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Regional electricity cooperation model for cost-effective electricity management with an emphasis on economic efficiency

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ABSTRACT

Effectively reducing the total electricity cost while ensuring its overall efficiency is vital for the sustainable development of power systems. Herein, we develop a regional cooperation optimization model to enhance the existing power cost model. This is achieved by incorporating power trading scenarios and pollution considerations, leveraging the distinct characteristics of power generation costs from various sources. The developed regional cooperation optimization model simultaneously accounts for production efficiency and overall power costs, ensuring equitable distribution and compensation of benefits among cooperating entities. In addition, the key findings indicate that the interregional cooperation optimization model significantly reduces the total cost of electricity operations in China. Specifically, during the 11th five-year plan period, the total electricity cost in China exhibited a noteworthy decline of USD 50,876 million owing to multi-objective cooperative optimization, constituting 25.99% of the total electricity cost compared with the preoptimization period. This study identifies the eastern and western regions as principal contributors to the cost savings achieved by the interregional cooperative optimization model. Simultaneously, recognizing their significant contributions, it is recommended that the eastern and western regions provide additional cost compensation to other regions to ensure the long-term viability of the cooperative alliance.

1. Introduction

The cooperative model reduces the information asymmetry among participating subjects and balances resource allocation between supply and demand. In China, energy resources and power loads exhibit an inverse distribution, and the regional imbalance between power supply and demand has led to serious resource waste challenges (Yi et al., 2019). Similar to other countries worldwide, China is actively conducting market-oriented reforms on the power system, mainly including the construction of a cooperative trading model of the regional power market to improve the power market mechanism. The goal of the establishment of the regional power cooperation model is to maximize the overall benefits. Hence, in the process of implementing the regional cooperation model, externality challenges exist, such as an increase in the electricity cost of the participating subjects, a loss of efficiency, and an imbalance in the distribution of the benefits of cooperation. How to reduce or eliminate these negative externalities has become an urgent challenge that must be solved to achieve sustainable economic and social development.

However, it is not easy to realize these goals because the premise of cost savings is the efficient allocation of resources, and the core issue is whether the reallocation of resources meets the actual needs of cooperation between the main parties; hence, the fair distribution of benefits and compensation between regions is particularly important to achieve long-term stable cooperative alliance relations. Therefore, the formulation of scientific and fair rules for the distribution of cooperative benefits is another important issue in the study of the power cooperation optimization model (Bistline et al., 2020; Cui et al., 2014). Liu and Lin (2017) constructed a carbon emission allowance allocation model using a nonlinear programming method that realizes the optimal emission allowance allocation result at the lowest cost. Moreover, Liang et al. (2023) constructed a synergistic emission reduction model to achieve the national carbon reduction target through interregional cooperation while reducing CO2 emissions at the lowest cost.

Previous studies on electric cooperation models and benefit distribution and compensation mechanisms continue to have research gaps. Although previous studies have more extensively discussed the cost of the electric power cooperation model, the single cost constraint target

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reduces the explanatory ability of the cooperation model in the current complex environment. Total factor productivity (TFP) is a key indicator to comprehensively measure regional economic development and has gained consensus in the academic community. Productivity is a factor that must be considered by current regional governments when developing policies (Su and Liang, 2021). Previous researchers have mostly focused on individual targets, such as pollutant emission targets, investment targets, and cost control (Chok et al., 2019; Muñoz et al., 2023; Yu et al., 2023). In addition, most of the previous studies have focused on electricity cost generation (de Lima et al., 2021).

This study simultaneously considers two development objectives to go beyond a single-objective study: enhancing efficiency and cost of electricity. Innovatively, the costs and benefits of electricity transactions are included in the study model, with the additional consideration of the costs of pollution from electricity consumption. This study is an enrichment and extension of the existing electricity cost model, extending it to a more general regional-level study rather than a separate study of power system costs. Finally, previous studies on the allocation of costs and benefits have generally focused on a particular stage (e.g., a particular year, a particular period) and have not emphasized the possible temporal characteristics of the study object in continuous time, whereas the stage-specific target planning (five-year plan policy) in China provides a natural period of comparison to inform the next stage of energy development by analyzing data from different periods. This categorization is valuable in time-phase analysis (Zhu and Lin, 2021). This study uses the unique five-year plans (specifically the 11th, 12th, and 13th five-year plans) of China as the study periods and validates the practical effects of the regional power cooperation optimization model in different consecutive periods.

The marginal contributions of this article are primarily reflected in four aspects.

(1) Development of a regional cooperation optimization model that considers production efficiency and overall electricity costs
(2) Inclusion of differences in the costs of power generation from various energy sources, accounting for the cost per kWh of thermal, wind, hydro, photovoltaic, and nuclear power generation in China to assess regional power production costs
(3) Enrichment and expansion of the existing electricity cost model by endogenizing the electricity trading scenario and incorporating considerations for electricity pollution
(4) Implementation of an equitable distribution and compensation mechanism for the benefits of cooperating entities over successive study periods, with a focus on forecasting for the next period

The remaining sections of the study are stated as: Section 2 reviews relevant literature. Section 3 introduces the model development. Section 4 explains the choice of study area and the data sources. Section 5 presents an analysis on the empirical study. Section 6 concludes the paper and provides corresponding policy recommendations.

2. Literature review

Power cost optimization is a crucial topic in the power industry and energy management, focusing on enhancing system efficiency and economic performance through technical and managerial approaches. In recent years, rising energy costs and growing environmental concerns have brought significant attention to power cost optimization. Research on power cost optimization focuses on two key areas: (i) enhancing power generation efficiency and reducing costs through technological innovation, and (ii) optimizing resource allocation and management via policy and market mechanisms (Holmberg and Tangeras, 2023; Lazkano et al., 2017; Wang et al., 2022). Power technology innovation is a fundamental driver of power cost optimization, primarily involving advanced technologies like high-efficiency gas turbines, combined-cycle generation, clean coal technologies, and optimized fuel use strategies (Xu et al., 2023). Additionally, market reforms and energy policies are crucial to power cost optimization. For instance, demand-side management policies implemented globally reduce costs by encouraging consumers to lower peak-hour consumption through time-of-day pricing (Zhao et al., 2021).

Existing studies have explored power market reforms and policy formulation, highlighting marketization strategies as a key method for reducing energy and power costs. Cheng et al. (2024) examined the effects of China's power market reforms on installed capacity and power generation from various sources. The reforms significantly impacted the cost of renewable energy production. Moreover, the development of diverse energy policies is crucial for reducing electricity costs. Energy policies influence electricity cost optimization across the entire system, including generation, transmission, distribution, and consumption. Zhao et al. (2024) confirmed the critical role of diverse energy policies in promoting renewable electricity consumption by comparing investment and operational subsidy policies. Energy policies and market-oriented reforms are synergistic, with existing policies in many countries primarily promoting reforms to optimize resource allocation and reduce costs.

As social and power system complexities increase, scholars have shifted their focus from single-objective power cost optimization to multi-objective joint optimization models. Traditional power cost optimization mainly targets generation and operation costs. However, with the rise of power marketization and growing inter-regional trading demands, multi-objective, multi-stakeholder regional cost optimization has gained practical significance. Dai et al. (2023) proposed a novel multi-objective scheduling strategy that accounts for the spatial and temporal distributions of pollutants in power systems. This strategy considers the comprehensive impact of pollutants while reducing power generation costs. Furthermore, regional economic growth, employment, and environmental goals are now key considerations in energy policy, as single-objective optimization no longer meets the needs of modern power systems. The multi-objective optimization model integrates economic, environmental, and reliability factors, enhancing the scientific rigor and rationality of decision-making (Fan et al., 2023; Tian et al., 2024)。

Existing electricity market research has focused on the important role of regional cooperation. In addition, different countries and regions have conducted a series of electricity market cooperation and trading models for market reform practices (Pineau et al., 2004; Singh et al., 2018; Timilsina and Toman, 2016). Compared with the noncooperative model, the regional electricity cooperation model maximizes the overall utility by considering the energy constraints of each region. Previous studies on cooperative models in electricity markets have focused on the cost advantages and emission reduction effects of regional electricity cooperative models. With respect to cost advantages, a stable and feasible cooperation model can reduce the information asymmetry between subjects, achieve a dynamic balance between the supply and demand sides of electricity, and minimize the cost of the entire electricity system (Poudineh et al., 2020). Xu et al. (2020) constructed a China-based multiregional power system optimization model, evaluated the potential economic benefits of cross-regional grid infrastructure investments in China under different scenarios, and demonstrated that investment cooperation among different grid systems in China is economically feasible. Regarding the effect of emission reduction, based on the comprehensive consideration of the differences in marginal emission reduction costs between different regions, by utilizing the cooperation mechanism between different subjects in the power industry, it is possible to equip the whole country to realize the maximum potential for emission reduction (Gazzotti et al., 2021). The advantage of cooperative abatement is that regions with high marginal abatement costs can choose to transfer their abatement tasks to regions with low marginal abatement costs, and this transfer is in line with the Pareto optimality rationale. This view is supported by many current studies. For instance, Xue et al. (2015) improved the effectiveness of pollution control across administrative units in China by constructing a cooperative air pollution control model for regional cooperation. In addition, Fyson et al. (2020) applied two common burden principles to validate cooperative burden sharing for CO_2 removal between regions. Moreover, Han et al. (2023) studied the cooperative game between different power sources in the spot market and established a two-stage stochastic optimization model to optimize the strategy. This study proves that a two- or three-party cooperative alliance leads to a multiwin situation.

In conclusion, while current research has made significant progress in power cost optimization, several research gaps remain that warrant further investigation. First, given the rapid changes in economic and social environments, a multi-objective regional cooperation model that balances efficiency and cost is more valuable. Second, as cross-regional power dispatch becomes more frequent, existing power cost optimization models should account for inter-regional power transactions. Finally, a more scientific and equitable benefit distribution mechanism should be designed for the stakeholders in the power cooperation model.

3. Model development

The development of the research model is delineated into three main components. (1) First is the construction of a regional cooperation optimization model: This entails the formulation of a model that considers production efficiency and overall electricity costs. (2) Second is the development of a benefit distribution model and compensation mechanism: Drawing on cooperative game theory, a model for the distribution of benefits and a compensation mechanism are established. (3) Third is the testing and application of the model: The model is put to the test and applied across different five-year plan periods in China, ensuring its robustness and applicability over time. Fig. 1 presents a workflow diagram depicting the various stages of this research model.

3.1. Key assumptions

(1) **Electricity Consumption Sources:** There are two main sources of electricity consumption, namely, the production of electricity within a region and electricity obtained through interregional trading. When the internal electricity production of a region exceeds its consumption needs, the region can trade the surplus through the electricity market and become a seller of electricity, thus gaining additional trading revenue. Conversely, if regional power production is insufficient to meet demand, the region must make up the shortfall by purchasing external power, becoming a power buyer, and incurring the corresponding purchase costs. This mechanism not only promotes rational flows of electricity resources but also contributes to the complementary development of interregional economies. Evidence in support of this view includes data on regional electricity trading volumes, indicating the distribution of electricity surplus and deficit regions, as well as an assessment of the specific impacts of electricity trading on regional economies (Lyu et al., 2024).

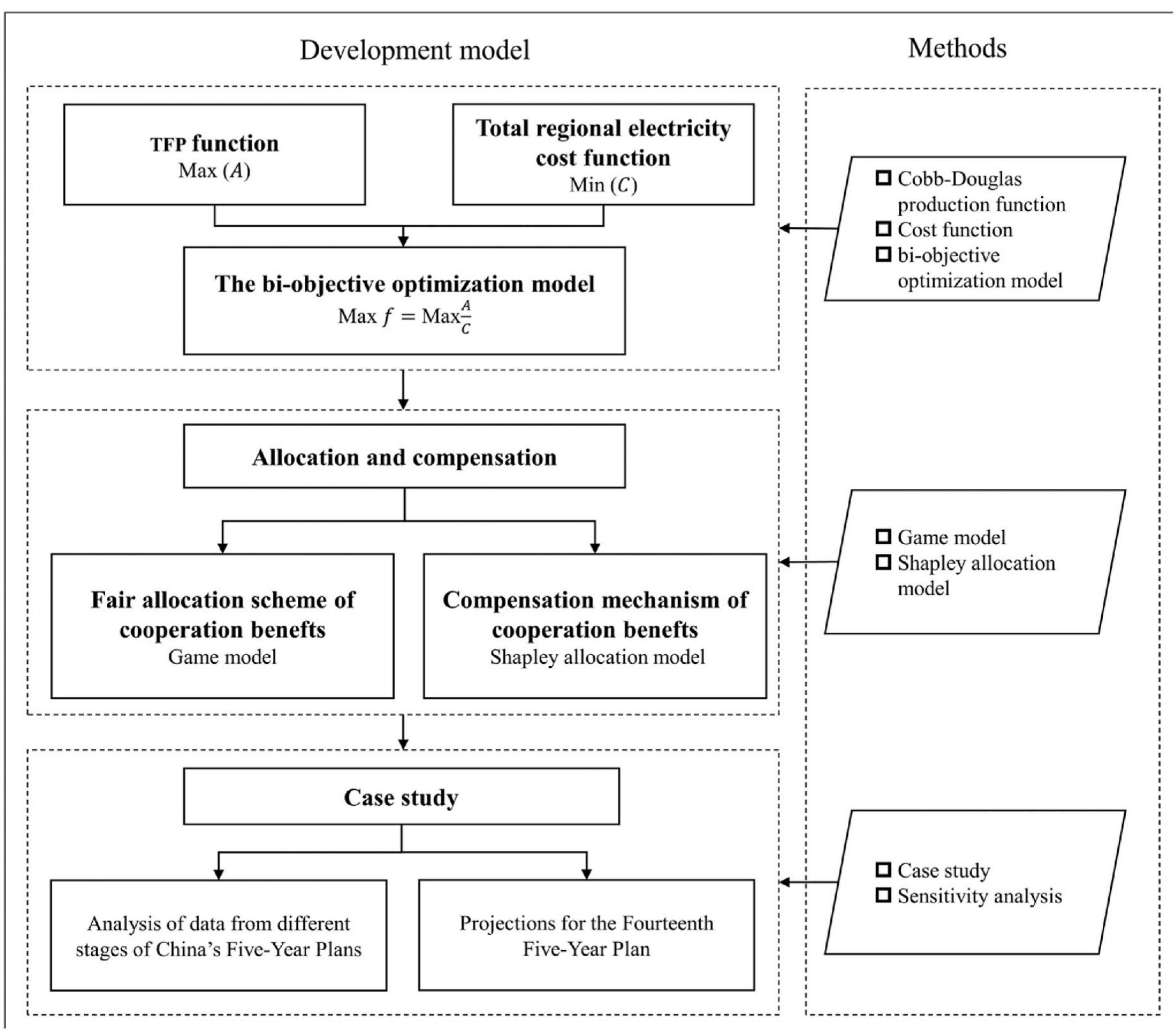

Fig. 1. Flow chart of this article.

(2) **Ensuring Basic Power Consumption:** To ensure that electricity consumption continues to support the production and economic activities of society in general, it is critical to guarantee that the basic electricity consumption needs are met. This study assumes that the total electricity consumption by the entire Cooperative Union remains stable when considered. This means that, although the patterns of electricity production and consumption may change in each region, the overall demand for electricity consumption in the cooperative union will not decrease, ensuring the basic supply of electricity for socioeconomic activities. The rationality of this setting is supported by studies on the correlation between electricity consumption and economic growth, showing that a stable electricity supply is a key factor in driving economic development (Shakouri et al., 2023).

(3) **Assumptions in Case Study:** In conducting the case study, we assume that the regions in the cooperative alliance do not differ with respect to production equipment and production technology conditions to simplify the model and focus on analyzing the impact of electricity trading on the cooperative alliance. Therefore, we further assume that the lower and upper limits of electricity consumption of each cooperative entity are set according to the same ratio, fairly assessing the potential benefits and costs of electricity trading for different regions. The rationale behind this assumption is supported by the reality of the standardization of production technologies and the increasing frequency of interregional technological exchanges (Xue et al., 2022).

3.2. Parameters and variables

Table 1 summarizes the parameters and variables used in this paper.

3.3. The multi-objective optimization model for regional electricity cost control

Herein, the constructed multi-objective optimization model aims to synergistically advance cost reduction and efficiency through regional cooperation. Specifically, it seeks to minimize the overall cost of electricity consumption while maximizing the value of TFP. Consequently, TFP stands out as a core variable of interest in this study. Following the classical Cobb–Douglas production function setting (Böhringer et al., 2012), our study integrates electricity consumption (E_i) as an energy input into the basic function setting. Capital inputs (K_i) and labor inputs (L_i) are traditional factor inputs, with GDP (Y_i) as the output and A_i as the TFP. With the mentioned inputs and outputs, we formulated the subsequent production function, as follows:

$$Y_i = A_i^{\alpha_1} \cdot K_i^{\alpha_2} \cdot L_i^{\alpha_3} \cdot E_i^{\alpha_4} \tag{1}$$

The coefficients of elasticity α_1, α_2, α_3, and α_4 have values between 0 and 1. i depicts different regions of China. Both sides of the equation were then subjected to a natural logarithm transformation to obtain a linear regression equation, as follows:

$$ln\, A_i = \beta_0 + \beta_1 \, ln\, Y_i + \beta_2 \, ln\, K_i + \beta_3 \, ln\, L_i + \beta_4 \, ln\, E_i \tag{2}$$

Where $\beta_1 = \frac{1}{\alpha_1}$, $\beta_2 = -\frac{\alpha_2}{\alpha_1}$, $\beta_3 = -\frac{\alpha_3}{\alpha_1}$, $\beta_4 = -\frac{\alpha_4}{\alpha_1}$. Therefore, the efficiency function can be obtained as follows:

$$A_i = e^{\beta_0} \cdot Y_i^{\beta_1} \cdot K_i^{\beta_2} \cdot L_i^{\beta_3} \cdot E_i^{\beta_4} \tag{3}$$

Most existing research on electricity costs primarily concentrates on the production costs and environmental performance of electricity, focusing less on the costs associated with electricity transactions among diverse entities. In reality, considering transactions involving multiple entities, distinct decisions in transactions yield various resource allocation patterns. These patterns frequently result in distinct cost outcomes. Building upon the aforementioned analyses, this study dissects the overall regional cost of electricity consumption (C_i) into two components: the economic cost of electricity consumption (EC_i) and the environmental cost (CC_i):

Table 1
Parameter and variable definitions.

Parameters and variables	Definition	Units
α_1, α_2, α_3 and α_4	Coefficient of elasticity for the production input factors in equation 1	dimensionless
A_i	Total factor productivity in region i, calculated using the DEA model	dimensionless
K_i	Net stock of fixed assets in region i	USD
L_i	Employment in region i	persons
E_i	Electricity consumption in region i	kWh
Y_i	GDP in region i	USD
C_i	Total cost of electricity consumption in region i	USD
EC_i	Economic cost of electricity consumption in region i	USD
CC_i	Environmental costs of electricity consumption in region i	USD
CEF_i	Grid carbon emission factor in region i	kg/kWh
PC_i	Total cost of electricity production for different types of generation in region i	USD
TE_{ij}	Electricity generation from energy type j in region i	kWh
UCT_{ij}	Cost of kWh of electricity generated from energy type j in region i	USD/kWh
TC_i	Total cost of electricity trading in region i	USD
$E_i^{production}$	Electricity generation in region i	kWh
E_i^{trade}	Volume of electricity traded in region i	kWh
EPP_i	Purchase price of electricity in region i	USD/kWh
g_i	Electricity consumption in region i during a given period	kWh
δ_{Li}	Lower limit of electricity consumption in region i	dimensionless
δ_{Ui}	Upper limit of electricity consumption in region i	dimensionless
TC_i	Economic compensation for region i	USD
C_i^N	Total cost of electricity consumption without cooperation in region i	USD
C_i^A	Total cost of electricity consumption in region i for mutual cooperation	USD
BA_i	Shapley allocation of cooperation benefits in region i	USD

Note: The fund conversions were based on data from the China Foreign Exchange Trading Centre, utilizing the average exchange rates for different five-year plan periods. During the 11th Five-Year Plan period, RMB was converted to USD at the rate of USD 1 = RMB 7.22; for the 12th Five-Year Plan period, the conversion rate was USD 1 = RMB 6.27; and during the 13th Five-Year Plan period, RMB was converted to USD at the rate of USD 1 = RMB 6.76.

$$C_i = EC_i + CC_i \tag{4}$$

Within this study, the economic cost of regional electricity consumption is broken down into two key components: the regional cost of electricity production for various generation types (PC_i) and the regional cost of electricity trading (TC_i). In addition, CEF_i represents the carbon emission factor of the power grid as follows:

$$EC_i = PC_i + TC_i \tag{5}$$

$$CC_i = E_i \cdot CEF_i \tag{6}$$

This study considers the actual circumstances of power production in China, accounting for the cost variability associated with power generation from diverse energy sources. Equation (7) is employed to accurately calculate the comprehensive cost of regional power production:

$$PC_i = \sum_{i=1}^{n} \sum_{j=1}^{m} TE_{ij} \cdot UCT_{ij} \tag{7}$$

where i represents different regions in China, j represents the type of power generation based on different energy sources (this study includes thermal, wind, hydro, photovoltaic, and nuclear power generation), UCT_{ij} represents the cost of kWh of power generation from j energy types in region i, and TE_{ij} represents the amount of power generation from j energy types in region i.

The innovation of this article lies in the introduction of the interregional power trading mechanism. The model for interregional trading costs of power is primarily designed based on the supply and demand dynamics within the power market. In instances where regional power consumption exceeds local production, additional power must be procured from other regions to offset the regional power deficit, thereby establishing the power purchase area. Conversely, when regional electricity production exceeds electricity consumption, it constitutes a power sales area. However, it is evident that the overall electricity production is equal to electricity consumption. On an individual regional level, regional electricity consumption equals regional electricity production plus inter-regional electricity trading. Building upon the above analyses, this paper formulates the ensuing electricity transaction cost model:

$$\begin{cases} TC_i = E_i^{trade} \cdot EPP_i \\ E_i = E_i^{production} + E_i^{trade} \\ E_i^{production} = \sum_{j=1}^{m} TE_j \end{cases} \tag{8}$$

Where E_i, $E_i^{production}$ and E_i^{trade} denote the electricity consumption, electricity production and electricity trading volume of region i. EPP_i denotes the electricity purchase price of region i, which is expressed in this paper by using the average residential electricity price of the Chinese region in the past years.

Based on equations (3) and (4), this study sets the multi-objective optimization model for cost reduction and efficiency as follows:

$$\begin{cases} max\, A = \sum_{i=1}^{n} A_i = \sum_{i=1}^{n} e^{\beta_0} \cdot Y_i^{\beta_1} \cdot K_i^{\beta_2} \cdot L_i^{\beta_3} \cdot E_i^{\beta_4} \\ min\, C_i = EC_i + CC_i = \sum_{i=1}^{n} \sum_{j=1}^{m} TE_{ij} \cdot UCT_{ij} + \left(E_i - \sum_{j=1}^{m} TE_j \right) \cdot EPP_i + E_i \cdot CEF_i \end{cases}$$
$$s.t. \begin{cases} \sum_{i=1}^{n} E_i = E \\ \delta_{Li} g_i \le E_i \le \delta_{Ui} g_i \end{cases} \tag{9}$$

Ensuring overall power consumption stability is a key constraint, allowing for independent adjustment and optimization of regional power consumption while maintaining normal economic activities. Here, g_i represents the power consumption of region i during a specific period (e.g., distinct five-year plan periods in China, as specified later in this section). Additionally, δ_{Li} and δ_{Ui} signify the lower and upper limits, respectively, of the power consumption for region i.

Building upon this foundation, by converting the two optimization objectives into a ratio, the multi-objective optimization model can be reshaped into a single-objective programming problem:

$$max\, f = max \frac{A}{C_i} = max \frac{\sum_{i=1}^{n} e^{\beta_0} \cdot Y_i^{\beta_1} \cdot K_i^{\beta_2} \cdot L_i^{\beta_3} \cdot E_i^{\beta_4}}{n\left[\sum_{i=1}^{n} \sum_{j=1}^{m} TE_{ij} \cdot UCT_{ij} + \left(E_i - \sum_{j=1}^{m} TE_j \right) \cdot EPP_i + E_i \cdot CEF_i \right]}$$
$$s.t. \begin{cases} \sum_{i=1}^{n} E_i \ge E \\ \delta_{Li} g_i \le E_i \le \delta_{Ui} g_i \end{cases} \tag{10}$$

In this study, the electricity consumption of each region, factoring in the electricity cost under the cost reduction and efficiency targets, was computed using Lingo 18.0 software (https://www.lingo.com/).

3.4. Cooperative game model: the shapley value for allocation of the cooperation benefits

Cooperation can facilitate the efficient allocation of factor resources, thereby optimizing overall costs. However, cooperative behavior doesn't occur spontaneously; it depends on whether the benefits of cooperation are fairly distributed. Ensuring an equitable distribution of benefits among regions is essential for the long-term stability of cooperation. In the cooperation game model, the Shapley value method provides a scientific approach to the fair distribution of cooperation benefits. It involves calculating the contribution value of different subjects in the cooperation model to objectively assess the contribution degree of each cooperation subject (An et al., 2019). Currently, the Shapley value method is widely utilized in research related to the distribution of cooperative benefits. Its effectiveness in achieving fair distribution has been demonstrated in various studies (Cubukcu, 2020; Voswinkel et al., 2022; Zhang et al., 2014).

Set $C = \{1, 2, \ldots, n\}$ is a set containing n regions. Any subset cooperation alliance s (denoting any combination in the set C containing n regions, in this study, $n = 3$.), corresponds to a real-valued function $v(s)$ satisfying $v(\Phi) = 0$, $v(s_i \cup s_j) \ge v(s_i) + v(s_j)$, where $[C, v]$ is said to be the cooperation strategy of n regions, v is called the characteristic function of the cooperation strategy, and $v(s)$ (billion USD) is benefit of the cooperation of the inter-regional cooperative alliance s. The Shapley value is determined by the characteristic function v, denoted as $I = \{I_1, I_2, \ldots, I_n\}$, represents the allocation strategy for a cooperative game beneft amongst regions, where $I_i(v)$ (billion USD) denotes the cooperative gain obtained when participating in inter-regional cooperation for any region i, $I_i(v)$ can be calculated by the following formula (He et al., 2018):

$$I_i(v) = \sum_{s_i \in i} w(|s|)[v(s) - v(s/i)] \tag{11}$$

Where $w(|s|)$ is a weighting factor denoting the probability that region i participates and forms inter-regional cooperative alliance s in a random form, $|s|$ representing the number of regions in the inter-regional cooperative alliance s, $v(s/i)$ denotes the benefits of cooperation when region i does not participate in the cooperation, and $v(s) - v(s/i)$ represents, for inter-regional cooperative alliance s, the impact on the alliance when region i does not participate in it, reflecting the contribution of region i to the cooperation benefits of inter-regional cooperative alliance s. The weighting factor $w(|s|)$ can be calculated as (He et al., 2018):

$$w(|s|) = \frac{(n - |s|)!(|s| - 1)!}{n!} \tag{12}$$

Based on the total electricity costs before and after the cooperation and the cooperation benefits calculated by the Shapley value method, the transfer compensation (TC_i) of each region can be obtained (Liang et al., 2023; Yang et al., 2021). The calculation formula is Eq. (14):

$$TC_i = C_i^N - C_i^A - BA_i \tag{13}$$

Where TC_i is the amount of economic compensation for region i, C_i^A is the total cost of electricity consumption for region i without cooperation, C_i^N is the total cost of electricity consumption for region i with mutual cooperation, and BA_i is the Shapley allocation of the benefits of cooperation for region i. If $TC_i \ge 0$, it means that region i needs to pay financial compensation to other regions; if $TC_i < 0$, it means that region i can get financial compensation from other regions.

4. Area selection and data sources

The National Bureau of Statistics of China divides China into three major regions, namely, eastern, central, and western, based on factors such as the level of regional economic development, geographic location, natural conditions, and resources. In addition, energy resources and power loads in China are distributed in the opposite direction. The eastern region is densely populated, has frequent economic activities, and has a high consumption of power resources. The western region is rich in energy resources and has an imbalance between interregional power supply and demand. The eastern region is densely populated and has a high electricity demand. The western region is less densely populated but rich in power resources. Therefore, this article selects the eastern, central, and western regions of China as the main study body and, through regional cooperation, realizes the synergy of the dual objectives of cost reduction and efficiency.

The study spans from 2006 to 2022 and is structured into distinct periods: the 11th five-year plan (2006–2010), aligned with the distinctive construction program objectives of China; the 12th five-year plan (2011–2015); the 13th five-year plan (2016–2020); and the forecast period for the study, the 14th five-year plan (2021–2025). The power generation and electricity consumption data for each type of energy in this study were obtained from the China Electric Power Statistical Yearbook and China Energy Statistical Yearbook, and socioeconomic data were obtained from the China Statistical Yearbook and CEIC database. Table B.2 presents the descriptive statistics analyses.

5. Results and discussion

5.1. Construction of a multi-objective optimization model

5.1.1. Determination of the efficiency function

This study uses data on energy consumption (E_i), labor input (L_i), capital stock (K_i), and GDP (Y_i) for each province in three regions of China from 2006 to 2022. The efficiency functions of each region were fitted using linear regression analysis based on Eq. (3) with Stata software, and the values of the fitted parameters were obtained (Table A.1):

$$A = 6.682 \cdot E_1^{-0.196} + 5.944 \cdot E_2^{-0.208} + 0.208 \cdot E_3^{0.159} \tag{14}$$

5.1.2. Determination of the overall regional electricity cost function

Based on the energy consumption data (E_i), electricity production cost data (PC_i), and electricity transaction data (TC_i) for the three regions from 2006 to 2022, a linear regression analysis is used to fit the economic cost function of electricity consumption in each region, which contains the electricity production transaction cost function and the electricity pollution cost function, and the fitted values of the corresponding parameters are obtained (Table A.2).

Based on the energy consumption data (E_i), electricity generation from different types of energy sources (TE_{ij}), and the cost of electricity generation (UCT_{ij}), in each region, the economic cost function of electricity consumption in each region is derived according to Eqs. (6), (8) and (9) (Table 2). The results for the cost of electricity generation for different types of energy sources are shown in Table A.3.

The economic cost of overall electricity consumption $EC = \sum_{i=1}^{3} EC_i$ is calculated as follows:

$$EC = 0.001 \cdot E_1 - 0.172 \cdot E_2 - 0.305 \cdot E_3 + 9551.247 \tag{15}$$

According to Eq. (7), based on the carbon emission factor data of power grids in each region (Table B.1), the environmental cost function of electricity consumption in each region can be derived (Table 3).

Table 2
Economic cost functions for electricity consumption in three regions.

Region	Economic cost of electricity consumption function
Eastern	$EC_1 = 0.001 \cdot E_1 + 4255.507$
Central	$EC_2 = -0.172 \cdot E_2 + 2082.124$
Western	$EC_3 = -0.305 \cdot E_3 + 3213.617$

Table 3
Economic cost functions for electricity consumption in three regions.

Region	Environmental cost of electricity consumption function
Eastern	$CC_1 = 0.139 \cdot E_1$
Central	$CC_2 = 0.138 \cdot E_2$
Western	$CC_3 = 0.120 \cdot E_3$

The environmental cost of overall electricity consumption $CC = \sum_{i=1}^{3} CC_i$, the specific results are calculated as follows:

$$CC = 0.139 \cdot E_1 + 0.138 \cdot E_2 + 0.120 \cdot E_3 \tag{16}$$

Based on Eqs. (4), (15) and (16), the equation for the overall regional electricity cost, C, can be derived as follows:

$$C = 0.140 \cdot E_1 - 0.0345 \cdot E_2 - 0.1849 \cdot E_3 + 9551.247 \tag{17}$$

5.1.3. Determination of multi-objective optimization model

Equations (14) and (17) are brought into Eq. (10) to convert the multi-objective optimization model into a single-objective model, and the specific optimization model results are shown in Eq. (18). The lower limit of regional electricity consumption, δ_{Li}, and the upper limit of regional electricity consumption, δ_{Li}, are set to 0.85 and 1.20, respectively, following Zeng et al. (2018). Multiplying the maximum electricity consumption indicators for each region by 0.85 and 1.20, respectively, allows us to obtain the upper and lower limits of electricity consumption for each region:

$$max\, f = max \frac{A}{EC_i} = \frac{6.682 \cdot E_1^{-0.196} + 5.944 \cdot E_2^{-0.208} + 0.208 \cdot E_3^{0.159}}{0.140 \cdot E_1 - 0.0345 \cdot E_2 - 0.1849 \cdot E_3 + 9551.247} \tag{18}$$

$$s.t. \begin{cases} \sum_{i=1}^{3} E_i = 173793.840 \\ 80618.463 \leq E_1 \leq 113814.300 \\ 33398.872 \leq E_2 \leq 47151.348 \\ 33707.430 \leq E_3 \leq 47586.960 \end{cases} \tag{19}$$

5.2. The impact of optimized cooperation on the total electricity cost savings

5.2.1. Comparison of the traditional regional electricity model with optimized cooperation

Utilizing Eq. (11), we compute the electricity cost across various regions in China using the cooperative optimization model for the 11th, 12th, and 13th five-year plan periods. We subsequently compare these results with the costs derived from the conventional regional electricity scenario, as presented in Table 4.

The findings presented in Table 4 indicate a substantial reduction in

Table 4
Comparison of total costs under different models (billion USD).

Time period	Region	Total cost before optimization	Total cost after optimization	Total cost savings
Eleventh Five-Year Plan period	Eastern	2427.07	2151.37	275.70
	Central	100.57	70.50	30.07
	Western	−570.12	−773.12	202.99
	Total	1957.51	1448.75	508.76
Twelfth Five-Year Plan period	Eastern	3727.19	3269.96	457.23
	Central	16.80	−20.17	36.96
	Western	−1516.06	−1921.82	405.77
	Total	2227.92	1327.97	899.95
Thirteenth Five-Year Plan period	Eastern	4223.95	3684.77	539.19
	Central	−58.02	−94.39	36.37
	Western	−2110.77	−2627.98	517.21
	Total	2055.16	962.40	1092.76

the electricity cost in China when employing the interregional cooperative optimization model compared with the traditional regional electricity usage scenario. Specifically, during the 11th five-year plan period, the total electricity cost in China exhibited a noteworthy decrease of USD 50,876 million through multi-objective cooperative optimization, constituting 25.99% of the total electricity cost compared with the preoptimization period. This translates to an average annual savings of USD 10,175 million.

As China progresses through its five-year plans, the advantages of the multi-objective optimization strategy based on interregional cooperation become even more pronounced. In the 12th five-year plan period, the total electricity cost in China can be reduced by USD 89.995 billion, and during the 13th five-year plan period, there is a further reduction of USD 109.276 billion, indicating a gradual increasing trend. Evidently, with the continuous expansion of economic volume, electricity demand is expected to rise. Therefore, reinforcing cooperation, optimizing interregional capacity, and scientifically adjusting power resources through synergistic allocation across different regions hold significant importance in reducing the overall electricity cost.

Horizontally comparing the different regions, the interregional cooperation optimization model demonstrates a notably more substantial cost advantage for the eastern and western regions, with the primary contribution to total power cost savings originating from these regions. Across the 11th to the 13th five-year plan periods, the total cost savings of electricity in the central region amounted to USD 3007 million, USD 3696 million, and USD 3637 million, respectively. This represents 29.81% of the total electricity cost compared with the preoptimization period, with marginal changes in cost savings observed. Consequently, the adjustment of the cooperation and optimization model has a more pronounced impact on the eastern and western regions of China, exhibiting significant economic development disparities. Strengthening interregional cooperation and optimization of power and facilitating synergistic allocation of power resources between these two major regions has the potential to narrow regional gaps and foster balanced and coordinated development across the entire China.

5.2.2. *Analysis of the reasons for the total cost-saving effects*

The core of the power cooperation optimization model lies in the systematic adjustment of power resource allocation among various regions within the multi-objective optimization framework. The principal factor contributing to the reduction in the total cost of power is the variation in power consumption among different regions. Fig. 2 presents the consumption of electricity resources in China during different five-year plan periods under the traditional regional electricity model and the cooperative optimization model.

The optimization of the multi-objective cooperation model has not altered the fundamental structure of electricity consumption in each region, aligning with the distinct economic characteristics of China, where electricity consumption is notably higher in the eastern region than in the central and western regions.

A noteworthy observation is that the reduction in the overall total electricity cost in China during the 11th and 12th five-year plan periods can be achieved by decreasing electricity consumption in the eastern region while concurrently increasing consumption in the central and western regions. Conversely, during the 13th five-year plan period, the reduction in power consumption in the central and western regions, coupled with an increase in power consumption in the eastern region, contributed to the overall cost reduction. The economic significance of this finding lies in its ability to achieve an overall reduction in power costs through the strategic reconfiguration of power consumption. This type of adjustment in power consumption inherently follows a logical configuration, allowing for the early-stage redirection of power resources toward the central and western regions, supporting their development, and, subsequently, in the later stage, leveraging the strengths of traditional capabilities for further improvement.

Table 5 presents the variations in the total electricity cost throughout the electricity production and trading processes. Owing to the fact that the cost of electricity production primarily hinges on the volume of electricity generated and the cost per unit of electricity, independent of the multi-objective optimization model, the cost savings in electricity production and trading are contingent on electricity transactions across different regions. China has accumulated extensive experience in interregional electricity market-oriented trading, providing a practical basis for the construction of regional electricity markets. Trading in interregional power markets can realize the sharing and optimal allocation of power resources on a wider scale and improve the efficiency of power utilization. By breaking down interregional trade barriers, the effective allocation of power resources is realized (Xu et al., 2020). The existence of a regional power market helps to alleviate the regional contradiction between power supply and demand and balance power supply and demand in different regions through interregional trading.

Table 5
Comparison of electricity production transaction costs/benefits under different models (billion USD).

Time period	Region	Electricity production transaction costs/ benefits before optimization	Electricity production transaction costs/ benefits after optimization	Total cost savings
Eleventh Five-Year Plan period	Eastern	602.18	600.22	1.97
	Central	−647.29	−797.18	149.89
	Western	−1227.74	−1562.25	334.51
	Total	−1272.85	−1759.22	486.37
Twelfth Five-Year Plan period	Eastern	700.79	697.53	3.27
	Central	−1240.37	−1424.64	184.28
	Western	−2830.57	−3499.24	668.67
	Total	−3370.15	−4226.36	856.21
Thirteenth Five-Year Plan period	Eastern	655.05	651.20	3.85
	Central	−1516.54	−1697.84	181.30
	Western	−3786.32	−4638.64	852.32
	Total	−4647.81	−5685.29	1037.47

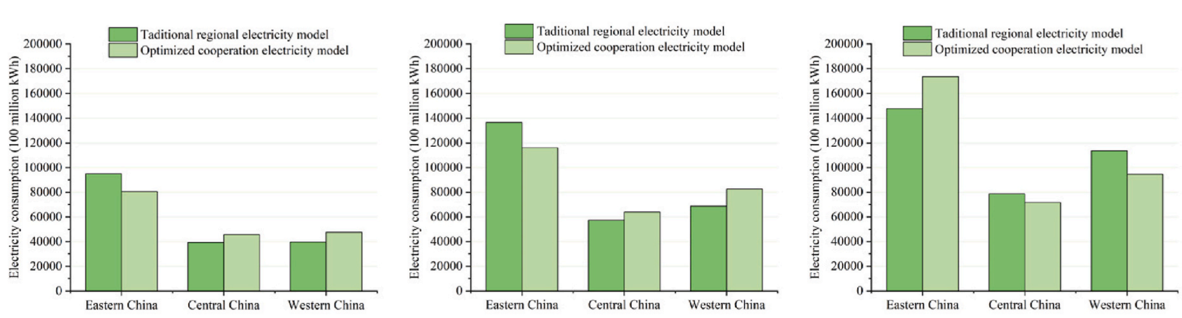

Fig. 2. Electricity resource consumption in China in different five-year plan periods under traditional regional electricity models and electricity cooperative optimization models.

Eastern China is densely populated, and the region is small, making the construction of power plants more costly. In contrast, it is more economical to build transmission lines for regional power trading. Western China has rich power resources (e.g., photovoltaic, wind, fossil energy), and the construction of large-scale extra-high voltage transmission lines promotes power market transactions in different regions, making power transactions between different regions more convenient and significantly reducing the cost of regional power consumption. Therefore, the interregional cooperation optimization model achieves a reduction in power generation transaction costs in the eastern region. In addition, it increases power trading revenue in the central and western regions. This dual impact is the main driver of the overall decrease in total electricity costs.

Table 6 presents the shifts in the cost of electricity pollution within the total electricity cost. The interregional cooperation and optimization model yielded a notable reduction in the overall electricity pollution cost, with reductions of USD 2239 million, USD 4374 million, and USD 5529 million observed during the 11th, 12th, and 13th five-year plan periods, respectively. At the regional level, the primary beneficiary is the eastern region, whereas there is a discernible upward trend in electricity pollution costs in the central and western regions.

Consequently, under the interregional cooperation and optimization model, vigilance is warranted in the central and western regions regarding the potential for excessive energy consumption and interregional pollution transfer. Simultaneously, while ensuring overall efficiency and cost optimization, it is crucial to equitably distribute the benefits of electricity cost savings and construct a compensation mechanism among different stakeholders in a scientifically sound manner.

5.3. Fair allocation scheme and compensation mechanism of cooperation benefits

5.3.1. Fair allocation scheme of cooperation benefits

In accordance with cooperative game theory, cross-cooperation among different entities results in varying benefits. It is noteworthy that the benefits of cooperation do not necessarily increase with the number of participating subjects. Interestingly, the maximum benefit appears to exist when all cooperating subjects participate together, although this does not imply a linear correlation between the number of subjects involved and the extent of cooperation benefits. Fig. 3 presents the benefits of a cooperative alliance under different numbers of cooperating subjects.

Regardless of the period, the optimization of electricity production transactions, environmental benefits, and overall electricity benefits reaches its maximum when the eastern, central, and western regions collaborate. Consequently, the analysis in this article is centered on the scenario in which all three cooperative subjects participate collectively. Utilizing the Shapley value allocation method, the total benefits are distributed equitably among the cooperative alliance based on the contribution degree of the three participating subjects. Table 7 presents the allocation results in detail.

Owing to the fact that the primary source of cost savings in the interregional cooperative optimization model stems from electricity production transactions, the benefits derived from these transactions outweigh the cost-saving benefits associated with electricity pollution in the Shapley value-based allocation. Regarding regional disparities in benefit distribution, the eastern and western regions can allocate a larger share of benefits, whereas the central region receives the least. This distribution is primarily determined by the contributions of different stakeholders participating in the cooperative alliance.

Notably, the eastern and western regions emerge as the primary contributors to the cost savings in the interregional cooperative optimization model. The eastern region serves as the main consumer of electricity in the power system, whereas the western region is the primary producer of clean energy electricity in China. Consequently, under the interregional cooperative optimization model, benefit distribution should consider the significant contributions from the power production and consumption sides. This approach aims to fortify the scale and resilience of the integrated interregional power system.

5.3.2. Compensation mechanism of cooperation benefits

Utilizing Equation (14), this article computes the values of regional economic compensation allocated to the eastern, central, and western regions within the cooperative optimization model, as presented in Table 8.

The eastern and western regions emerge as the primary beneficiaries in the cooperative optimization model, and it is incumbent upon them to provide additional cost compensation to other regions, ensuring the sustained operation of the cooperative alliance in the long term. Consequently, the regions responsible for compensation are the eastern and western regions. This compensation arrangement is attributed to the advanced economic development in the eastern region, which enjoys a certain scale advantage, and the western region, with its abundant renewable resources, particularly in power transmission, thus possessing a resource advantage.

For instance, during the 13th five-year plan period, the central region is expected to receive additional compensation of USD 12.654 billion. In this scenario, the eastern region contributes USD 4.152 billion toward compensation, whereas the western region contributes USD 8.498 billion. These economic incentives foster active participation of the eastern region in the cooperative alliance, promoting a collaborative approach to achieve optimal overall goals and creating a win–win situation for each region and the entire nation.

5.3.3. Distributional projections for the 14th five-year plan period

Herein, the value added of the cost of electricity production transactions and the cost savings from electricity pollution during the 11th and 12th five-year plan periods and the value added of the cost of electricity production transactions and electricity pollution cost savings during the 12th and 13th five-year plan periods have been calculated. The average of these two periods is considered the value added for the cost of electricity production transactions and electricity pollution cost savings during the 12th and 13th five-year plan periods. Subsequently, the distribution of various cost savings in electricity during the 14th five-year plan period was projected based on the Shapley values, as outlined in Table 9.

Throughout the 14th five-year plan period, the total electricity cost savings in each region exhibited a gradual and incremental trend with minimal variations. An intriguing observation is the reduction in the assigned value of electricity production transaction cost savings in the central and western regions, coupled with a general decrease in the value of electricity pollution cost savings. This suggests that the overall cost of electricity pollution in China experienced a decline during the 14th five-year plan period.

Table 6
Comparison of electricity pollution costs under different models (billion USD).

Time period	Region	Electricity pollution costs before optimization	Electricity pollution costs after optimization	Total cost savings
Eleventh Five-Year Plan period	Eastern	1824.89	1551.15	273.73
	Central	747.86	867.69	−119.82
	Western	657.61	789.13	−131.52
	Total	3230.36	3207.97	22.39
Twelfth Five-Year Plan period	Eastern	3026.39	2572.43	453.96
	Central	1257.16	1404.48	−147.31
	Western	1314.51	1577.42	−262.90
	Total	5598.07	5554.33	43.74
Thirteenth Five-Year Plan period	Eastern	3568.91	3033.57	535.34
	Central	1458.52	1603.46	−144.94
	Western	1675.55	2010.66	−335.11
	Total	6702.98	6647.69	55.29

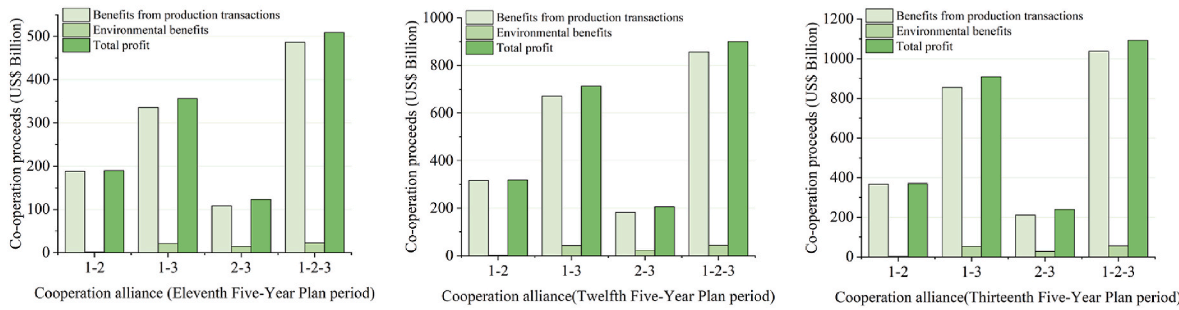

Fig. 3. Benefits of cooperative alliances under different numbers of cooperative agents in different five-year plan periods in China.

Table 7
Equitable distribution of benefits based on Shapley values (billion USD).

Time period	Region	Equitable distribution of electricity production transactions cost savings	Equitable distribution of electricity pollution cost savings	Equitable distribution of total cost of electricity
Eleventh Five-Year Plan period	Eastern	213.38	6.46	219.84
	Central	99.66	3.14	102.80
	Western	173.37	12.83	186.20
Twelfth Five-Year Plan period	Eastern	389.25	13.96	403.21
	Central	144.88	5.03	149.91
	Western	322.08	24.73	346.81
Thirteenth Five-Year Plan period	Eastern	479.13	18.56	497.69
	Central	157.16	5.77	162.93
	Western	401.19	30.98	432.17

Table 8
Regional economic compensation schemes (billion USD).

Time period	Region	Total cost savings	Equitable distribution of total cost savings	Regional economic compensation
Eleventh Five-Year Plan period	Eastern	275.7	219.77	55.93
	Central	30.07	102.73	−72.67
	Western	202.99	186.2	16.79
Twelfth Five-Year Plan period	Eastern	457.23	403.21	54.01
	Central	36.96	149.91	−112.95
	Western	405.77	346.81	58.96
Thirteenth Five-Year Plan period	Eastern	539.19	497.67	41.52
	Central	36.37	162.91	−126.54
	Western	517.21	432.23	84.98

This outcome is notably influenced by the dual-carbon strategy and the broader initiative of China toward greening the economy. The evident reduction in the assigned values indicates that the efforts toward greening and fostering low-carbon development in the electricity industry have yielded significant results during this period.

5.4. Sensitivity analysis

In this section, a sensitivity analysis is conducted to investigate the impact of changes in the upper and lower bounds of regional electricity consumption on the cost savings of the cooperative model. δ_L and δ_U are the lower and upper bounds, respectively, of changes in regional electricity consumption, and in this study, δ_L and δ_U are changed by $\pm$ 0.05 in Eq. (9) to conduct the sensitivity analysis. Table 10 presents the results of the sensitivity analysis.

The results in Table 10 show that as the regional electricity consumption floor as well as the ceiling increase, the savings in electricity production transaction costs, electricity pollution costs, and total cost savings will increase. This is mainly owing to the fact that an increase in the lower and upper limits of electricity consumption implies an increase in regional electricity consumption, and the increase in electricity demand leads to more frequent electricity trade. The biggest advantage of cooperation is the coordination of the interests of each participant, and the increase in electricity demand makes the cost-saving effect under the cooperation mode more obvious, so the change of the upper and lower limits of electricity consumption will significantly affect the change in electricity cost.

Table 9
Forecast for the fourteenth Five-Year period (billion USD).

Region	Forecast of total cost savings in electricity	Forecast of equitable distribution of electricity production transactions cost savings	Forecast of equitable distribution of Electricity Pollution cost Savings
Eastern	632.36	607.93	24.51
Central	190.43	183.39	6.96
Western	551.71	511.81	39.89
Total	1374.50	1303.13	71.36

Table 10
Sensitivity analysis of adjusting the lower limit of electricity consumption (billion USD).

Time period	Cost comparison	Change δ_L: [0.80,1.20]	Baseline [δ_L, δ_U]: [0.85,1.20]	Change δ_U: [0.85,1.25]
Eleventh Five-Year Plan period	Electricity production transaction cost savings	392.85	486.37	522.79
	Electricity pollution costs savings	17.03	22.39	27.24
	Total cost savings	409.88	508.76	550.04
Twelfth Five-Year Plan period	Electricity production transaction cost savings	740.41	856.21	929.01
	Electricity pollution costs savings	33.66	43.74	53.45
	Total cost savings	774.07	899.95	982.47
Thirteenth Five-Year Plan period	Electricity production transaction cost savings	916.60	1037.47	1130.27
	Electricity pollution costs savings	42.67	55.29	67.67
	Total cost savings	959.27	1092.76	1197.94

6. Conclusion and policy implications

In contrast to that of several countries, the power system of China possesses a unique nonprofit and universal character, making it challenging to allocate electricity costs to consumers through market mechanisms. Therefore, the government faces the complex task of reducing the total cost of electricity operations while ensuring alignment with decision-making objectives. This study introduces a regional cooperation optimization model that considers productivity and overall electricity costs. It leverages the distinctive five-year plan framework of China as a case study period, focusing on the eastern, central, and western regions.

This research represents a significant advancement over previous studies by innovatively incorporating the costs and benefits of electricity trading between regions into the model. Beyond economic costs, the study considers pollution costs associated with electricity consumption. Given that the electricity sector in China contributes to over 40% of the national total carbon emissions, this broader perspective is crucial for a comprehensive analysis. Finally, the study proposes a distribution method and compensation mechanism for interregional benefits based on the contribution degree of participating subjects and the principle of fair distribution. This holistic approach aims to enhance the understanding of regional cooperation in optimizing electricity systems and provides valuable insights for policymakers in shaping sustainable and efficient energy strategies.

The key findings of this study are as follows: (1) Significant reduction in total cost: The interregional cooperation optimization model demonstrates a substantial decrease in the total cost of electricity operations in China. Furthermore, the multi-objective optimization strategy based on interregional cooperation exhibits an increasingly advantageous cost profile as China progresses through its five-year plans. (2) Strengthening cross-regional electricity trading: The primary driver for the reduction in the total electricity cost is the positive impact of the interregional cooperation optimization model on electricity production and trading. This model notably enhances income from electricity trading in the central and western regions, balancing the relationship between electricity production and consumption through interregional trading of electricity and realizing the value gained by cooperating entities in the trade. (3) Contribution of eastern and western regions: The eastern and western regions emerge as the primary contributors to the cost savings achieved by the interregional cooperative optimization model. Consequently, these regions are positioned to allocate more benefits. In addition, to ensure the long-term operation of the cooperative alliance, the eastern and western regions should provide supplementary cost compensation to other regions. These findings not only offer a theoretical foundation for comprehensive cost control studies but also provide decision-makers with an objective reference point to develop effective energy policies.

Our results have a number of policy implications. First, the government should promote the nationwide application of inter-regional cooperation mechanisms. Research indicates that this model can significantly reduce electricity operational costs in China, particularly during the implementation of the Five-Year Plan. Policymakers should simultaneously strengthen inter-regional power dispatch infrastructure and encourage power cooperation and trading. This would enhance regional synergy in power production and trading while promoting deeper market-oriented reforms. Second, given the critical role of the eastern and western regions in power cooperation, a fair benefit distribution and compensation mechanism is recommended. The transparency and fairness of the trading process must be ensured during the market-oriented reform of power trading. The eastern and western regions, benefiting from greater cost savings, should offer appropriate compensation to other regions to maintain stable and continuous cooperation. An improved compensation mechanism will ensure that all regions benefit from cooperation and support long-term sustainable development. Finally, the government should strengthen policy support to enhance power trading revenues across regions. Policy guidance and technical support should be provided to enhance the power production efficiency and trading capacity of the central and western regions, maximizing their potential in cross-regional power dispatch. Furthermore, continuous cost control studies and regular assessments of regional cooperation models are needed to ensure policy adaptability and effectiveness.

Although this study investigates the cost optimization and allocation mechanisms of the regional power cooperation model, several limitations remain. First, due to limited availability of regional transmission cost data, future inclusion of transmission costs in power trading models is crucial for developing more complex regional cooperation optimization models. Second, this study focuses on the economic cost effects of the regional power cooperation model and does not account for technical details in the electricity sector. Future research should consider the technical and tariff advantages of renewable energy, such as environmental benefits and cost efficiencies. Finally, given the complexity of power market reforms, future research should expand benefit distribution models tailored to the development contexts of different countries, which would be valuable for both national power market transformations and international cooperation. These perspectives aim to make future research more aligned with real-world developments, enabling deeper exploration of regional power cooperation and offering valuable insights for policymakers and industry stakeholders.

CRediT authorship contribution statement

Yubao Wang: Writing – review & editing, Formal analysis, Data curation, Conceptualization. **Junjie Zhen:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A.1
Fitting results for the efficiency function (equation (3)) for the three regions

Statistical indicators	Eastern	Central	Western
β_0	19.427	−8.616	−124.003
β_1	0.535	0.4315	−0.089
β_2	0.312	0.0249	−0.881
β_3	−4.363	0.9248	23.177
β_3	−0.196	−0.208	0.159

Table A.2
Fitting results for the cost function (equation (4)) for the three regions

Statistical indicators	Eastern	Central	Western
Economic Cost Function for Electricity Consumption			
Slope of the function	0.001	−0.172	−0.305
Constant term of the function	4255.507	2082.124	3213.617
Environmental cost function of electricity consumption			
carbon emission factor	0.139	0.138	0.120

Table A.3
The cost of generating electricity from different types of energy sources. (billion USD)

Year	Region	Wind power cost	Photovoltaic cost	Hydroelectric power cost	Thermal power cost	Nuclear power cost
Eleventh Five-Year Plan period	Eastern	20.309	0.000	155.136	4035.523	197.433
	Central	8.285	0.000	312.820	1968.849	0.000
	Western	17.341	0.000	540.525	1448.794	0.000
Twelfth Five-Year Plan period	Eastern	139.889	7.333	212.885	6318.765	412.289
	Central	60.691	1.786	459.683	3229.267	0.000
	Western	151.261	27.875	1300.038	2713.904	0.480
Thirteenth Five-Year Plan period	Eastern	294.338	160.604	225.060	6491.379	889.251
	Central	193.734	110.800	496.313	3441.859	0.000
	Western	399.883	161.289	1765.507	3210.582	46.488

Appendix B

Table B.1
Grid carbon emission factors in the Chinese provinces

Provinces	Grid carbon emission factors(kgCO2/kWh)	Provinces	Grid carbon emission factors(kgCO2/kWh)
Beijing	0.615	Henan	0.738
Tianjin	0.841	Hubei	0.316
Hebei	1.092	Hunan	0.487
Shanxi	0.841	Guangdong	0.445
Inner Mongolia	1.000	Guangxi	0.526
Liaoning	0.910	Hainan	0.459
Jilin	0.839	Chongqing	0.432
Heilongjiang	0.814	Sichuan	0.117
Shanghai	0.548	Guizhou	0.420
Jiangsu	0.695	Yunnan	0.146
Zhejiang	0.532	Shannxi	0.641
Anhui	0.763	Gansu	0.460
Fujian	0.489	Qinghai	0.095
Jiangxi	0.616	Ningxia	0.872
Shandong	0.742	Xinjiang	0.749

Table B.2
Descriptive statistical analysis

Region	Variable	Mean	SD	Max	Min	P50
Eastern	*E*	29000.000	8331.979	43000.000	16000.000	29000.000
	K	830000.000	410000.000	1500000.000	280000.000	790000.000
	L	574.722	20.796	596.820	536.016	580.290
	Y	82000.000	7394.524	94000.000	66000.000	82000.000
	A	0.961	0.025	0.995	0.917	0.970
	EC	4283.488	2353.597	9489.525	1515.510	3584.991
	CC	4073.939	1158.252	6004.046	2223.617	4053.953
	C	8357.426	2624.447	13000.000	3739.127	8203.515
Central	*E*	12000.000	3527.333	18000.000	6384.600	12000.000
	K	470000.000	290000.000	950000.000	110000.000	430000.000
	L	457.308	10.454	469.593	439.442	458.820
	Y	36000.000	3461.751	41000.000	28000.000	36000.000
	A	0.945	0.025	0.985	0.885	0.948
	EC	16.016	1356.700	3111.917	−852.025	−682.413
	CC	1684.411	485.000	2571.518	905.330	1678.443
	C	1700.426	1218.076	4435.643	631.918	1186.045
Western	*E*	15000.000	5862.614	25000.000	6252.120	15000.000
	K	400000.000	250000.000	810000.000	93000.000	360000.000
	L	330.887	8.570	341.404	316.903	331.810
	Y	27000.000	3237.271	32000.000	20000.000	27000.000
	A	0.905	0.053	0.990	0.811	0.923
	EC	−1300.000	2085.472	2708.596	−3600.000	−2200.000
	CC	1653.468	702.942	2823.254	643.830	1670.187
	C	353.743	1521.472	3747.197	−1100.000	−323.326
Total	*E*	19000.000	9604.613	43000.000	6252.120	16000.000
	K	570000.000	370000.000	1500000.000	93000.000	500000.000
	L	454.306	101.533	596.820	316.903	458.820
	Y	48000.000	25000.000	94000.000	20000.000	36000.000
	A	0.937	0.043	0.995	0.811	0.944
	EC	999.926	3089.719	9489.525	−3600.000	−38.242
	CC	2470.606	1404.954	6004.046	643.830	2133.467
	C	3470.532	3988.434	13000.000	−1100.000	1495.907

Appendix C

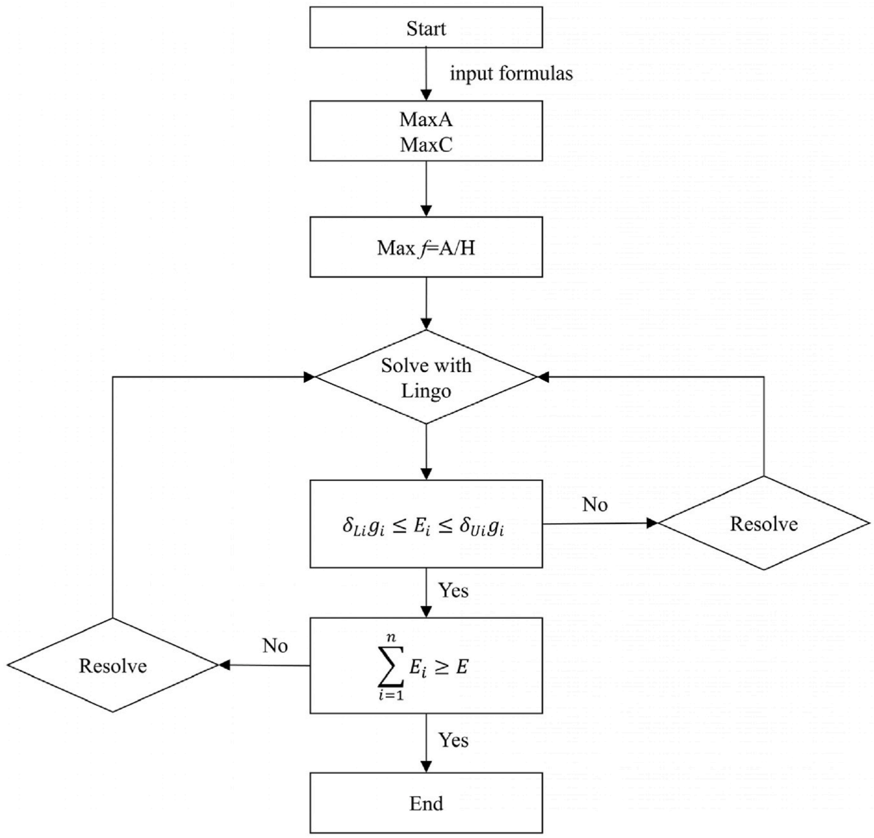

Fig. C.1. Algorithmic process scheme.

Data availability

Data will be made available on request.

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