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Comparative Economic Analysis of Transmission Lines Adopted for Energy-Saving Conductors Considering Life Cycle Cost

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Abstract: Transmission lines serve as pivotal equipment within the power system. Conductors, the primary medium for power transmission and distribution, directly influence the construction cost, operational performance, and long-term benefits of transmission line projects. This study first provides a detailed introduction to the life cycle cost of transmission lines. It utilizes linear regression analysis, the grey model, and the autoregressive integrated moving average model to forecast the electricity sales benefit and quantify the carbon reduction benefits of energy-saving conductors through a methodology. Through the life cycle cost model, we found that operating costs, particularly energy loss costs, dominate the total expenses, accounting for 65% to 66.2%. The JLHA3-425 scheme offers the lowest life cycle cost of 22,891.66 k$. Comparing economic indicators like ENPV, EIRR, and DPP confirmed that the JLHA3-425 medium-strength aluminum alloy stranded wire emerged as the most economically viable option among the evaluated schemes, holding substantial promise for fostering economic and environmental sustainability in electrical power transmission.

Keywords: transmission line project; conductor selection; life cycle cost; electricity sales; carbon reduction benefits; economic evaluation index system

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1. Introduction

In recent years, China's economic growth has driven an increasing demand for power systems and electrical grid engineering [1]. Transmission line projects, crucial for grid construction, are rapidly developing nationwide. The significance of economic operation within transmission line projects is increasingly prominent, directly affecting their feasibility and long-term operational benefits [2]. The choice of conductors directly affects transmission lines' Life Cycle Cost (LCC) as they carry electrical energy, making it essential to optimize conductor selection [3]. Forecasting sales benefits and quantifying the carbon reduction benefits of energy-saving conductors are vital in identifying the most suitable conductors for a particular application [4]. A comprehensive comparison of economic evaluation indicators for different conductor options is necessary.

Extensive research has been conducted on various aspects of transmission lines, including LCC, load forecasting, and economic evaluations.

Many scholars have conducted relevant research on the theory of the life cycle of transmission lines. These studies encompass various stages of transmission line design, construction, operation, and maintenance to improve transmission lines' reliability, safety, and economic efficiency. They also provide theoretical support for future technological innovations and developments. Jingshuang Gan et al. [5] developed an LCC model that incorporates macroeconomic factors, encompassing investment costs, operational expenses, maintenance estimation, and fault estimation derived from the ratio of output value to unit energy consumption. Zhenyu Zhu et al. [6] introduced an LCC analysis method for 10 kV lines, employing the Monte Carlo algorithm to determine the Expected Energy Not Supplied (EENS) when simulated values are lacking. Hakan Acaroğlu and Fausto

Pedro García Márquez [7] conducted a thorough LCC analysis of a multinational High-Voltage Direct Current (HVDC) overhead transmission line in Turkey, and subsequently determined the economic indicators. Xiaomin Chen et al. [8] proposed an innovative method for estimating carbon emissions in power transmission and transformation projects, termed the extended life cycle method. The proposed methodology estimates the LCC, encompassing both economic and carbon expenses. Wenhui Zeng et al. [9] presented an interval cost model that utilizes the fluctuation coefficient amplitude to mitigate cost uncertainty in lifecycle calculations.

In the research on electricity sales forecasting, Hend M. Farkash et al. [10] address the challenge of electrical demand forecasting by utilizing the Nonlinear AutoRegressive with eXogenous inputs (NARX) tool on the MATLAB platform to train artificial neural networks (ANN). Guohua Cao and Lijuan Wu [11] integrate the support model with the fruit fly optimization algorithm to adjust exponentially and forecast monthly electricity consumption. Tapanee Treeratanaporn et al. [12] utilized the linear regression classification method to analyze electricity sales revenue and cost using the RapidMiner Studio Tool. Hadjout et al. [13] utilized a combination of Long Short-Term Memory (LSTM) Neural Networks, Gated Recurrent Unit (GRU) Neural Networks, and temporal convolutional network models to predict monthly electricity sales. This analysis was based on data from approximately 2000 customers and 14 years of monthly electricity usage in Béjaïa, Algeria.

Regarding the evaluation of power grid economics, Hadi et al. [14] assess the technical and economic viability of constructing a substation for a Mine Mouth Steam Coal Fired Power Plant (PLTU), with a focus on financial indicators such as Return on Investment (ROI), Internal Rate of Return (IRR), and Net Present Value (NPV). Kuusela et al. [15] assessed the economic viability of incorporating on-demand flexibility into transmission systems, introducing an innovative approach for stochastic modeling of electricity market prices and congestion management. Their findings indicate that utilizing on-demand flexibility is economically viable, providing substantial benefits in cost reduction and mitigating environmental impacts. Jia et al. [16] analyze the economic advantages of Inter-Regional Power Transmission (IRPT), emphasizing its theoretical foundations, empirical findings, and methodologies for assessing economic effects. They highlight the role of IRPT in fostering balanced regional development and shared prosperity across regions, especially following the initial phase of China's West-to-East electricity transmission project. Salci [17] presents a concise analytical framework for evaluating the impacts of transmission line investments, focusing on rehabilitation investments in fragmented electricity networks with reduced demand and unreliable supply.

In summary, several scholars have extensively studied transmission lines' LCC, forecasting electricity sales and economic assessments of power grid initiatives. However, there is still room for improvement regarding electricity sales revenue and the carbon emission reduction benefits of energy-saving conductors. Therefore, this paper utilizes an LCC model to conduct a comparative analysis of cost differences and expense proportions between conventional steel-core aluminum stranded wires and three types of energy-saving conductors in transmission line projects [18]. It utilizes various forecasting techniques to assess the load levels of transmission lines throughout their lifespan, thereby determining the revenue derived from electricity sales and quantifying the carbon reduction benefits of energy-saving conductors. Furthermore, an economic evaluation index system is constructed to compare and evaluate the optimal conductor scheme [19,20], comprehensively assessing both economic feasibility and operational reliability of transmission lines. The research framework is illustrated in Figure 1.

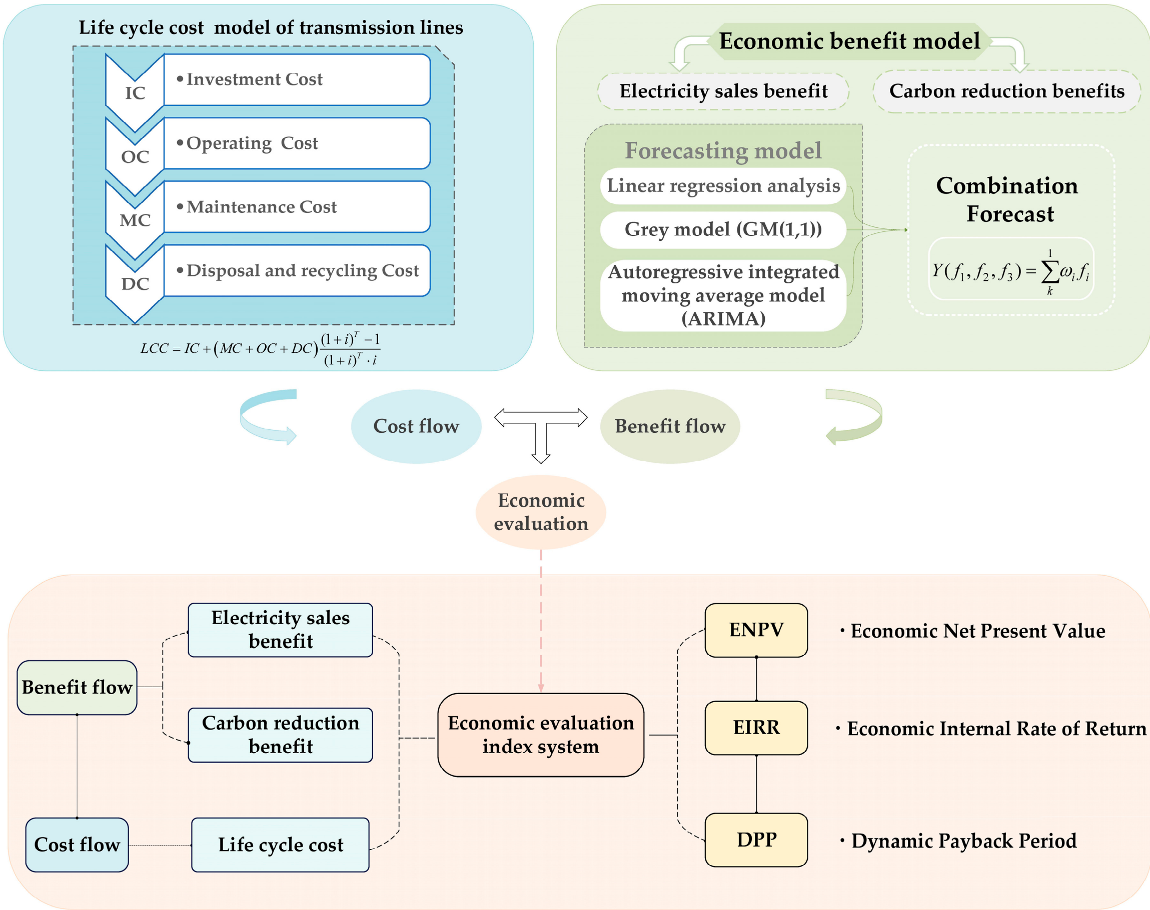

Figure 1. Diagram of research framework.

2. Materials and Methods

2.1. Life Cycle Cost Analysis

The transmission line components comprise conductors, towers, guy wires, insulators, foundations, line fittings, and grounding devices. Among these elements, the type and performance of conductors are crucial in determining the economic cost of transmission lines. Figure 2 illustrates the LCC estimation model for transmission lines [21,22].

(1) Investment cost IC_{L}

This study primarily investigates the influence of conductors on the transmission line costs, specifically focusing on the investment costs related to conductors. While the costs of other components in transmission lines exert a relatively minor influence on the project's overall economics, their cost calculation formulas are generally considered stable [23]. The formulas for calculating the investment cost of conductors are provided below:

$$IC_{\mathrm{L}} = C_{\mathrm{I1}} \cdot L + \sum IC_{\mathrm{o}} \tag{1}$$

$$C_{\mathrm{I1}} = L \cdot n \cdot n \cdot m \cdot p_1 \tag{2}$$

where C_{I1} is the investment cost of conductors per unit length, \$/km; L is the length of the transmission line, km; $\sum IC_{\mathrm{O}}$ is the sum of other costs during the initial investment phase of the transmission line, \$; n is the number of branches of conductors in the transmission line; n' is the number of loops in the line; m is the mass of conductors per unit length, t/km; P_1 is the unit price of conductors, \$/t [24].

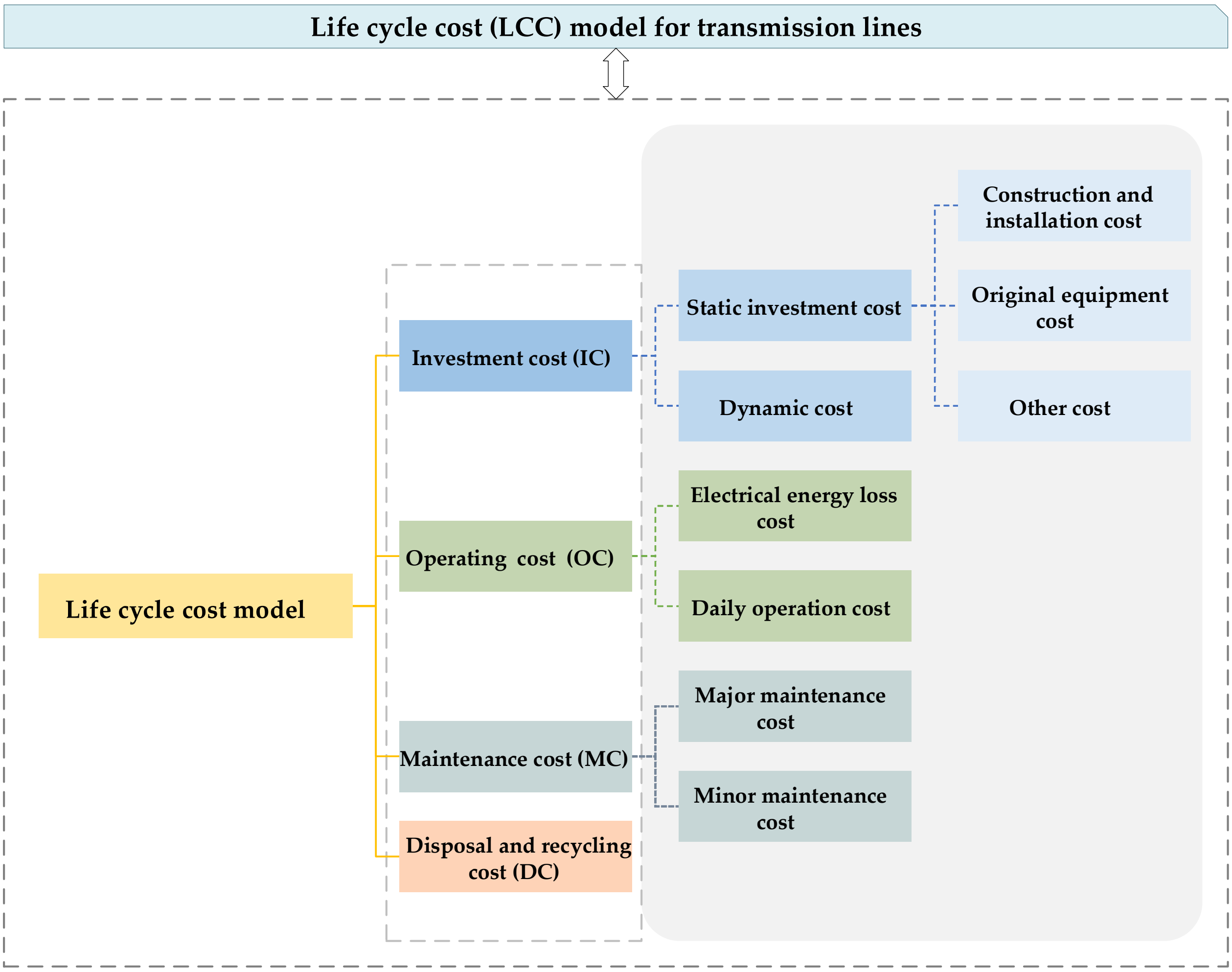

Figure 2. Diagram of transmission lines LCC model.

(2) Operation cost OC_L

The operation cost of transmission lines is primarily composed of the cost of electrical energy loss and the cost of routine line operation, which can be formulated as:

$$OC_L = (C_{el} + C_d) \tag{3}$$

$$C_{el} = 3n'\tau C_e\left(\frac{P^2 R}{3nU^2\cos^2\alpha} + P_k\right) \tag{4}$$

where C_{el} is the cost of electrical energy loss of the line, \$/year; C_d is the daily operation cost of the line, \$/year; τ is the annual maximum loss hours of transmission lines; C_e is the electricity price, \$/kWh; P is the transmission power of the line, MW; R is the direct current resistance of the conductor per unit length, Ω/km; U is the transmission voltage, kV; $\cos^2\alpha$ is the power factor; P_k represents the corona loss of the conductor, kW [25].

$$P_k = \frac{n^2 {r_L}^2}{8760 E_{m0}} \sum_{i=1}^{4} P_i \tag{5}$$

$$P_1 = (E_{mA} + E_{mB} + E_{mC}) \frac{F_1 T_1}{\delta^{\frac{2}{3}} E_{m0}} \tag{6}$$

$$P_{2,3,4} = (E_{mA} + E_{mB} + E_{mC}) \frac{F_{2,3,4} T_{2,3,4}}{E_{m0}} \tag{7}$$

where E_{mA}, E_{mB}, E_{mC} are the surface electric field strengths of the three-phase conductors, MV/m; P_i is corona losses under different weather conditions, MV/m; T_i represents the calculation hours of different weather conditions within a year, h; i = 1, 2, 3, 4, represent fine weather, rainy weather, snowy weather, and freezing rain weather, respectively; r_{L} represents the radius of the conductor, cm. As the operational duration increases, conductors incur losses, resulting in annual variations in electrical energy loss costs and transmission line operation and maintenance costs over time. The annual cost method, which adjusts for the time value of funds, is commonly employed to evaluate different types of conductor schemes economically. The total cost from a base year is evenly distributed across each year of the project's operational period, and the average annual electrical energy loss cost and average annual operation and maintenance cost of the line are calculated as research indicators [26].

The daily operational cost is typically estimated as a percentage of the initial investment cost:

$$C_{\mathrm{d}} = \beta \cdot IC_{\mathrm{L1}} \tag{8}$$

where β is the daily maintenance rate of the line, typically set at 1.4%.

(3) Maintenance cost MC_{L}

Optimization of the maintenance cost calculation model for transmission lines involves considering two types of maintenance: major maintenance and minor maintenance [27]. The calculation formulas are as follows:

$$MC_{\mathrm{L}} = \sum_{t=1}^{T} \lambda(t)[\mathrm{Cb}(t)\omega + \mathrm{Cs}(t)(1-\omega)] \tag{9}$$

where $\lambda(t)$ is the failure probability of the transmission line; ω is the frequency of major maintenance performed after the failure of the transmission line; γ is the frequency of minor maintenance; $C_{\mathrm{b}}(t)$ is the average cost required for a overhaul of the transmission line, \$; $C_s(t)$ is the average cost required for a minor repair of the transmission line, \$; T is the life cycle, years.

(4) Disposal and recycling cost DC_{L}

The formula for calculating the disposal and recycling cost of transmission lines is as follows:

$$DC_{\mathrm{L}} = C_{\mathrm{R}} - SV \tag{10}$$

where C_R represents the disposal cost of transmission lines when they are scrapped, and SV represents the salvage value of the transmission line. The residual rate of transmission lines is typically set at 5% [28].

The LCC model for assessing transmission line costs considers economic factors such as discount rates. During the initial investment phase, there is no need to account for the time value of money. However, during the operation and maintenance phases, as well as the overhaul and scrap recovery phases, which span longer periods, these costs must be discounted to their present value [29]. Thus, the calculation model for the LCC of transmission lines is defined as follows:

$$LCC_{\mathrm{L}} = IC_{\mathrm{L}} + (MC_{\mathrm{L}} + OC_{\mathrm{L}} + DC_{\mathrm{L}})\frac{(1+i)^T - 1}{(1+i)^T \cdot i} \tag{11}$$

2.2. Load Forecasting Models

Accurate long-term load forecasting of transmission lines is a critical component of economic dispatch in power systems [30]. This study specifically focuses on annual level load forecasting, employing various methods including time series analysis, regression analysis, gray forecasting, neural networks, and combined forecasting analysis [31]. The models utilized encompass the linear regression analysis, the Grey Model (GM (1, 1) model) [32], and the ARIMA model for time series analysis. Through integration of these models' results, this study predicts annual load levels of transmission lines to determine electricity sales while maintaining supply-demand balance in the power system.

2.2.1. Linear Regression Analysis

Linear regression analysis is acknowledged as a prevalent forecasting method that has been widely acknowledged in the field of statistics. Its primary aim is to identify the best-fitting line by minimizing the sum of squared residuals between observed and predicted values generated by the model. This process facilitates the description of the relationship between independent and dependent variables. Within this context, the optimal intercept and slope of the best-fitting line are determined to minimize the sum of squared errors between the observed values of the sample data and the fitted line [33]. The equation governing simple linear regression is typically expressed as follows:

$$Y = \beta_0 + \beta_1 X + \varepsilon \tag{12}$$

where Y is the dependent variable (the variable being predicted), X is the independent variable (the variable used for prediction), β_0 is the intercept, β_1 is the slope, and ε is the error term.

2.2.2. Grey Model

The Grey Model (GM (1, 1) model) is a prediction model that utilizes the theory of grey systems. It is particularly suitable for predicting data with a small sample size and limited historical information [34]. By applying the greying method to the data sequence, the original data is transformed into a sequence that exhibits apparent regularity, thereby facilitating analysis and prediction. The computational steps and corresponding formulas of this model are illustrated in Figure 3.

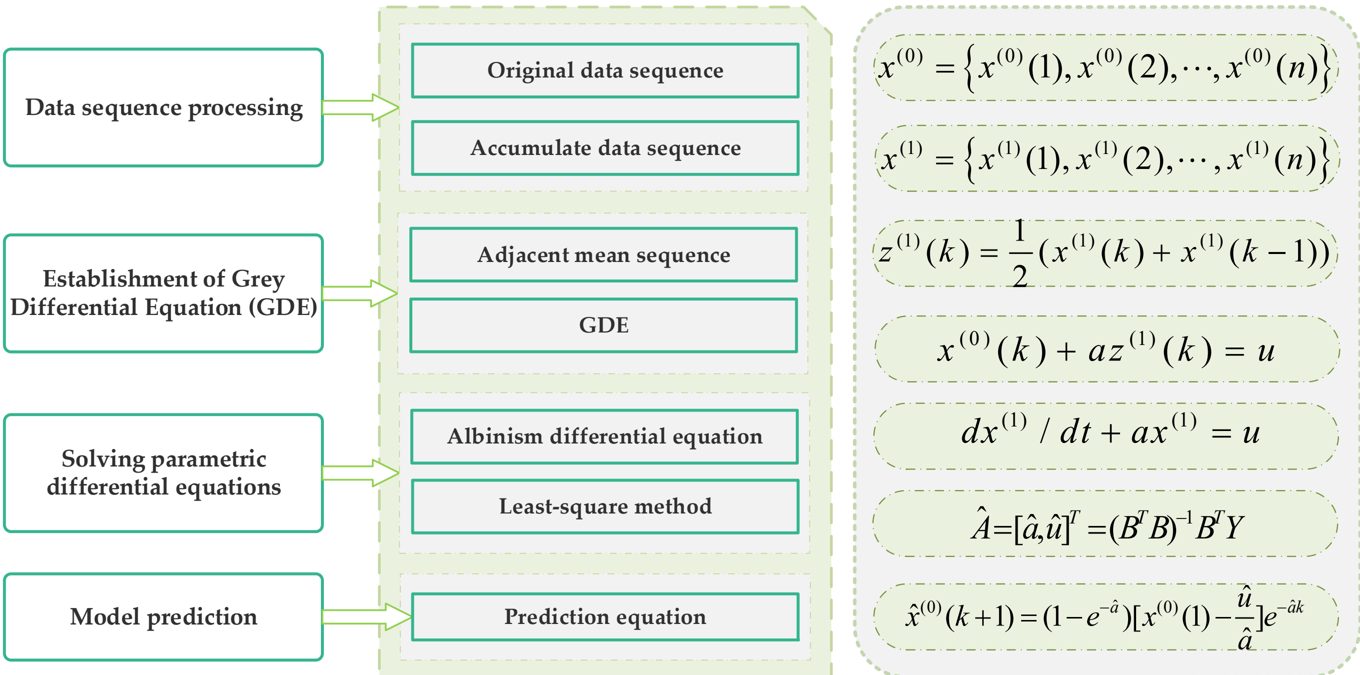

Figure 3. Flowchart of the GM (1, 1) model calculation steps.

2.2.3. Autoregressive Integrated Moving Average Model

The ARIMA model is a statistical tool utilized for time series analysis and forecasting. It combines the concepts of Autoregressive (AR) and Moving Average (MA) models, along with the notion of differencing (integrated) [35]. The modeling process flowchart of this model is illustrated in Figure 4.

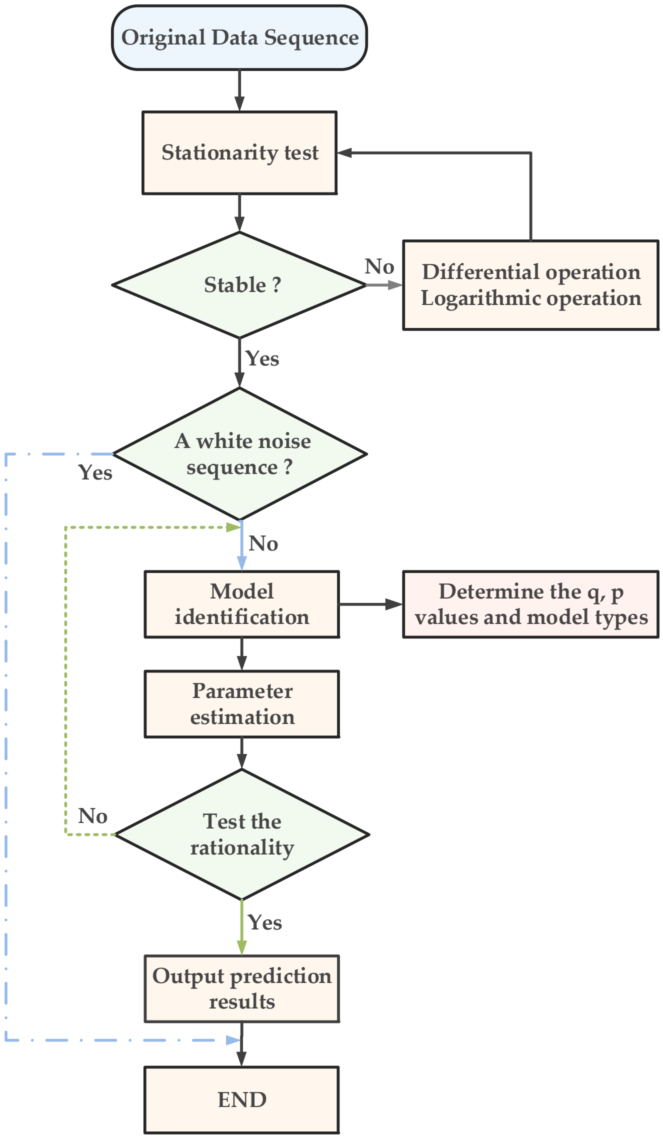

Figure 4. Flowchart of ARIMA model calculation steps.

2.2.4. Combination Forecasting Model

The composite forecasting model represents a comprehensive approach that typically involves the utilization of multiple forecasting methods or models, including time series analysis, regression analysis, and grey forecasting. The use of a single forecasting method may lead to inaccurate forecasting outcomes [36]. Therefore, composite forecasting analysis integrates the strengths of different methods and considers various forecasting outcomes to enhance the overall accuracy and reliability of predictions. The composite forecasting model can be represented as:

$$\begin{cases} Y(f_1, f_2, \cdots, f_k) = \sum_{k}^{1} \omega_i f_i \\ \sum_{k}^{1} \omega_i = 1 \end{cases} \tag{13}$$

where $Y(f_1, f_2, \cdots, f_k)$ is the combination forecast value, f_i is the forecast result corresponding to each forecasting model, and $\omega = [\omega_1, \omega_2, \cdots, \omega_k]$ is the weighting coefficient of different forecasting methods in the combination forecasting model, which is determined by analyzing the forecast errors of each model.

2.3. Economic Evaluation

To analyze the economy of energy-saving conductors, we examine the transmission line economically using the following index system in Figure 5 [37]:

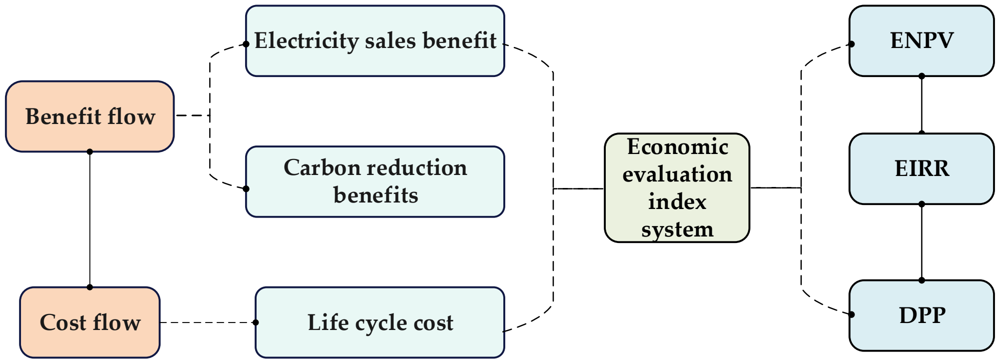

Figure 5. Economic evaluation index system of transmission lines.

2.3.1. Economic Benefit

(1). Electricity sales

The main purpose of transmission lines is to deliver electricity to customers to meet their energy requirements. Therefore, this study defines the income earned by grid companies from electricity sales as the benefit of these transactions. This income is calculated by multiplying the annual electricity sales volume by the corresponding transmission tariff [38].

(2). Carbon reduction

Using energy-saving conductors in transmission lines can improve efficiency and minimize line loss, which indirectly helps in reducing carbon emissions. In China, three principal types of energy-saving conductors are employed: steel-core aluminum strand wire with high electrical conductivity, aluminum alloy stranded wire, and medium-strength aluminum alloy stranded wire. Energy-saving conductors can reduce resistance loss in transmission lines compared to conventional steel-cored aluminum strand conductors with the same cross-section, resulting in greater electric energy savings to meet the same demand [39]. This contributes to environmental benefits through reduced carbon dioxide emissions and corresponding carbon reduction advantages. Therefore, the benefits of carbon emission reduction are quantified as the advantages of using energy-saving conductors over ordinary conductors [40]. The formula for calculating these benefits is as follows:

$$C = \Delta Q_{\mathrm{p}} \cdot F \cdot C_{\mathrm{e}} \cdot \frac{(1+i)^{T-1} - 1}{(1+i)^{T-1} \cdot i} \tag{14}$$

where C is the carbon emission reduction income (USD), \$; ΔQ_{p} is the reduction of power loss caused by the use of energy-saving wires compared with ordinary wires, kWh; F is the regional power grid emission factor, $\mathrm{kgCO_2/kWh}$; $\Delta Q_{\mathrm{p}} \cdot F$ is the amount of electricity saved after the use of energy-saving wires, kWh; C_{e} is the electricity price of transmission and distribution, \$/kWh.

2.3.2. Evaluation Indicators

The cash flow of a project, which is known as the cost flow, encompasses cash expenses, such as fixed asset investment and maintenance fees, without considering annual depreciation costs, taxes, surcharges, and loan interest. Therefore, this paper considers LCC to be synonymous with cost flow. The difference between cost and benefit flow is economic net cash flow.

A transmission line project's economic net present value (ENPV) involves discounting each year's economic net cash flows within the project's lifecycle to their present value in the first year. This approach accounts for the time value of money and comprehensively evaluates the project's economic feasibility [41]. It enables decision-makers to evaluate the potential profitability of a transmission line project investment by accounting for all pertinent costs and revenues throughout its lifespan.

Additionally, the Economic Internal Rate of Return (EIRR) is the discount rate at which the total discounted economic net cash flow over the calculation period equals zero [42]. Essentially, it indicates the projected annual rate of return on invested capital for a transmission line project, considering initial costs and future revenue streams.

In addition to utilizing ENPV and EIRR to evaluate the financial viability of projects from an investor's viewpoint, the Dynamic Payback Period (DPP) serves as another crucial metric. It signifies the duration necessary to recover an investment in a project, factoring in inflation and the time value of money. This metric aids stakeholders in comprehending the timeframe required to recuperate their initial investment, taking into account fluctuations in purchasing power over time due to inflationary forces [43].

$$\text{ENPV} = \sum_{t=1}^{T} (BI - BO)_t \times (1 + i_s)^{-t} \tag{15}$$

$$\sum_{t=1}^{T} (BI - BO)_t (1 + \text{EIRR})^{-t} = 0 \tag{16}$$

$$P_t = (t_1 - 1) + \frac{y_{t-1}}{y_n} \tag{17}$$

where BI is the benefit flow, \$; BO is the cost flow, \$; $(BI - BO)_t$ is the total economic net cash flow in period t, \$; t is the project calculation period, namely the life cycle; i_s is the social discount rate, %; t_1 represents the year in which the present value of cumulative net cash flow becomes positive; y_{t-1} is the absolute value of the present value of the cumulative net cash flow in the previous year, \$; y_n is the net cash flow in the positive year, \$; when ENPV ≥ 0, EIRR $\leq i_s$, the economic feasibility of the project is better. The payback period of the benchmark investment in the power industry is usually 12 years. If the DPP is less than the industry benchmark, the project is economical. Through the comprehensive calculation of the above economic indicators, we can more fully understand whether the energy-saving conductor has better economic performance and investment return than the ordinary conductor.

3. Results

3.1. Life Cycle Cost

This paper presents a sample calculation for a practical example—a newly built 220 kV transmission line project in City A, Jilin Province. The line is 32 km long and is scheduled to begin construction in 2022. The project has a 30-year lifecycle, with a 2-year construction phase, a 27-year operational phase, and a 1-year retirement phase. In order to choose the best materials for this project, we conducted a detailed comparison and analysis of four different wire models: JL/G1A-400/35 conventional steel core aluminum stranded wire, JL(GD)/G1A-400/35 steel core high conductivity aluminum stranded wire, JL/LHA1-210/220 aluminum alloy core high conductivity aluminum stranded wire, and JLHA3-425 medium-strength aluminum alloy stranded wire. Tables 1 and 2 contain the meteorological combination condition table for line design and the basic parameters of transmission lines using various wire models.

Table 1. Meteorological factors in line design.

Operating Condition	Temperature (°C)	Wind Speed (m/s)
Low temperature	−20	0
Annual average	5	0
Strong wind	−5	24
Ice coating	−5	10
High temperature	40	0
Installation	−10	10
No wind outside	15	0
Windy outside	15	10
Inside	10	15
70 °C high temperature	70	0

Table 2. Basic parameters of the conductors.

Parameter	JL/G1A-400/35	JL(GD)/G1A-400/35	JL/LHA1-210/220	JLHA3-425
Core wire section (mm^2)	34.36	34.36	218.9	0.00
Outer cross section (mm^2)	390.88	390.88	207.38	426.28
Total cross section (mm^2)	425.24	425.24	426.28	426.28
Diameter (mm)	26.82	26.82	26.81	26.81
20 °C DC resistance (Ω/km)	0.074	0.072	0.073	0.071
Number of splitting roots	2.00	2.00	2.00	2.00
Splitting spacing (mm)	400.00	400.00	400.00	400.00
Total weight of wire (t/km)	8.09	8.09	7.06	7.07
Critical electric field strength (MV/m)	2.14	2.14	2.14	2.14
Conductor operating temperature (°C)	29.79	29.78	29.78	29.77
AC resistance (Ω)	0.04	0.04	0.04	0.04
Transmission power (MW)	2154.87	2187.39	2214.77	2246.67
The field strength of A-phase surface conductor at average height (MV/m)	4.036	4.036	4.038	4.038
The field strength of B-phase surface conductor at average height (MV/m)	4.157	4.157	4.158	4.158
The field strength of C-phase surface conductor at average height (MV/m)	3.913	3.913	3.915	3.915
Conductor surface coefficient	0.82	0.82	0.82	0.82
Unit price (k$/t)	2.36	2.70	2.80	2.95
Wire cost (k$/km)	19.12	21.41	19.77	20.83
Steel quantity for tower (t/km)	49.21	49.21	48.84	48.72
Unit price of steel (k$/t)	1.32	1.32	1.32	1.32
Good weather calculation hours (h)	6310.00	6310.00	6310.00	6310.00
Calculation hours in rainy days (h)	1160.00	1160.00	1160.00	1160.00
Calculation hours of snow days (h)	640.00	640.00	640.00	640.00
Calculation hours of rime days (h)	420.00	420.00	420.00	420.00
Relative air density	1.09	1.09	1.09	1.09
Air pressure (Pa)	101,325.00	101,325.00	101,325.00	101,325.00

The LCC of the transmission line under four schemes—JL/G1A-400/35 conventional steel core aluminum stranded wire (Scheme I), JL (GD)/G1A-400/35 steel core high conductivity aluminum stranded wire (Scheme II), JL/LHA1-210/220 aluminum alloy core high conductivity aluminum stranded wire (Scheme III), and JLHA3-425 medium-strength aluminum alloy stranded wire (Scheme IV)—is predicted and calculated based on basic parameters and an economic calculation method. The time dimension spans from the beginning of project construction in 2022 to the end of the line scrapping year of 2051, including a construction period from 2022 to 2023, a decommissioning period starting from 2051 without counting electricity sales benefits, and an operating period from 2024 to 2050 considering electricity sales revenue. The initial investment cost is a one-time investment without considering the time value of capital. The calculation results are presented in Table 3.

Table 3. Initial investment cost of the studied case.

Parameter	JL/G1A-400/35	JL(GD)/G1A-400/35	JL/LHA1-210/220	JLHA3-425
Construction and installation cost (k$)	3947.62	3947.62	3947.62	3947.62
Original equipment cost (k$)	2296.54	2300.46	2289.62	2294.18
Conductor investment cost (k$)	611.81	615.73	604.89	609.45
Other component costs (k$)	1684.73	1684.73	1684.73	1684.73
Other costs (k$)	1309.23	1309.82	1309.37	1309.55
Total static investment cost (k$)	7553.39	7557.89	7546.60	7551.34
Dynamic cost (k$)	151.07	152.55	151.22	151.80
Total initial investment cost (k$)	7704.45	7710.44	7697.82	7703.15

The annual cost of a construction project, including operational and loss expenses, can be estimated by calculating the total yearly expenses [44]. The calculation takes into account the following conditions:

(1) The project's lifespan is 30 years, with a two-year construction period and a 6:4 investment ratio during construction.
(2) The maximum annual loss hours for transmission lines are 3500 h, 4000 h, 5000 h, and 6000 h.
(3) The discount rates are 8%, 10%, and 12%.

When considering an 8% discount rate, a comparison of the average annual electrical energy loss cost under the four schemes is derived by considering the influence of the annual maximum loss hours and the electricity price on the line's annual electrical energy loss cost shown in Figure 6.

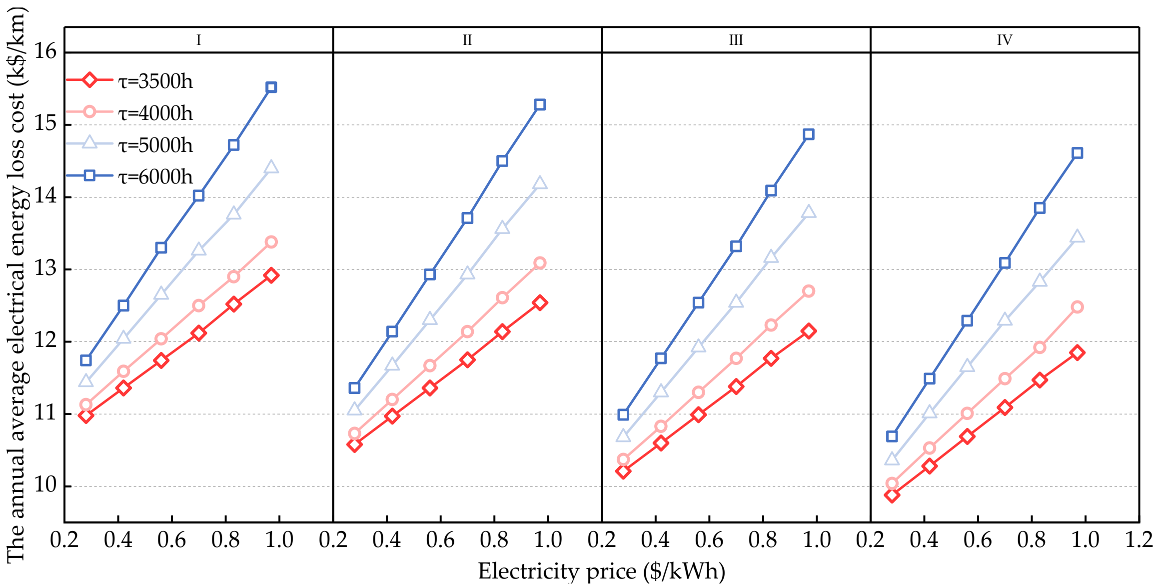

Figure 6. Variation of annual electrical energy loss cost of the line across different schemes with electricity price and annual maximum loss hours.

As shown in the figure, it can be directly seen that the four parts of the image represent four different conductor schemes (I, II, III, IV). Within the same scheme, when the annual maximum loss hours remain unchanged, the annual average cost of electrical energy losses for the line project increases with rising electricity prices. At the same electricity price, the cost of energy losses increases with the maximum loss hours, whereas, among different schemes, when both the electricity price and loss hours are the same, scheme I has the highest overall cost of electrical energy losses, and scheme IV has the lowest. A lower cost of electrical energy losses indicates that the conductor scheme is more energy efficient.

When the maximum annual loss hours of the line take 6000 h as the benchmark, the electrical energy loss costs of the four schemes under different discount rates are compared in Figure 7.

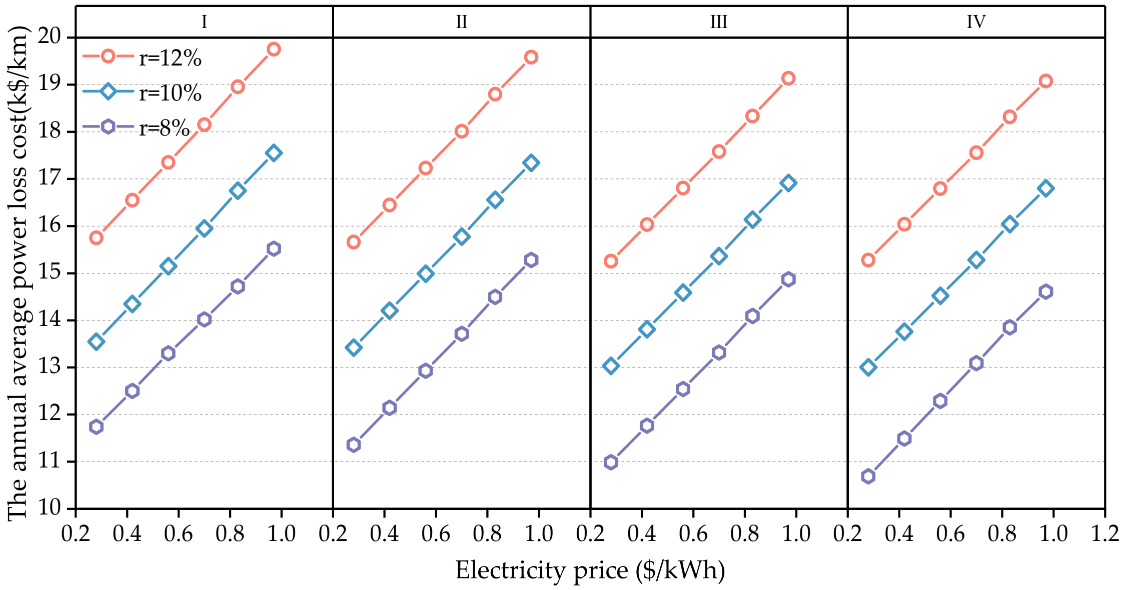

Figure 7. Variation of annual electrical energy loss cost of the line across different schemes with electricity price and discount rate.

When the annual discount rate remains constant within the same framework, the annual average cost of electrical energy losses for the line project increases as electricity prices rise. At the same electricity price, energy loss costs increase with a higher discount rate. When both the electricity price and discount rate are the same among different schemes, scheme I has the highest overall cost of electrical energy losses, and scheme IV has the lowest.

Daily operating costs are mainly determined by comprehensive conditions such as terrain and line corridors. With the increase in the line's service life, the line's operation and maintenance cost increases year by year. According to the historical data and the fixed data stipulated by the State Grid, this paper simplifies the calculation and refers to the historical average level to simplify the processing. The daily operation and maintenance cost is set to 2.6 k$/km, increasing by 1.32 k$/km, ignoring the impact of the difference in the conductor model.

Since the maintenance costs of different types of conductors are the same, based on the project information and relevant data, the parameters related to the line maintenance cost are shown in Table 4 [45].

Table 4. Maintenance cost of the studied case.

Parameter	Value
Minor maintenance cost (k$)	1.39
Minor maintenance cycle (year/times)	1
Major maintenance cost (k$)	11.4
Major maintenance life (year/times)	7

The disposal and recycling costs of the four schemes are: 250.51 k$, 251.23 k$, 251.76 k$, and 252.34 k$. The total LCC and the percentage of each cost is shown in Figure 8.

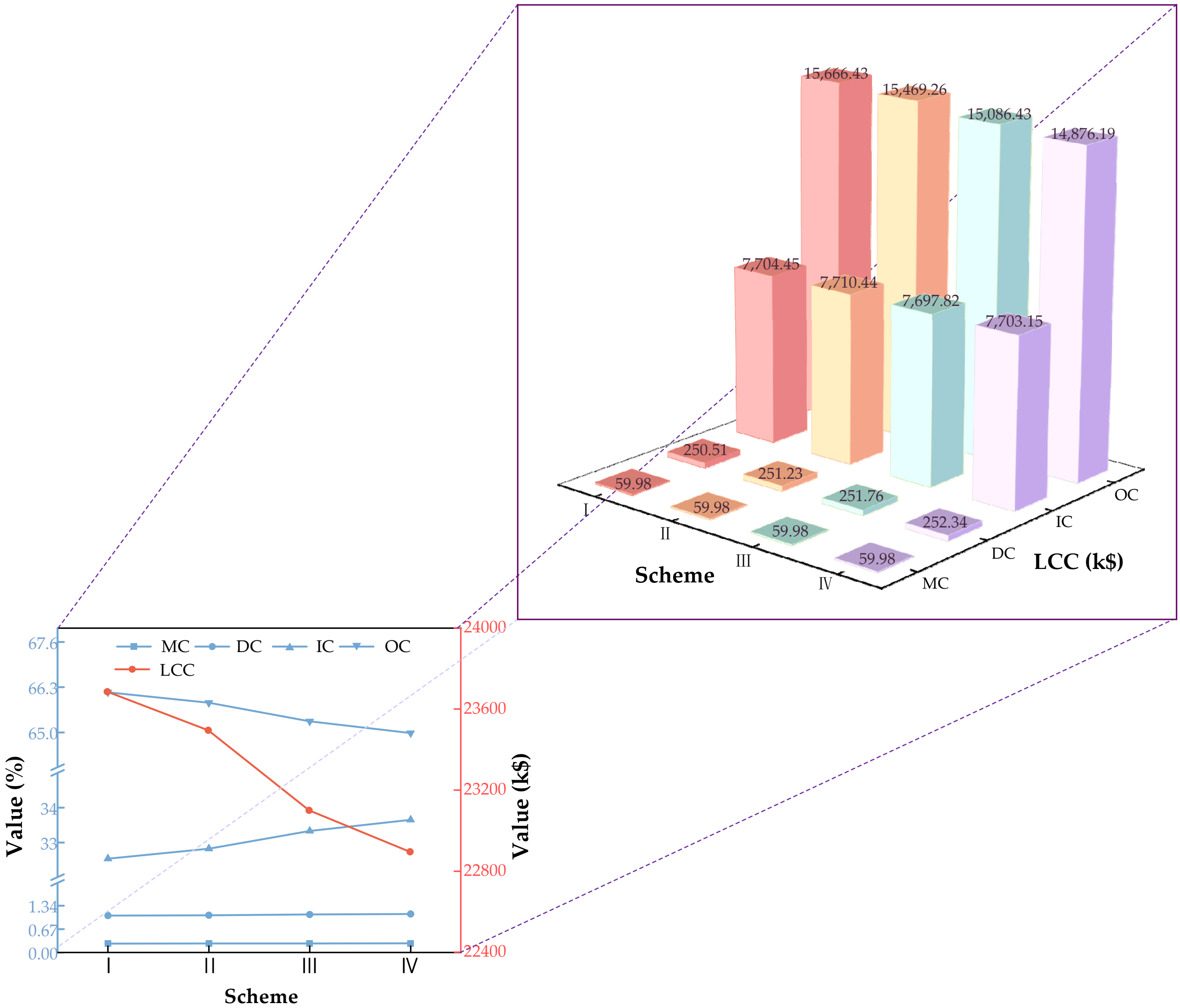

Figure 8. LCC and proportions of four schemes.

Based on their LCC, the highest proportion of the total cost is attributed to operational costs, ranging from 65% to 66.2%, followed by initial investment costs, ranging from 32.5% to 33.7%. Maintenance costs and disposal and recycling costs are relatively small, at 0.3% and 1.1%, respectively.

3.2. Electricity Sales Forecasting

According to data from the Jilin Provincial Bureau of Statistics, the electricity consumption of residents in city A from 2009 to 2021 was used to compare various prediction methods for predicting the load level of a transmission line project in city A. The actual and predicted values of different methods are shown in Figure 9.

The results of error evaluation indexes and fitting effect parameters of different prediction methods are shown in Table 5.

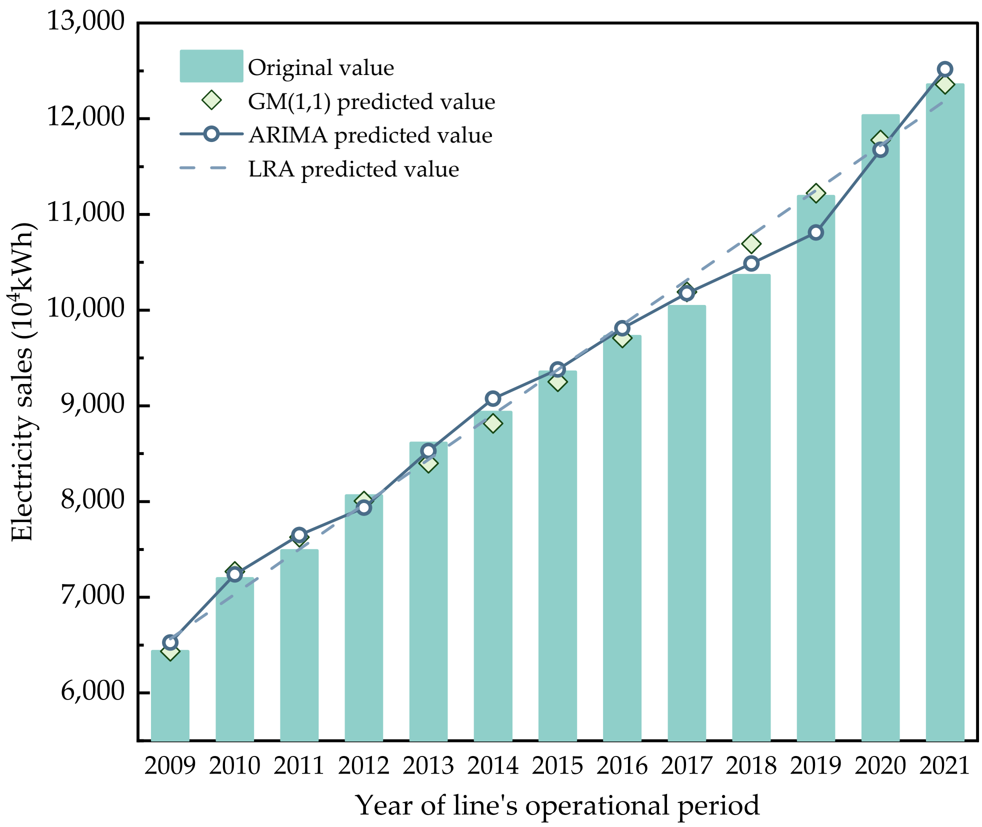

Figure 9. Regression analysis diagram of electricity sales from 2009 to 2021 of the studied case.

Table 5. Error evaluation indexes of forecasting results.

Parameter	LRA	GM(1,1)	ARIMA
Mean relative deviation	−0.043%	0.003%	0.042%
Mean absolute percentage error	1.55%	1.31%	1.52%
R^2 value	0.987	0.998	0.971

Based on the prediction accuracy of three different methods, a combined prediction analysis was conducted with weight coefficients of 0.3, 0.4, and 0.3. This analysis resulted in the prediction of electricity sales during the operation period from 2024 to 2050.

3.3. Economic Evaluations

Additionally, the annual operation costs for the four schemes were predicted separately. Considering the cost of maintenance during operation, a predicted value of cost flow was obtained, illustrated in Figure 10.

With the increase of the year, the cost flow under the four schemes increases sharply in the maintenance year, but it shows an increasing trend. In addition, the operation investment of the three energy-saving conductors is lower than that of the conventional steel-cored aluminum stranded wire. The cost of the project operation period of scheme IV is the lowest, indicating that the medium-strength aluminum alloy stranded wire has the best energy-saving effect, followed by aluminum alloy core high conductivity aluminum stranded wire and steel core high conductivity aluminum stranded wire.

Combining the parameters in Table 1, according to Equation (5), the resistive loss energy generated by this line project under the four conductor schemes is calculated, and at the same time, using the 2020 Liaoning provincial grid emission factor data as a reference, the additional carbon reduction benefits generated by the use of energy-saving conductors can be predicted for the period from 2024 to 2050.

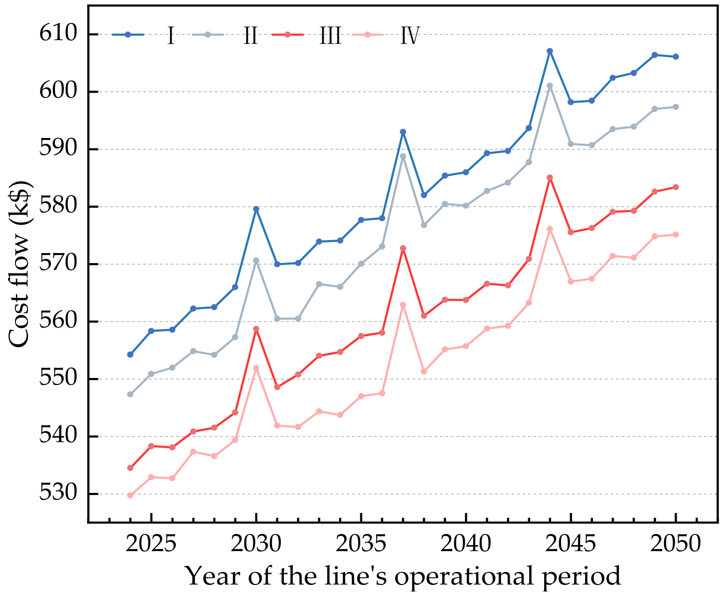

Figure 10. Trends in cost flow of the studied case from 2024 to 2050.

The trend of projected benefit flow for the line project across four different scenarios is illustrated in Figure 11, emphasizing that the overall benefit of utilizing three energy-saving conductors surpasses that of the conventional steel-core conductor. Upon operationalization of the line, the energy-saving conductors yield carbon reduction benefits, leading to additional advantages.

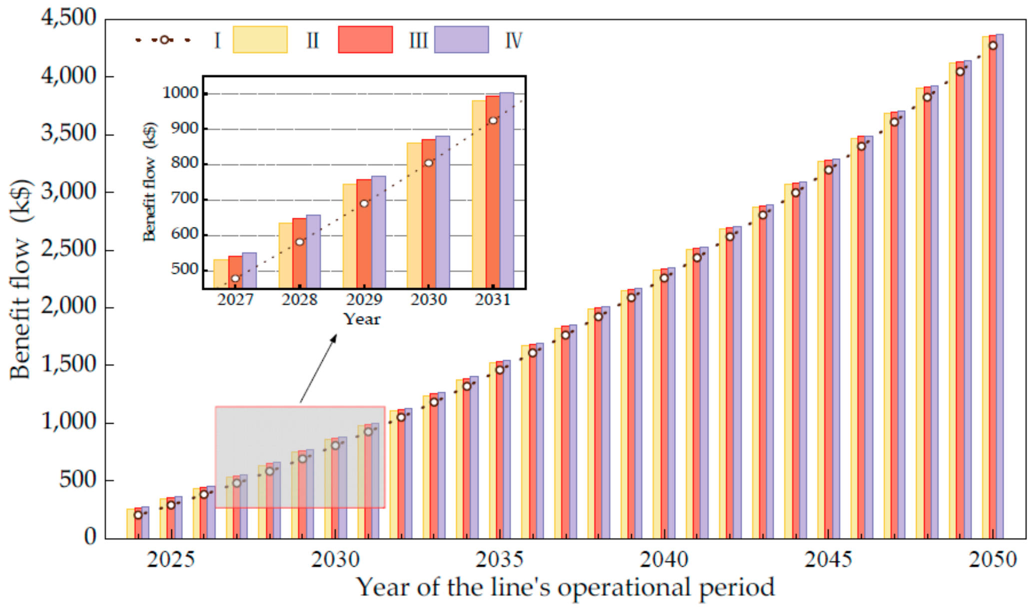

Figure 11. Trends in benefit flows from 2024 to 2050 for the studied case under various schemes.

The economic net cash flows of the four schemes are calculated by combining the life cycle benefit and cost flows, using a social discount rate of 8%. Figure 12 illustrates the projected trend of benefit flow for the line project under four different schemes, confirming that the overall benefit of utilizing three energy-saving conductors exceeds that of the conventional steel-core conductor. Once the line becomes operational, the energy-saving conductors generate carbon reduction benefits, which are pivotal in determining additional advantages. The amount of energy saved by the conductors plays a significant role in determining these additional benefits, thereby rendering the energy-saving conductors more advantageous overall.

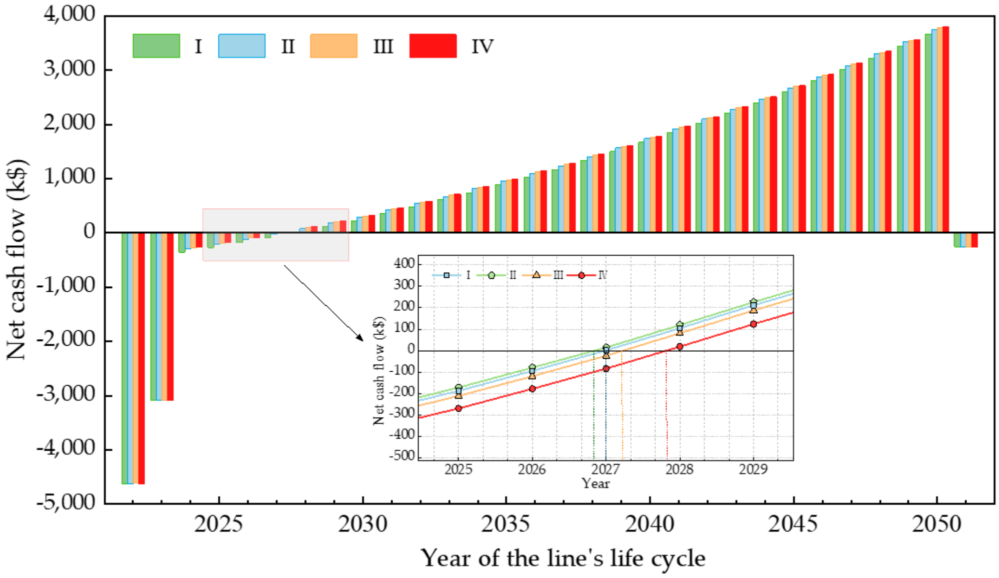

Figure 12. Life cycle net cash flow of the studied case.

The project's net cash flow is initially negative during the construction period, but it gradually increases throughout its life cycle. From 2022 to 2023, only the initial investment cost is considered, resulting in a negative net cash flow during this time. Once the project becomes operational, operation and maintenance costs, as well as income from electricity sales and carbon reduction benefits from energy-saving conductors, are considered. Consequently, benefits will gradually exceed costs, turning the project's economic net cash flow positive at a specific point. The earlier this point is reached, the greater the conductor's energy-saving capability. In scheme I, net income is generated between 2027 and 2028, and the net cash flow of the three energy-saving conductors transitions from negative to positive between 2026 and 2027. The sole cost considered in the decommissioning year is the disposal and recycling cost of the line, leading to a negative economic net cash flow. The project employing the energy-saving conductor scheme exhibits a marginally higher overall net cash flow than scheme I, suggesting superior economics for the transmission line utilizing energy-saving conductors.

The economic evaluation indicators for the four conductor schemes have been calculated, as shown in Table 6.

Table 6. Economic indicators of four conductor schemes.

Parameter	Scheme I	Scheme II	Scheme III	Scheme IV
ENPV	−446.489	233.305	494.217	661.847
EIRR (%)	7.85%	9.65	10%	11.28%
DPP (year)	12.89	12.51	12.43	12.39

Scheme I has a negative ENPV, and its EIRR is less than the social discount rate. On the other hand, schemes II, III, and IV have a positive ENPV, and their EIRR is greater than the social discount rate (8%). Additionally, the dynamic payback periods of all four schemes are more extended than the industry benchmark (12 years), indicating that scheme IV is the most economically efficient, followed by schemes III and II. The study concludes that the conventional conductor is less economically.

4. Discussion

In practice, the cost of a line project may vary due to several external factors. Therefore, it is essential to conduct sensitivity analyses to ascertain the impact of critical parameters (such as grid load levels, altitude, and weather conditions) on the project's average life cycle cost. Grid load levels directly influence the level of power loss in the conductor, which in turn affects the economic cost of the line project. Conversely, the maximum load hours also impact the operating costs. The preceding conclusions indicate that the optimal energy-saving conductor is JLHA3-425. Consequently, JLHA3-425 is selected to represent the energy-saving conductor, while the traditional conductor remains JL/G1A-400/3. The annual value of the life cycle cost of the case project under the two schemes is taken as the object of the cost sensitivity analysis for the number of hours of line loss under the different load growth models (low, medium, and high load models). A sensitivity analysis was conducted to determine the sensitivity of the maximum loss hours of the line economic cost to the LCC under the high load model, as shown in Figure 13.

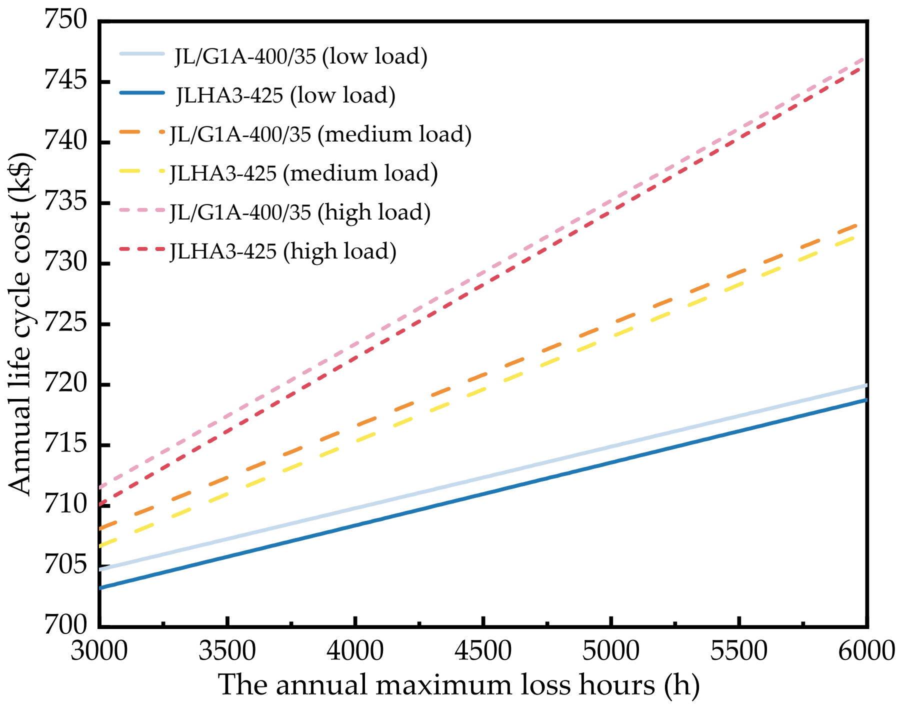

Figure 13. Sensitivity analysis of the maximum power loss hours of transmission line on annual life cycle cost under different load models.

The results indicated that the load level significantly influences the line economic cost. Furthermore, the sensitivity difference between standard and energy-saving conductors was minimal under the same load growth model.

Furthermore, environmental factors and meteorological conditions exert a considerable influence on the outcomes of economic investment. By analyzing the local climate and altitude conditions in city A, Jilin Province, it is possible to ascertain the variations in O&M costs associated with different scenarios when the number of hours of sunshine and altitude is within a specified range, as shown in Figure 14.

As altitude progressively increases, the resistance of the conductor significantly enlarges, leading to a continual rise in operational loss expenses and consequently elevating the overall cost of line projects. Conversely, when the annual number of sunlight hours increases, it exhibits a trend of gradual reduction, clearly revealing that favorable weather conditions can optimize line operations to a certain extent and reduce investment costs. It is noteworthy that although different models of conductors vary in cost, their sensitivity to changes in altitude and annual sunlight hours is almost identical—meaning the degree to which they are affected by these two factors is quite comparable.

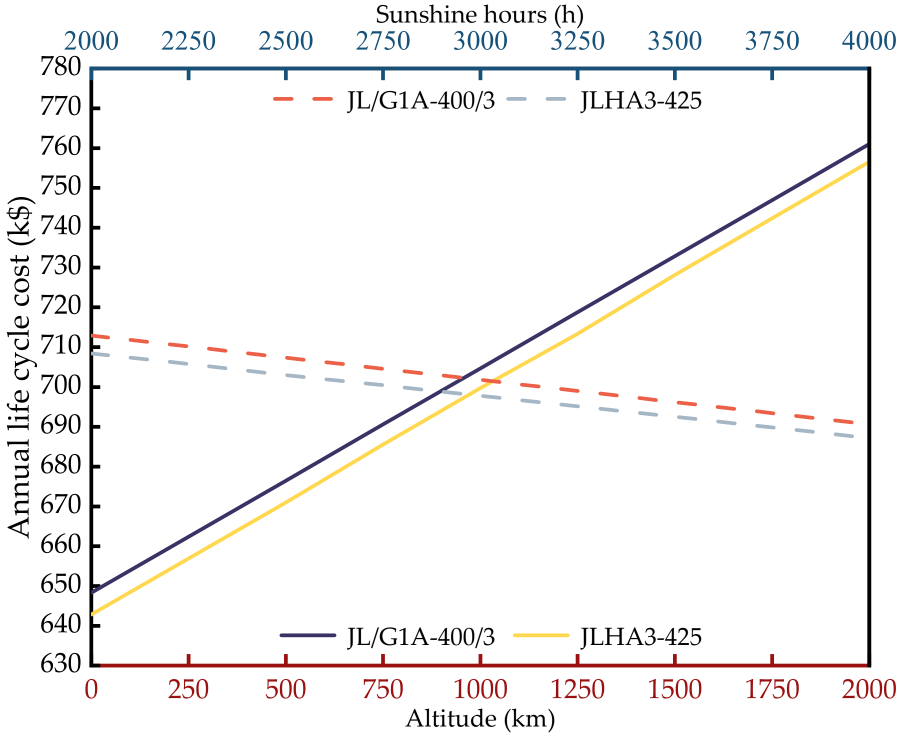

Figure 14. Sensitivity analysis of altitude and sunshine hours on annual life cycle cost.

5. Conclusions

In this study, we analyze the cost difference of a 220 kV transmission line project in city A, Jilin Province, under four conductor schemes: JL/G1A-400/35 conventional steel core aluminum stranded wire, JL(GD)/G1A-400/35 steel core high conductivity aluminum stranded wire, JL/LHA1-210/220 aluminum alloy core high conductivity aluminum stranded wire, and JLHA3-425 medium-strength aluminum alloy stranded wire. Through constructing the life cycle cost model of the transmission lines, we compare the cost differences of four conductor schemes. Three forecasting methods are selected to predict the electricity sales of the line over its life cycle. Carbon reduction benefits are also predicted. Economic indicators such as net cash flow and economic internal rate of return are assessed. The conclusions are presented below:

(1) In the life cycle cost analysis of transmission lines, operating costs account for the highest proportion, as much as 65% to 66.2%, with energy loss costs particularly significant. Specifically, the annual average cost of energy loss is influenced by several parameters; increases in electricity prices, discount rates, and the maximum number of loss hours per year will all lead to higher energy loss costs. Among the different types of conductor schemes, JL/G1A-400/35 has the highest life cycle cost (23,681.37 k$), followed by JL(GD)/G1A-400/35 (23,490.91 k$), JL/LHA1-210/220 (23,095.87 k$), and JLHA3-425 (22,891.66 k$). Therefore, energy-saving conductors can effectively reduce energy losses and have lower costs.

(2) The electricity sales after the transmission line was put into service were predicted using a linear regression model, GM (1, 1) model, and ARIMA model. The three methods' prediction error and fitting effect were compared, and the benefits of electricity sales of the transmission line were assessed through the combination analysis. After adopting energy-saving conductors, the reduction in line losses increases the carbon reduction benefit and economic benefits of the transmission line.

(3) This study analyzes the operation of 220 kV transmission lines in the Jilin Province Power Grid of China from 2018 to 2022. It provides a new direction for the low-carbon construction of transmission lines. By comprehensively considering the costs and benefits of different schemes and comparing three economic indicators: ENPV, EIRR, and DPP, it is verified that the JLHA3-425 type conductor is the most economical among the three energy-saving conductors. Based on its better energy-saving effect and economy, the JLHA3-425 medium-strength aluminum alloy stranded wire emerged as the most economically viable option among the evaluated schemes, holding substantial promise for fostering economic and environmental sustainability in electrical power transmission.

(4) This paper does not consider the cost implications of variations in carbon emission factors, and further research is needed to quantify the benefits of carbon emissions.

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