included energy consumption, quality metrics, and carbon parameters.

(1) Criterion Layer

The judgment matrix A for the criterion layer, with rows and columns corresponding to production energy consumption, quality inspection, and carbon footprint respectively, is derived from expert averages and presents as follows:

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 0.5 & 1 & 1.5 \\ 0.333 & 0.667 & 1 \end{bmatrix}.$$

The principal eigenvector yields the weight vector W = [0.545, 0.273, 0.182], with λ_{max}= 3.000, CI= 0.001, and CR = 0.001, confirming perfect consistency. Consequently, the criterion weights emphasize production energy consumption most heavily, following by quality inspection and carbon footprint.

(2) Production Energy Consumption Set

The raw data matrix for production energy consumption includes 20 batches × 5 indicators: wire drawing, stranding, insulation extrusion, inner sheath extrusion, outer sheath extrusion(all cost-type in kWh).The minima and maxima per indicator are $mins$ = [111, 70, 141, 80, 101] and $maxs$ = [130, 89, 160, 99, 120].The standard deviations vector is [0.303, 0.303, 0.303, 0.303, 0.303]. leading to the conflict vector $Conflict_{prod}$= [4, 6, 4, 6, 4] and information vector C_{prod} = [1.214, 1.821, 1.214, 1.821, 1.214]. Thus, the weights are w_{prod} = [0.167, 0.250, 0.167, 0.250, 0.167], highlighting stranding and inner sheath extrusion as more variable contributors.

(3) Quality Inspection Set

The judgment matrix B for the quality inspection indicators (rows and columns: insulation average thickness, outer sheath thickness, DC resistance, insulation resistance, load elongation rate, shrinkage rate) is

$$B = \begin{bmatrix} 1 & 2 & 3 & 4 & 3 & 5 \\ 0.5 & 1 & 2 & 3 & 2 & 4 \\ 0.333 & 0.5 & 1 & 2 & 1 & 3 \\ 0.25 & 0.333 & 0.5 & 1 & 0.5 & 2 \\ 0.333 & 0.5 & 1 & 2 & 1 & 3 \\ 0.2 & 0.25 & 0.333 & 0.5 & 0.333 & 1 \end{bmatrix}.$$

The weight vector is $W_{quality}$ = [0.366, 0.231, 0.136, 0.080, 0.136, 0.052], with λ_{max} = 6.073, CI = 0.015, and CR = 0.012, indicating high consistency. This distribution underscores the prominence of insulation average thickness in quality assessments.

(4) Carbon Footprint Set

The raw data matrix for carbon footprint includes 20 batches × 6 indicators: clean energy proportion (benefit), copper transportation distance (cost), XLPE transportation distance (cost), steel transportation distance (cost), waste copper price ratio (benefit), XLPE price ratio (benefit). It can be derived: the conflict vector $conflict_{carb}$ = [0.707, 0.707, 1.277, 1.277, 0.644, 0.632] and information vector C_{carb} = [0.215, 0.215, 0.386, 0.386, 0.196, 0.193]. Hence, the weights are w_{carb} = [0.135, 0.135, 0.243, 0.243, 0.123, 0.121], with transportation distances for XLPE and steel exhibiting greater influence due to their higher variability.

The composite global weights, derived by scaling sub-weights with criterion weights and normalizing them to sum to 1 across all 17 indicators, are as follows: for production energy consumption indicators [0.091, 0.136, 0.091, 0.136, 0.091]; for quality inspection [0.100, 0.063, 0.037, 0.022, 0.037, 0.014]; and for carbon footprint [0.025, 0.025, 0.044, 0.044, 0.022, 0.022]. This holistic weighting scheme integrates the diverse dimensions, allowing for a nuanced green quality evaluation.

4. Green Quality Evaluation and Analysis

The green quality evaluation model for the power cable uses the weights established before to calculate the final scores. A straightforward weighted summation approach is applied to combine the normalized indicator values, thus quantifying the overall green quality performance based on our survey data from 20 production batches data. The evaluation encompasses production energy consumption, quality inspection and carbon footprint characteristics, it offers insights into the manufacturer's low-carbon practices.

4.1 Green Quality Evaluation Model

The evaluation model employs a hierarchical weighted summation method, where the overall green quality score S for each batch is calculated as follows:

$$S = w_p \cdot S_p + w_p \cdot S_q + w_c \cdot S_c \quad (15)$$

where w_p = 0.545, w_q = 0.273, and w_c = 0.182 are the criterion weights for production energy consumption, quality inspection, and carbon footprint respectively; and S_p , S_q , and S_c represent the sub-scores for each criterion, computed as the weighted sum of their normalized indicator values.

Sub-scores are derived by multiplying the normalized values by their respective indicator weights and summing them. This process yields scores ranging from 0 to 1, where higher values indicate superior green quality. The average score across batches provides an overall assessment for the cable manufacturer.

4.2 Scoring Results

Based on the survey data, the computation results revealed the following sub-scores for each criterion across the 20 batches.

Production energy consumption sub-scores: [0.501, 0.501, 0.500, 0.501, 0.500, 0.501, 0.500, 0.501, 0.500, 0.501, 0.500, 0.500, 0.501, 0.500, 0.501, 0.500, 0.501, 0.500, 0.501, 0.500]

Quality inspection sub-scores:
[0.500, 0.608, 0.391, 0.706, 0.293, 0.804, 0.195, 0.901, 0.098, 0.999, 0.000, 0.554, 0.657, 0.342, 0.755, 0.244, 0.853, 0.146, 0.950, 0.049]

Carbon footprint sub-scores:
[0.510, 0.290, 0.625, 0.411, 0.567, 0.345, 0.682, 0.253, 0.740, 0.468, 0.392, 0.394, 0.214, 0.828, 0.156, 0.885, 0.099, 0.943, 0.041, 1.000]

The total scores per batch are
[0.502, 0.492, 0.493, 0.540, 0.456, 0.555, 0.450, 0.565, 0.434, 0.631, 0.344, 0.496, 0.491, 0.516, 0.508, 0.500, 0.524, 0.484, 0.540, 0.468].

The average green quality score across all batches is 0.499, indicating a moderate performance level. This suggests opportunities for improvement by optimizing energy-intensive processes and enhancing material sustainability to elevate the overall green quality. Additionally, carbon footprint indicators suggest opportunities for optimizing transportation distances and adopting clean energy.

5. Conclusion

This article has constructed a green evaluation system for the production and manufacturing of 10kV cables. Firstly, it is proposed that the framework consists of three indicator sets, namely the production process energy consumption indicators set, the quality inspection indicators set, and the carbon footprint characteristic indicators set, and the constituent elements of each indicator set are given; Then, the CRITIC is used to assign weights to the energy consumption index set and carbon emission index set of the production process; The AHP method is adopted to assign weights to the quality inspection indicator set and criterion layer indicators, and finally the weights of each indicator are obtained, thus achieving the green quality evaluation of cable products. Taking 20 batches of data obtained from a survey of a cable manufacturer as an example, we have rated the green quality of the manufacturer's cables and gave suggestions for green production of cables.

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