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Research on the decision framework of an energy storage traction system plan for rail transit from the low-carbon perspective—based on the interval-value Pythagorean intuitionistic fuzzy environment

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Low carbonization of the traction system is the key to low-carbon rail transit operation, and its preliminary plan decision plays a decisive role in whether low carbon can be achieved in later stages. Therefore, how to achieve scientific decisions of energy storage traction systems in a low-carbon background is a problem that needs to be solved. The innovation of this paper is as follows: first, aiming at the reality of the rail transit energy storage traction system, a decision index system of the energy storage traction system which contains seven attributes and 18 criteria is constructed; second, aiming at the uncertainty of decision information and the decision makers' aversion to risk, the decision model adapted to the energy storage traction system decision is constructed based on the interval Pythagorean intuitionistic fuzzy number and VIKOR model principle. The decision index system and decision model together constitute the decision framework. The case study results show that the decision index system can provide scientific guidance for the decision of the energy storage traction system, and the decision model can provide risk aversion type decision results with good robustness.

KEYWORDS

rail transit, energy storage traction system, plan decision, interval Pythagorean, VIKOR

1 Introduction

On 22 September 2020, at the 75th United Nations General Assembly, President Xi Jinping proposed that China's carbon dioxide emissions should strive to reach the peak by 2030 and strive to achieve the dual carbon goals of carbon peaking and carbon neutrality by 2060. Therefore, all fields are facing an important transformation of low-carbon development. From a global perspective, compared to other fields, such as construction and industry, low-carbon transportation development has always been a global challenge due to factors such as high resource utilization and unreasonable energy consumption.

Meanwhile, due to the rapid development of urbanization in China, the rapid development of the transportation industry has brought about a sharp increase in pressure on energy conservation and emission reduction.

In the transportation industry, rail transit has been favored by government departments due to its advantages, such as large volume, fast speed, dense schedules, safety and comfort, high punctuality rate, all-weather operation, and low freight costs. Its proportion in the transportation industry is increasing day by day. The main energy consumed by rail transit is the use of electricity generated by burning coal, and its rapid growth will greatly increase carbon emissions, which is not conducive to achieving the dual carbon target of China.

The main energy consumption of rail transit comes from the traction system in the electrical system. Therefore, in the context of dual carbon targets, to achieve the low-carbon development of rail transit, the low-carbon development of the traction system is crucial, and an energy storage traction system (ESTS) is one of the important directions for the low-carbon development of the traction system.

In the decision stage of newly built rail transit projects, the design unit will provide multiple sets of ESTS plans. However, how to scientifically select suitable plans based on the characteristics of specific rail transit lines is an urgent problem that needs to be solved in the current low-carbon development process of rail transit.

1.1 Literature review on the decision index system of an energy storage traction system plan for rail transit

The energy storage devices in the ESTS can be divided into capacitor-based energy storage devices and flywheel energy storage devices (Dan et al., 2020), and capacitor-based energy storage devices are widely used. Decision-making research on the ESTS mainly focuses on the following aspects: when it is a renovation project, that is, the traction system has been determined, the main research focus is on the selection of energy storage batteries, for example, Hou Pengqi's research on the plan of energy storage systems based on supercapacitors through ESTS simulation (Pengqi et al., 2022); when it is a new project and the energy storage system and traction system are not determined, the optimization research of the system is mainly based on simulation, for example, Dong Wenzhe's research on the optimization operation of integrated hybrid energy storage and the RPC traction power supply system (Wenzhe et al., 2023); Li Ling studied an energy storage train with supercapacitors as the sole power source and verified the feasibility of traction system operation through simulation (Ling et al., 2018).

The aforementioned research studies are mainly based on simulation technology and scenario analysis methods to study the impact of new energy storage batteries and new ESTS techniques on rail transit operation and to select energy storage equipment or optimize system design based on the obtained characteristics of energy storage batteries and system operation.

The aforementioned research provides a good foundation for this study, but the plan of the ESTS should not only consider the characteristics of the equipment but also consider the cost of the system, as well as reliability, availability, maintainability, and safety, abbreviated as RAMS, to ensure the sustainability of rail transit projects.

Therefore, the development of ESTS plans needs to be considered from seven aspects: energy storage battery characteristics, system operation characteristics, system cost, reliability, availability, maintainability, and safety. Currently, there is a lack of relevant decision index systems to guide the plan and decision of ESTS plans.

1.2 Review of relevant literature on decision models for the ESTS in rail transit

To achieve scientific decision of ESTS plans, in addition to a scientific decision index system, it is more important to develop a scientific decision model, and the most important aspect of the scientific nature of the decision model is its suitability for the specific decision environment. The characteristics of ESTS decisions are the uncertainty of decision information and risk aversion decision.

The uncertainty of decision information mainly comes from the qualitative evaluation of the system. Due to the need for qualitative evaluation to be scored by experts, who are limited by their knowledge level and background limitations, hesitation is inevitable when facing newly developed systems, such as the ESTS. Therefore, the qualitative evaluation values provided by experts are inevitably uncertain.

Fuzzy mathematics is often used to deal with the uncertainty of decision information, such as intuitionistic fuzzy numbers (IFNs) (Kumar and Chen, 2022), interval-valued intuitionistic fuzzy numbers (IVIFNs) (Percin, 2022), interval-valued Pythagorean intuitionistic fuzzy numbers (IVPIFNs) (Peng and Yang, 2016), or directly using linguistic terms, such as the probability linguistic term set (Malik et al., 2018)[6].

Due to the large amount of engineering data involved in the ESTS plan, the evaluation value of the plan is mainly based on quantitative data, so it is best to use fuzzy mathematics. According to the data expression ways of the IFN, IVIFN, and IVPIFN, as shown in Table A1, the sum of the satisfaction degree and non-satisfaction degree of the IVPIFN can be greater than 1, and this feature enables it to better handle uncertainty. Therefore, the IVPIFN will be used in this article.

In addition, the decision of the ESTS plan belongs to the risk aversion decision because rail transit involves people's life and property safety, so the ESTS does not have to have the best performance, but must not have accidents.

The commonly used decision models in the field of rail transit are the AHP (Dong et al., 2022), ANP (Peng et al., 2022), and TOPSIS methods (Yin et al., 2022), which pursue the maximization of utility value (refer to Table 2 for details). Therefore, there is an implicit assumption that criteria can compensate each other, and the mutual compensation between criteria will lead to risk preference decision results. For example, the evaluation values of ESTS plans X and Y on the energy storage battery characteristic criterion (marked A) and reliability criterion (marked B) are ($X_A = 8$, $X_B = 1$) and ($Y_A = 4, Y_B = 4$). If the weights of criteria A and B are both 0.5, then the scores of plans X and Y are 4.5 and 4, respectively. However, the alternative plan X is significantly weaker in reliability criterion than

TABLE 1 Decision criterion system for the ESTS plan from the perspective of low-carbon development.

No.	Attribute	No.	Index	Characteristic	Source
A1	Energy storage battery characteristics	C11	Energy density	Positive	Khodaparastan et al. (2019)
		C12	Cycle life	Positive	
		C13	Battery capacity	Positive	
A2	System operation characteristics	C21	Control the status of train operation	Positive	Alshammari et al. (2011)
		C22	Total traction energy consumption	Positive	
		C23	Energy feedback percentage of regenerative braking	Positive	
A3	System cost	C31	Construction cost	Negative	Shaojie (2015)
		C32	Operating cost	Negative	
A4	System reliability	C41	Mean time between failures (months)	Positive	Ding, 2019; Lu et al. (2022)
		C42	Trip fault time interval of traction power supply system (months)	Positive	
		C43	Fault frequency (times/month)	Negative	
		C44	Steady-state unavailability	Negative	
A5	System maintainability	C51	The convenience of system fault detection	Positive	Ding, 2019; Alencar (2023)
		C52	Convenience in identifying and locating system faults	Positive	
		C53	The degree of modularity of the system	Positive	
A6	System safety	C61	Probability of safety accidents occurring	Negative	Ding, 2019; Fang et al. (2022)
		C62	Maintainability of safety-related components	Positive	
		C63	System operation safety	Positive	

Positive criteria indicate that a larger value is better, while negative criteria indicate that a smaller value is better.

the alternative plan Y. Choosing option X will result in lower system reliability.

In the field of decision science, the VIKOR method is different from other methods. It is a risk aversion decision-making method, which is the judgment standard for the optimal plan to determine whether the degree of regret is the minimum or not. Therefore, it is more suitable for the ESTS plan decision (Kim and Ahn, 2020).

1.3 Contributions and originality

This article will construct a decision index system for the rail transit ESTS from seven aspects, energy storage battery characteristics, system operation characteristics, system cost, reliability, availability, maintainability, and safety, to make scientific decisions. On this basis, the IVPIFN is used to deal with the uncertainty of the decision information of the rail transit ESTS, and the VIKOR model is used to deal with the risk aversion problem. Based on the decision index system and decision model, a decision framework for the ESTS of rail transit is jointly constructed to achieve scientific decisions. The specific innovation points are as follows:

- The decision index system for the ESTS in rail transit is established, providing direction for scientific decision.
- The IVPIFN is used to handle uncertainty in decision information and improve the robustness of decision results.
- A decision model of the rail transit ESTS based on the VIKOR model is constructed to realize risk aversion decisions and conform to the decision habits of decision makers.

2 Research on the decision index system of an ESTS plan of rail transit

In the introduction, the ESTS needs to be considered from seven aspects: energy storage battery characteristics, system operation characteristics, system cost, reliability, availability, maintainability, and safety. However, availability is reflected through relevant data on reliability and maintainability during post-project evaluation because availability cannot be reflected during the decision stage. Therefore, this factor is not considered when constructing a decision index system. In this article, the decision index system for ESTS plans is mainly examined from energy storage battery characteristics, system operation characteristics, system cost, reliability, maintainability, and safety attributes. The specific decision criteria, criteria characteristics, and sources under each attribute are shown in Table 1. The data of alternatives on each criterion in the decision index system can be obtained through expert scoring, experimentation, or examining projects of the same type.

The energy storage traction system can be transformed from the determined traction system to the energy storage traction system. Since the traction system has been determined at this time, the

TABLE 2 Decision values of the ESTS.

	S1	S2	S3
C11	21.84	24	22.8
C12	4.7	4.95	5
C13	12,000	10,000	11,000
C21	[(0.77, 0.78), (0.14, 0.25)]	[(0.70, 0.71), (0.23, 0.28)]	[(0.73, 0.74), (0.22, 0.32)]
C22	4.97	4.57	4.72
C23	53.00	45.05	46.11
C31	1	0.95	0.98
C32	0.96	0.94	1
C41	15.432	16.942	14.547
C42	0.0665	0.0645	0.0647
C43	0.0709	0.0768	0.065
C44	3.95	3.79	4.07
C51	[(0.64, 0.65), (0.35, 0.39)]	[(0.48, 0.50), (0.22, 0.24)]	[(0.53, 0.54), (0.32, 0.37)]
C52	[(0.60, 0.63), (0.23, 0.26)]	[(0.41, 0.42), (0.35, 0.37)]	[(0.42, 0.44), (0.31, 0.34)]
C53	[(0.77, 0.78), (0.14, 0.25)]	[(0.63, 0.71), (0.23, 0.28)]	[(0.62, 0.74), (0.22, 0.32)]
C61	0.0304	0.0293	0.0309
C62	[(0.94, 0.96), (0.06, 0.07)]	[(0.86, 0.86), (0.09, 0.24)]	[(0.95, 0.98), (0.05, 0.07)]
C63	[(0.85, 0.86), (0.09, 0.24)]	[(0.88, 0.89], (0.12, 0.15)]	[(0.96, 0.97), (0.06, 0.07)]

Due to confidentiality, the cost is presented in proportion here.

problem of studying the energy storage battery is to consider the characteristics of the energy storage battery as an attribute when making the decision and meet the low-carbon, economical, efficiency, and sustainability requirements. To make planning decisions for energy storage traction systems from a low-carbon perspective, it is necessary to evaluate the system economy. To meet the dual carbon goals, high-performance batteries must be selected to meet the economic requirements of low-carbon development in energy storage traction systems. Otherwise, the battery life is short and the economy is poor. Therefore, the cycle life of energy storage batteries should be considered as an indicator. When the battery energy density and capacity are high, the power supply and storage efficiency of the system are higher, so energy density and battery capacity should be used as indicators. At the same time, when it belongs to a new project, the energy storage system and traction system are still uncertain, and optimization research based on simulation is needed for the system. Therefore, the operational characteristics of the system should be taken as the attribute. Because the main energy consumption of the project during system operation comes from the traction system, the total energy consumption of the system traction should be considered. In addition, the stable state of the system should be considered during operation, while the energy storage traction system should be applied in rail transit, so the control state of train operation should be considered.

To meet the requirements of low-carbon environmental protection and economy, the energy feedback percentage of regenerative braking should also be considered.

The energy storage traction system is an important heart that provides power for the normal operation of rail transit and is a core component of the entire high-speed railway system. The operation of high-speed railways is risky and accidents might occur due to the influence of the environment and operating conditions. Moreover, due to the nature of the high-speed railway system's work and operation, which involves people's livelihoods, the consequences and subsequent impacts of accidents are very serious and severe. According to statistics, the proportion of accidents causing rail operation interruption due to traction system failures is quite large in all types of rail transit accidents. Therefore, to avoid rail transit accidents, the reliability, maintainability, and safety of the system should be considered in the planning and decision making of the rail transit energy storage traction system.

Under the reliability attribute, its characteristic quantity is generally a quantitative indicator that reflects the overall reliability of the system. Therefore, the average number of faults in the system and the number of tripping faults in the traction power supply system should be counted. Based on this, the interval time and fault frequency should be calculated, and the reliability of the system in terms of sustainability should be represented by the interval time and fault frequency between system faults. Since the energy storage traction system provides energy for the rail transit system and the unavailability represents the ratio of the system failure time to the sum of the failure time and the normal power supply time, the unavailability of the system in the stable state is also an important indicator to measure the system reliability.

Under the maintainability attribute, it is very important to quickly check the cause of system faults when a system malfunctions. Therefore, the convenience of system fault

TABLE 3 Weights of decision criteria for the ESTS.

No.	Subjective importance	Subjective weight	No.	Subjective importance	Subjective weight	Objective weight	Comprehensive weight	Criterion weights considering attribute
A1	7	0.17	C11	8	0.44	0.33	0.39	0.07
			C12	4	0.22	0.34	0.28	0.05
			C13	6	0.33	0.33	0.33	0.06
A2	7	0.17	C21	7	0.33	0.25	0.29	0.05
			C22	8	0.38	0.35	0.37	0.06
			C23	6	0.29	0.40	0.35	0.06
A3	4	0.10	C31	5	0.38	0.50	0.44	0.04
			C32	8	0.62	0.50	0.56	0.06
A4	8	0.20	C41	8	0.31	0.24	0.28	0.05
			C42	8	0.31	0.27	0.29	0.06
			C43	5	0.19	0.24	0.22	0.04
			C44	5	0.19	0.26	0.23	0.04
A5	7	0.17	C51	6	0.33	0.25	0.29	0.05
			C52	6	0.33	0.22	0.28	0.05
			C53	6	0.33	0.53	0.43	0.07
A6	8	0.20	C61	6	0.33	0.31	0.32	0.06
			C62	6	0.33	0.35	0.34	0.07
			C63	6	0.33	0.33	0.33	0.07

detection, identification, and location of system faults should be considered. The modularization level of the system can make it easier to check the system's partition. Therefore, to facilitate inspection and maintenance, it should also become a key indicator in decision making and planning.

Under the safety attribute, the probability of safety accidents occurring can directly reflect the safety level of the system, and the maintainability of safety-related components and the safety level of the system operation can indirectly reflect the safety of the system.

When evaluating a system solution, cost is an essential attribute. It can be divided into construction cost and operating cost, of which construction cost is inevitable but can be compressed through improved project plans and construction cost is a factor that must be considered before project implementation. The operating cost is directly related to the profitability and survival and development of the project, which can directly reflect the competitiveness and sustainable development ability of the project, and is conducive to resource allocation. Therefore, operating cost is also a necessary indicator to consider.

3 Research on the decision model of the ESTS plan from the perspective of low-carbon development

After determining the decision index system for the ESTS plan, it is necessary to determine the decision model based on the decision characteristics of the ESTS plan. In this paper, the IVPIFN will be used as the data expression of decision values to reduce the impact of uncertainty, and risk aversion decisions will be realized through the basic principles of the VIKOR model. In this section, the relevant theories of the IVPIFN are introduced first, and based on this, a decision model for ESTS plans will be constructed based on the basic principles of the VIKOR model and the decision characteristics of the ESTS plan.

3.1 Relevant theory of the IVPIFN

Definition 1. (Peng and Yang, 2016). Let X be a finite nonempty set, and the IVPIFN can be defined as follows:

$$P = \{\langle x, \tilde{\mu}(x), \tilde{v}(x)\rangle, x \in X\}, \tag{1}$$

where $\tilde{\mu}(x) = [\mu^L(x), \mu^U(x)]$ indicates the degree of satisfaction, $\mu^L(x)$ indicates the lower limit of satisfaction, $\mu^U(x)$ indicates the upper limit of satisfaction, $\tilde{v}(x) = [v^L(x), v^U(x)]$ denotes the non-satisfaction degree, $v^L(x)$ indicates the lower limit of non-satisfaction, $v^U(x)$ indicates the upper limit of non-satisfaction, and satisfaction and non-satisfaction satisfy the following relationship: $(\mu^U(x))^2 + (v^U(x))^2 \leq 1$. In addition, the IVPIFN also has interval hesitation, which is $\tilde{\pi}(x) = [\pi^L(x), \pi^U(x)]$, $\pi^U(x) = \sqrt{1 - \mu^L(x)^2 - v^L(x)^2}$, and $\pi^L(x) = \sqrt{1 - \mu^U(x)^2 - v^U(x)^2}$. x_i is the i-th element in the X set. The IVPIFN can be expressed as $([\mu_P^L(x_i), \mu_P^U(x_i)], [v_P^L(x_i), v_P^U(x_i)])$; for convenience of expression, a_i is used to represent $\mu_P^L(x_i)$, b_i is used to represent $\mu_P^U(x_i)$, c_i is used to represent $\upsilon_P^L(x_i)$, and d_i is used to represent $\upsilon_P^U(x_i)$. Therefore, $([\mu_P^L(x_i), \mu_P^U(x_i)], [\upsilon_P^L(x_i), \upsilon_P^U(x_i)])$ can be expressed as $([a_i, b_i], [c_i, d_i])$ in this article.

Definition 2. (Peng and Yang, 2016). We assume $p = ([a, b], [c, d])$, $p_1 = ([a_1, b_1], [c_1, d_1])$, and $p_2 = ([a_2, b_2], [c_2, d_2])$ for three IVPIFNs, and $\lambda > 0$。. Then, the operation is defined as follows:

$$p_1 \oplus p_2 = \left(\left[\sqrt{a_1^2 + a_2^2 - a_1^2 a_2^2}, \sqrt{b_1^2 + b_2^2 - b_1^2 b_2^2}\right], [c_1 c_2, d_1 d_2]\right), \quad (2)$$

$$p_1 \otimes p_2 = \left([a_1 a_2, b_1 b_2], \left[\sqrt{c_1^2 + c_2^2 - c_1^2 c_2^2}, \sqrt{d_1^2 + d_2^2 - d_1^2 d_2^2}\right]\right), \quad (3)$$

$$p^\lambda = \left(\left[a^\lambda, b^\lambda\right], \left[\sqrt{1 - (1 - c^2)^\lambda}, \sqrt{1 - (1 - d^2)^\lambda}\right]\right), \quad (4)$$

$$\lambda p = \left(\left[\sqrt{1 - (1 - a^2)^\lambda}, \sqrt{1 - (1 - b^2)^\lambda}\right], \left[c^\lambda, d^\lambda\right]\right), \quad (5)$$

$$p^c = ([c, d], [a, b]). \quad (6)$$

Definition 3. (Peng and Li, 2019). According to the Shannon entropy, the IVPIFN entropy $E_j\,(j = 1, 2, ..., n)$ on the j-th criterion can be calculated by using the following equation:

$$E_j = 1 - \sqrt{\frac{1}{2n} \sum\nolimits_{j=1}^{n} \left(\left(a_{ij}^2 - c_{ij}^2\right)^2 + \left(b_{ij}^2 - d_{ij}^2\right)^2\right)}. \quad (7)$$

Definition 4. (Peng and Yang, 2016). Assuming $p_1 = ([a_1, b_1], [c_1, d_1])$ and $p_2 = ([a_2, b_2], [c_2, d_2])$ are two IVPIFNs, the distance between p_1 and p_2 is defined as follows:

$$d(p_1, p_2) = \frac{1}{4}\left(\left|a_1^2 - a_2^2\right| + \left|b_1^2 - b_2^2\right| + \left|c_1^2 - c_2^2\right| + \left|d_1^2 - d_2^2\right| + \left|\tau_1^2 - \tau_2^2\right| + \left|\sigma_1^2 - \sigma_2^2\right|\right), \quad (8)$$

where $[\tau_1, \sigma_1] = [\sqrt{1 - a_1^2 - c_1^2}, \sqrt{1 - b_1^2 - d_1^2}]$ or $[\tau_2, \sigma_2] = [\sqrt{1 - a_2^2 - c_2^2}, \sqrt{1 - b_2^2 - d_2^2}]$.

Definition 5. (Peng and Yang, 2016) For any IVPIFN $p = ([a, b], [c, d])$, $M(p)$ and $\Delta(p)$ are the score function and accuracy function of the IVPIFN p. Their calculation equations are as follows:

$$\begin{cases} M(p) = \dfrac{a^2 + b^2 - c^2 - d^2}{2}, M(p) \in [-1, 1] \\ \Delta(p) = \dfrac{a^2 + b^2 + c^2 + d^2}{2}, \Delta(p) \in [0, 1] \end{cases}. \quad (9)$$

If $M(p_1) < M(p_2)$, then $p_1 < p_2$; if $M(p_1) = M(p_2)$, there are two situations:

- When $\Delta(p_1) < \Delta(p_2)$, then $p_1 < p_2$.
- When $\Delta(p_1) = \Delta(p_2)$, then $p_1 = p_2$.

3.2 Decision model for the ESTS plan based on the IVPIFN

For the sake of expression, assuming that there are m alternative ESTS plans $A_i\,(i = 1, 2, ..., m)$, n criteria $C_j\,(j = 1, 2, ..., n)$, the flowchart of the decision model is shown in Figure 1.

3.2.1 Phase 1: establishing a decision matrix for ESTS plans based on the IVPIFN

Step 1: Converting the quantitative decision values of the ESTS plan into the IVPIFN. The quantitative decision value of the ESTS plan can be converted into the IVPIFN decision value by the following equation:

$$\mu_{ij}^L = \mu_{ij}^U = \begin{cases} \alpha \times \dfrac{EV_{ij}}{EV_i{}^{\max}}\,(i \in \Omega_b) \\ \alpha \times \dfrac{EV_i{}^{\min}}{EV_{ij}}\,(i \in \Omega_c, EV_i{}^{\min} \neq 0) \\ \alpha \times \left(1 - \dfrac{EV_{ij}}{EV_i{}^{\max}}\right)(i \in \Omega_c, EV_i{}^{\min} = 0) \end{cases} \text{and}\ \upsilon_{ij}^L = \upsilon_{ij}^U = \begin{cases} 1 - \alpha \times \dfrac{EV_{ij}}{EV_i{}^{\max}}\,(i \in \Omega_b) \\ 1 - \alpha \times \dfrac{EV_i{}^{\min}}{EV_{ij}}\,(i \in \Omega_c, EV_i{}^{\min} \neq 0) \\ 1 - \alpha \times \left(1 - \dfrac{EV_{ij}}{EV_i{}^{\max}}\right)(i \in \Omega_c, EV_i{}^{\min} = 0) \end{cases}, \quad (10)$$

where $EV_i{}^{max}$ and $EV_i{}^{min}$ are the maximum and minimum decision values on the i-th decision criterion, EV_{ij} refers to the decision value of the j-th ESTS plan on the i-th decision criterion, Ω_b is a set of positive decision criteria, Ω_c is a set of negative decision criteria, and μ_{ij}^U, μ_{ij}^L, υ_{ij}^L, and υ_{ij}^U are the upper and lower limits of the IVPIFN decision value.

Step 2: Obtaining IVPIFN decision values for ESTS plans based on qualitative decision criteria. Experts evaluate ESTS plans based on qualitative decision criteria. First, the interval value of the satisfaction degree and the interval value of the non-satisfaction degree are determined between [0,1], respectively. The satisfaction and non-satisfaction degrees together form the IVPIFN decision value of ESTS plans on the qualitative decision criterion. When the qualitative decision criterion is negative, it should be converted into complementary values through Eq. 6.

Step 3: Building a decision matrix for the ESTS plan. We sort the IVPIFN decision values on qualitative and quantitative decision criteria in the order of decision criteria and alternative ESTS plans. A decision matrix for ESTS plans is constructed by the following equation:

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1m} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nm} \end{bmatrix}. \quad (11)$$

3.2.2 Phase 2: determining the weight of decision criteria for ESTS plans

Step 1: Determining the weight of subjective decision criteria. Experts determine the importance of decision criteria between [1,10], with larger values indicating greater importance. The importance of the i-th decision criterion is marked as ID_i. The calculation equation for the subjective weight of the decision criterion is shown in the following equation:

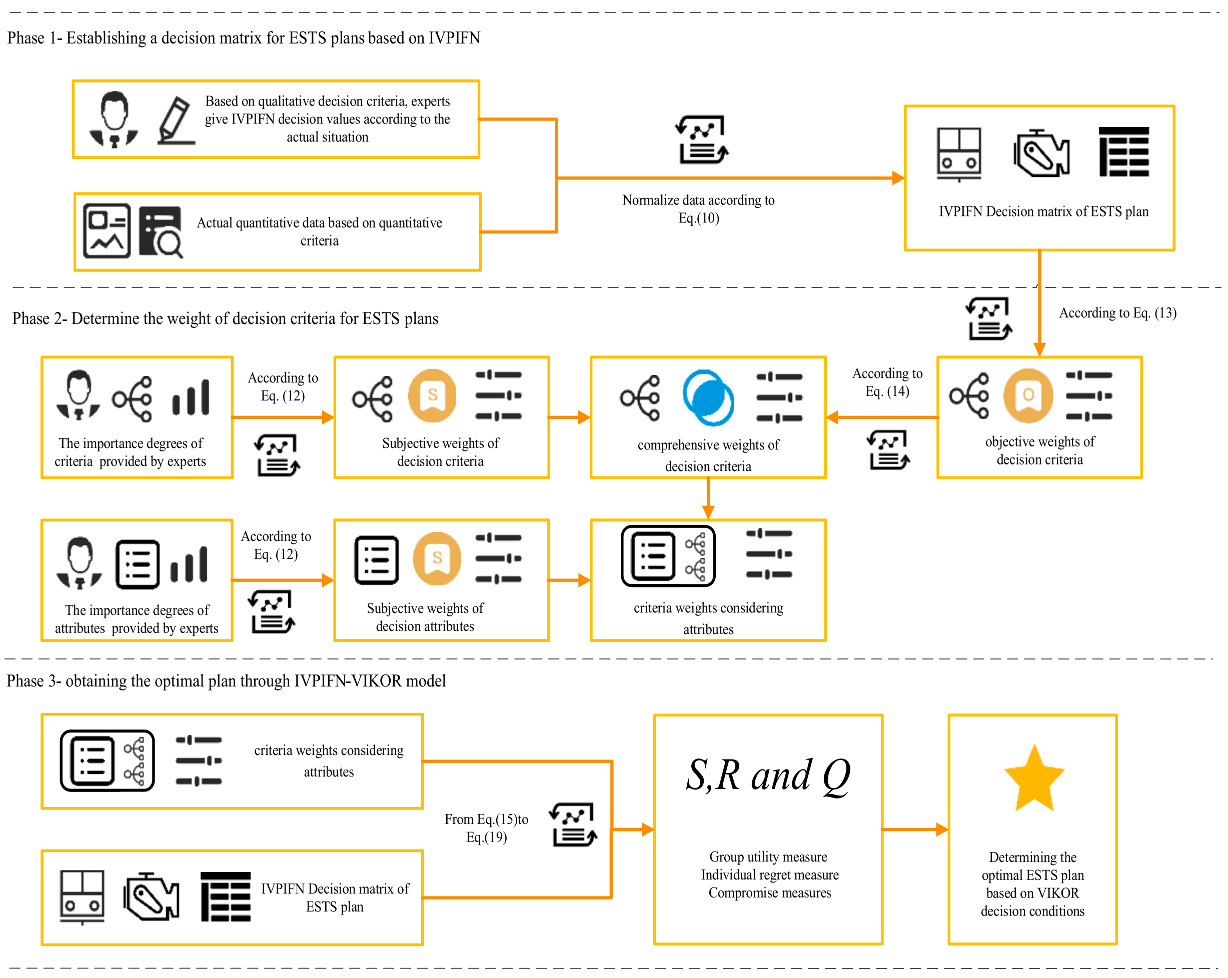

FIGURE 1
Flowchart of the decision model for the ESTS plan based on the IVPIFN.

$$w_i^s = \frac{ID_i}{\sum_{i=1}^n ID_i}, \tag{12}$$

where $\sum_{i=1}^n w_i^s = 1$.

Step 2: Determining the weight of objective decision criteria. The objective weight of the decision criteria for the ESTS plan is calculated by using the entropy weight method, where the IVPIFN entropy on each criterion can be calculated using Eq. 7, while the objective weight calculation equation is

$$w_i^o = \frac{1 - E_i}{n - \sum_{i=1}^n E_i}. \tag{13}$$

Step 3: Determining the comprehensive weight of decision criteria. The comprehensive weight can be obtained through the following equation:

$$w_i^c = a \times w_i^o + (1 - a) \times w_i^s, \ (i = 1, 2, ..., n), \tag{14}$$

where w_i^o is the objective weight of the i-th decision criterion, w_i^s is the subjective weight of the i-th decision criterion, and a is the comprehensive parameter that determines the proportion of subjective weight and objective weight.

3.2.3 Phase 3: obtaining the optimal plan through the IVPIFN–VIKOR model

Step 1: Determining the positive and negative ideal solutions according to Definition 4, PIS_i and NIS_i are the positive and negative ideal solutions, which can be found by Eqs 15, 16, respectively.

$$PIS_i = \max_j \{p_{ij}\}, \tag{15}$$

$$NIS_i = \min_j \{p_{ij}\}. \tag{16}$$

Step 2: The group utility measure S_j, individual regret measure R_j, and compromise measure Q_j of the alternative ESTS plan A_j are determined based on the positive and negative ideal solutions and the following equations:

$$S_j = \sum_{i=1}^n \frac{w_i d\left(p_{ij}, PIS_i\right)}{d\left(PIS_i, NIS_i\right)}, \tag{17}$$

$$R_j = \max \frac{w_i d\left(p_{ij}, PIS_i\right)}{d\left(PIS_i, NIS_i\right)}, \tag{18}$$

TABLE 4 Optimization results of plans based on VIKOR.

Alternative options	S_i	R_i	Q_i	Priority		
				S	R	Q
S1	0.595	0.073	1.000	3	3	3
S2	0.445	0.066	0.114	2	1	1
S3	0.401	0.068	0.169	1	2	2

TABLE 5 Sensitivity analysis.

No.	η	S1	S2	S3
1	0.000	1.00	0.00	0.34
2	0.100	1.00	0.02	0.30
3	0.200	1.00	0.05	0.27
4	0.300	1.00	0.07	0.24
5	0.400	1.00	0.09	0.20
6	0.500	1.00	0.11	0.17
7	0.600	1.00	0.14	0.14
8	0.700	1.00	0.16	0.10
9	0.800	1.00	0.18	0.07
10	0.900	1.00	0.20	0.03
11	1.000	1.00	0.23	0.00

$$Q_j = \eta \frac{S_j - S^-}{S^+ - S^-} + (1-\eta)\frac{R_j - R^-}{R^+ - R^-}, \tag{19}$$

where $S^+ = \max\limits_j \{S_j\}$, $S^- = \min\limits_j \{S_j\}$, $R^+ = \max\limits_j \{R_j\}$, $R^- = \min\limits_j \{R_j\}$, and η is the weight of the group utility maximization strategy; generally speaking, $\eta = 0.5$.

Step 3: Assuming that the optimal ESTS plan is determined based on the size of the compromise measure Q, and the minimum compromise measure value is optimal, $A^{(1)}$ is the optimal solution sorted based on the compromise measure, and two conditions need to be met:

C1: The alternative ESTS plan $(A^{(1)})$ has an acceptable advantage, which is $Q(A^{(2)}) - Q(A^{(1)}) \geq DQ$, where $DQ = 1/(m-1)$.

C2: The alternative ESTS plan $(A^{(1)})$ has acceptable stability, which means that the optimal alternative is also the optimal solution when ranked based on the group utility measure S_j or individual regret measure R_j.

If one of the conditions is not met, a set of compromise solutions can be submitted, but the following conditions must be met:

- If only condition C1 is satisfied, then there is a compromise solution set $\{A^{(1)}, A^{(2)}\}$
- If only condition C2 is satisfied, then the inequality can be satisfied as $Q(A^{(m)}) - Q(A^{(1)}) < DQ$; in this case, the maximum value m is taken to obtain a compromise solution set of $\{A^{(1)}, A^{(2)}, \ldots, A^{(m)}\}$.

4 Case study

4.1 Data sources

The data, in this case, come from the feasibility study report, preliminary design plan, and meeting minutes of the previous plan argumentation of Kunming Metro Line 5. The IVPIFN decision value, importance score of decision attributes, and importance score of decision criteria for the alternative ESTS plans are derived from the statistical analysis of expert scoring in plan argumentation.

4.2 Case analysis

Kunming Metro Line 5 starts from Expo Park Station in the north and ends at Baofeng Village Station in the south. It runs through Panlong District, Wuhua District, Xishan District, Resort, and Guandu District, connecting tourist attractions, such as Expo Park, Yuantong Park, Cuihu Lake, and the International Convention and Exhibition Center. The total length of the line is about 26.45 km, and it is laid underground with a total of 22 stations. The construction of this rail transit project needs to reflect the concept of "ecological livability in Kunming—harmonious coexistence between humans and nature." Therefore, from this perspective, the decision of ESTS plans is made, and the most important thing is to reflect the low-carbon nature of the traction system. Therefore, in the preliminary design stage, three ESTS design plans are proposed, labeled S1, S2, and S3 in this case.

TABLE 6 Cross comparison.

	Interval Pythagorean fuzzy numbers	VIKOR model	Practice	Sort			
					S1	S2	S3
Scenario 1	Replace with real numbers	Retain	The average satisfaction degree in interval	S	0.598	0.407	0.397
				R	0.073	0.066	0.068
			Pythagorean fuzzy numbers is taken as the evaluation value	Q	1.000	0.024	0.169
				Sort	2	1	1
Scenario 2	Retain	Replace with the TOPSIS method	TOPSIS model	Score	0.37	0.67	0.57

Experts have demonstrated these three alternative ESTS plans and simulated the operation of the ESTS on rail transit. Based on the organization of the aforestated data, the decision data of these three alternatives are shown in Table 2. At the same time, experts rate the importance degree of decision attributes and criteria, and the attribute weights, criterion weights, and criterion weights considering attribute could be calculated using Eqs 12–14, the weights can been seen in Table 3. From the weight of decision attributes, it can be seen that experts have less consideration for cost, and the importance of system reliability, maintainability, and safety is slightly higher than that of energy storage battery performance and system operating characteristics. This means that under the influence of policies, it is necessary to strike a balance between system reliability, maintainability, and safety and energy storage battery performance and system operating characteristics, and cost has instead become a non-important criterion.

On this basis, the group utility measure, individual regret measure, and compromise measure of these three ESTS plans are calculated based on the IVPIFN–VIKOR model, as shown in Table 4. According to the VIKOR optimal solution judgment rules, from the compromise measure Q, S2 is optimal, but the difference between the Q value of S3 and the Q value of S2 in the second place is not greater than 0.5. Therefore, according to the judgment condition: if only condition C2 is met, then the inequality can be satisfied: $Q(A^{(m)}) - Q(A^{(1)}) < DQ$; in this case, the maximum value m is taken to obtain a compromise solution set of $\{A^{(1)}, A^{(2)}, \ldots, A^{(m)}\}$. Therefore, the optimal solution is two S2 and S3.

5 Discussion

The sensitivity analysis is conducted to test the robustness of the decision results. The specific steps are to adjust the parameter η in the calculation process of the compromise measure. The value range of η is [0,1]. The sensitivity analysis starts from 0 and takes values every 0.1 intervals, so there are 11 sensitivity analysis results, which are shown in Table 5. According to the calculation results, it was found that the results are still S2 and S3, so the results have sufficient robustness. Experts choose S3 as the best plan based on maximizing group utility.

To prove the progressiveness of the model, this paper uses real numbers instead of IVPIFNs as comparison scenario 1 and the TOPSIS method instead of the VIKOR model as comparison scenario 2 for the comparison experiments. The comparison experimental results are shown in Table 6. According to comparison scenario 1, after using real numbers, the compromise measure of S2 decreases due to the influence of uncertainty, but S1 and S3 do not change. This effect, which causes the difference between values to change, will lead to changes in the decision results in the VIKOR model. That is, when the two values are exactly at the boundary of C1 conditions, the change in the difference between values will lead to changes in the decision results. According to comparison scenario 2, after the TOPSIS model is adopted, S2 is the optimal solution, but this solution does not take into account the biggest weakness of alternatives, which cannot meet the needs of risk aversion decision makers. Therefore, the model proposed in this article can better solve the problem of ESTS plan decisions.

6 Conclusion

The main energy consumption of rail transit projects comes from the electrical system, and the main power consumption system is the traction system. Therefore, in the context of the dual carbon targets, if the low-carbon development of rail transit is to be achieved, the low-carbon development of the traction system is crucial. To achieve low-carbon traction systems, the ESTS is an important development direction. For new projects, the following problems must be faced when scientifically selecting an ESTS: ① lack of a scientific decision index system for ESTS plans; ② the adverse impact of uncertainty in decision information on the scientific nature of decision; and ③ the decision of the ESTS belongs to risk aversion decision.

Therefore, based on the ESTS characteristics, this article constructs a decision index system for ESTS plans. The criterion system includes six decision attributes and 18 decision criteria, among which the decision attributes are energy storage battery characteristics, system operation characteristics, system cost, reliability, maintainability, and safety. According to the characteristics of the plan decision of the ESTS, this paper uses the IVPIFN as the expression form of the decision data to reduce the adverse impact of uncertainty on the scientificity of the decision and realizes risk aversion decisions through the VIKOR model.

In this case, experts have given less consideration to cost, and the importance of system reliability, maintainability, and safety is slightly higher than that of energy storage battery performance and system operating characteristics. This means that under the influence of policies, it is necessary to strike a balance between system reliability, maintainability, safety, and energy storage battery performance and system operating characteristics, and cost becomes a non-important criterion.

The issues that need further research in this article are as follows: the correlation between decision criteria was not considered in this study, and the correlation between criteria also has a significant impact on the scientific nature of the decision. Therefore, how to scientifically measure the correlation between the ESTS decision criteria is a problem that needs to be solved.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

WX: conceptualization. BL: methodology. WW: writing—original draft. YZ: writing—original draft. All authors contributed to the article and approved the submitted version.

Conflict of interest

MT was employed by the company Kunming Rail Transit Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Appendix

TABLE A1 Summary of fuzzy mathematics.

Data type	Expression form	References
Intuitionistic fuzzy number	$\langle \mu, \upsilon \rangle$, where μ is the member level and υ is the non-member level, $0 \leq \mu + \upsilon \leq 1$, such as $\langle 0.7, 0.2 \rangle$	Kumar and Chen (2022)
Interval-valued intuitionistic fuzzy number	$\langle (\mu^L, \mu^U), (\nu^L, \nu^U) \rangle$, where $\mu^L \, and \, \mu^U$ are the higher and lower member levels and $\nu^L and \, \nu^U$ are the higher and lower non-member levels, $0 \leq \mu^U + \nu^U \leq 1$, such as $\langle (0.65, 0.70), (0.15, 0.25) \rangle$	Percin (2022)
Interval-valued Pythagorean intuitionistic fuzzy number	$\langle (\mu^L, \mu^U), (\nu^L, \nu^U) \rangle$, where $\mu^L \, and \, \mu^U$ are the higher and lower member levels and $\nu^L and \, \nu^U$ are the higher and lower non-member levels, $(\mu^U (x))^2 + (\nu^U (x))^2 \leq 1$, such as $\langle (0.7, 0.9), (0.1, 0.2) \rangle$	Percin (2022)