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A Bi-Level Optimization Model for Inter-Provincial Energy Consumption Transfer Tax in China

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Abstract: The serious energy crisis and environmental problems resulting from fossil energy excessive consumption have caused severe challenges to the control of energy consumption and intensity (dual controls) and the sustainable development of China's economy and society. The current territorial management model (TMM) of energy consumption "dual control" needs urgent improvement. Therefore, this study proposes an inter-provincial energy consumption transfer tax model (ECTTM) based on the Stackelberg game and bi-level optimization theory. In this model, the central government is the leader at the upper-level, and provincial governments are the lower-level followers. An optimization algorithm based on NSGA-II was designed to solve this model to obtain the optimal transfer tax rate and provincial energy consumption. The ECTTM aims to maximize the socioeconomic benefits of energy consumption overall and in each province under the premise of achieving the dual control target. The model's effectiveness and superiority were illustrated through an empirical study of electricity consumption in Shanghai, Zhejiang, Shaanxi, and Guizhou. Compared with the TMM, the socioeconomic benefits under the ECTTM increased by 14.67%, and the electricity consumption per unit of gross domestic product decreased by 12.8%. Policy suggestions on the ECTTM's implementation are proposed to promote further improvements in dual controls.

Keywords: dual controls; transfer tax; bi-level model; socioeconomic benefits

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1. Introduction

Currently, the threats of the global warming and environmental pollution caused by the continuous rise in fossil energy consumption are becoming increasingly urgent concerns [1]. Global economic development is accompanied by excessive energy consumption and carbon emissions. As the world's demand for energy increases, the scarcity of fossil fuels continues to rise, and the unstable energy supply is having a negative impact on economic development. And the environmental pollution caused by the burning of fossil fuels has also caused great damage to human health and ecosystems [2,3]. As a global task, energy conservation and emission reductions are fundamental ways to solve global warming and alleviate environmental problems. To further promote energy conservation and emission reductions, China has established a dual control system of total energy consumption and consumption intensity (i.e., "dual controls") in the 13th Five-Year-Plan [4]. "Dual controls" refers to the control of the sum total of all kinds of energy consumed by all sectors of the national economy and households in a certain geographical area over a certain period of time, and the control of the energy consumed per unit of gross domestic product (GDP) produced [5]. As the core system of energy governance, the dual control plays a positive role in improving energy efficiency and slowing down the growth rate of energy consumption. Since the proposal of dual controls, the growth rate of energy consumption has continued to slow down, and the energy intensity has been declining in China. In addition, the dual control is the key support and an important measure to achieve the goal of carbon neutrality, which strongly supports the reduction in carbon emission intensity and plays a positive role in promoting economic transformation and development [6].

As the country with the largest energy consumption worldwide [7], China's coal consumption accounted for 56.0% of the total energy, while clean energy accounted for 25.5% in 2021. Owing to the special energy structure and resource endowment in China, the characteristics of coal as the main energy source will not change radically in the short term, which indicates that dual controls will still have an important role for a long time to come [8–10]. The effective implementation of dual controls relies on a scientific management model, which is crucial for China to solve environmental and energy problems and achieve its sustainable development goals [11].

China's current territorial management model (TMM) for dual controls adopts a dual control target responsibility system and an assessment and evaluation system [12,13]. The achievement of dual control targets is directly related to the assessment results of relevant government officials. Regionally responsible leaders who fail to achieve the task of dual controls will be held accountable or even dismissed. Indubitably, TMM has significantly contributed to China's dual controls. However, under this model, some simple and extensive management approaches—such as mandatory power rationing—have further increased economic losses and adversely affected residents' lives in order to achieve the dual controls' goal at the end of the assessment period and alleviate the energy shortage. In addition, due to differences in resource endowments, energy structure and economic development in different regions, there are obvious differences in energy consumption and energy intensity. As shown in Figures 1 and 2, taking electricity as an example, although the electricity consumption in the eastern region is large, the energy intensity is generally lower than that in the western region. This indicates that there is an obvious asymmetry between the east and west of China in terms of energy consumption and energy consumption intensity. It can be deduced that due to the differences in economic development, technological level and industry structure, each province also shows large differences in energy consumption, which shows that it is very important to promote inter-provincial coordinated development. The TMM ignores each region's economic development and energy efficiency advantages and affects the further implementation of dual controls. In the long run, with the continuous promotion of dual controls, the disadvantages of low efficiency and the high cost of the TMM will become increasingly prominent [14]. To improve the current management model and meet the requirement of reducing energy consumption and carbon emission per unit GDP by 13.5% and 18%, respectively, in the 14th Five-Year Plan [15,16], exploring an efficient energy consumption management model becomes pertinent for the sustainable development of China's economy and society. Based on this premise, in order to improve the energy consumption control and management mode, enhance the management efficiency, alleviate the negative impact of energy consumption control on the economic growth, and promote the coordinated development of various regions, this study proposes an inter-provincial energy consumption transfer tax model (ECTTM) by combining administrative and economical means. The purpose of this study is to stimulate the initiative of energy consumption control in each province and scientifically promote the implementation of dual controls and the realization of dual control goals in a flexible and efficient manner.

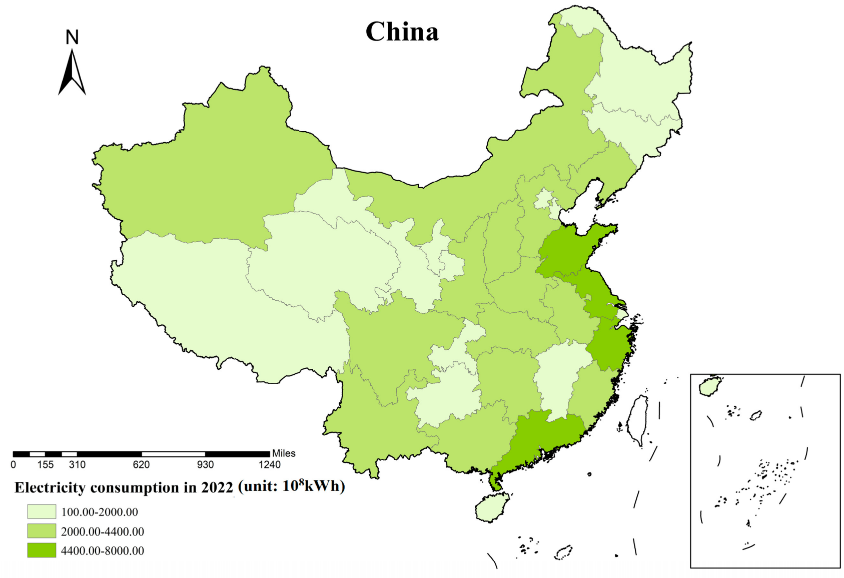

Figure 1. Electricity consumption of each province in 2022.

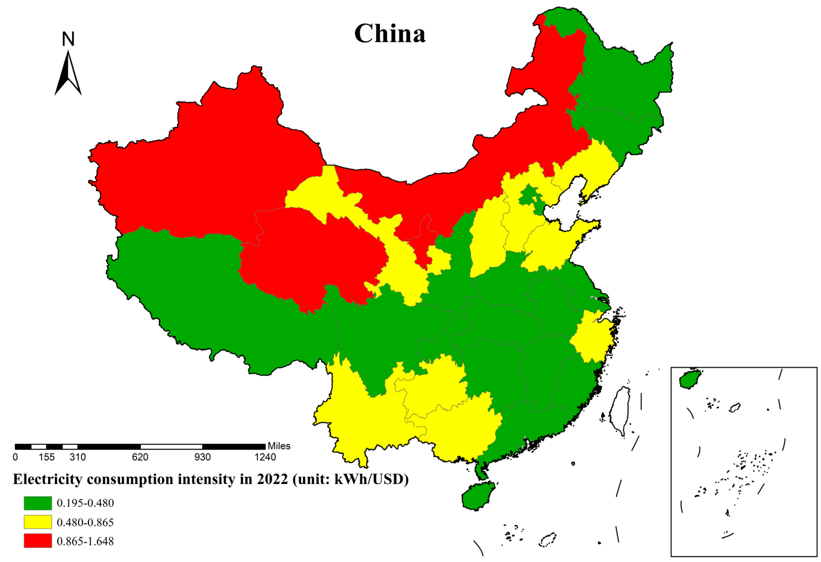

Figure 2. Electricity consumption intensity of each province in 2022 (electricity consumption divided by GDP).

2. Literature Review

To solve the energy crisis and environmental problems and achieve sustainable development goals, scholars have conducted extensive research on strengthening resource conservation and energy consumption management [17]. Administrative and economic means are generally regarded as the two main measures of total energy consumption control and management [18]. Administrative means primarily include administrative orders and government regulations [19]. For example, the control of total energy consumption is promoted by establishing binding targets for energy conservation and environmental pollution control and by implementing a series of mandatory dual control policies [20,21]. Studies have demonstrated that the control of total energy consumption positively affects energy efficiency, especially economic incentive policy tools [22].

Although the role of administrative means in the control of total energy consumption is effective, such top-down pressure transmission mechanisms are difficult to fully mobilize the enthusiasm of regional governments to implement energy conservation policies [23].

This has also led to some regions facing the dilemma that economic and energy efficiency are difficult to improve simultaneously. By comparison, the implementation of energy consumption control measures based on economic means [24], such as energy-consuming right trading [25], energy performance contracting [26] and energy consumption license transactions [27], can compensate for the deficiency of administrative means to achieve dual control targets efficiently [28–30]. This method of energy consumption control based on economic means aims to minimize the cost of energy conservation or maximize the socioeconomic benefits of energy consumption to achieve the energy consumption control target. Under the incentive of an economic approach, each subject of energy consumption will more actively choose the optimal method of energy consumption according to their own situation [31]. However, the trading mechanism in economic means in the fight climate change have been disappointing [32,33]. At present, since the market-oriented economic mechanism is in the initial stage, the smooth implementation of the market-oriented economic mechanism needs the support of the government, the formulation of the system and the enthusiasm of the participants [34,35]. Take the white certificate mechanism being implemented in the UK, Italy and France as an example. Due to the free pricing of the market, there are many uncertainties in the development of the mechanism [36,37].

Most scholars have studied energy consumption management models from the perspectives of costs and benefits. Zeng et al. [12] constructed China's inter-provincial cooperative energy consumption model based on the perspective of electric power and found that the energy-saving benefits under the cooperative model were greater than those of the existing territorial management model. Yu et al. [38] studied the impact of industrial restructuring on energy saving and emission reduction by establishing a multi-objective optimization model, including the minimization of energy consumption and major pollutant emissions and maximization of GDP. Xue et al. [39] established an inter-provincial energy conservation cooperation model based on futures trading that considers the maximization of socioeconomic benefits from energy consumption. Zheng et al. [40] proposed an analytical framework to measure the marginal energy-saving cost and construct an energy conservation supply curve to help formulate and implement energy consumption control policies. Zhang et al. [41] found that in the context of energy consumption "dual control", energy efficiency management can partially solve the conflict between economic growth and the increase in energy consumption and related emissions. Besides economic costs and benefits, other factors, such as employment rate, environmental damage and health, have also been considered in studies of energy consumption management [42–44]. Furthermore, reportedly, the implementation of economic means can improve the efficiency of resource allocation, which is conducive to improving energy efficiency [45]. As stated above, scholars have proposed ideas to remedy the defects of administrative means. However, there are still some gaps that need to be filled. On the one hand, there are relatively few studies on the management model of provincial energy consumption control, and provincial energy consumption management means and models need to be improved. On the other hand, relatively little attention has been paid to the imbalance between the total amount of energy consumption and the intensity of consumption in each province, and research on optimizing inter-provincial resource allocation and promoting the coordinated development of each province has yet to be improved.

As an effective mechanism to adjust the distribution of benefits, tax has the function of transferring payments and the characteristics of compulsory execution. Hence, numerous researchers have applied taxes to solve existing social development problems. Some scholars believe that tax—as an effective policy instrument—is an important choice for future energy consumption management under the double pressure of controlling total energy consumption and greenhouse gas emissions [46–49]. And the study found that mandatory tax and fine policies are more useful than energy conservation subsidy for sustainable energy development [32]. In terms of theoretical research, the transfer tax is also used to prevent and control water and air pollution across regional boundaries, and its theoretical effect is significant [50–53]. However, only a few studies have applied transfer taxes to energy consumption management. This study creatively employs the means of transfer tax to construct an inter-provincial energy consumption transfer tax model. Different from the energy tax implemented by EU countries, in which energy consumption is controlled mainly through fines and taxes [54], the transfer tax proposed in this study considers levying taxes on provinces that exceed their energy consumption quotas while subsidizing provinces with surplus energy consumption quotas. By the means of a transfer tax, the provinces can realize the coordination of dual controls and economic development. The essence of the transfer tax design lies in the secondary distribution of energy consumption quotas through economic means. It ensures that the economic benefits of each province are increased while the overall economic benefits are increased. The transfer tax is levied in a specialized way and is used in a targeted manner. In the model, the transfer tax promotes the coordination of inter-provincial energy consumption quotas by changing the cost or benefit of the use of excess energy consumption quotas, giving full play to the advantages of each province in controlling energy consumption and is conducive to the implementation of the energy consumption "dual-control" policy.

This model combines the flexibility of economic means with the authority of administrative means. On the one hand, it can fully mobilize the enthusiasm of provinces to reduce energy consumption and achieve energy consumption control goals flexibly and efficiently. On the other hand, the ECTTM can be better integrated with the current dual controls and give full play to the advantages of controlling the total energy consumption of the target management system. In the ECTTM, central and regional governments need to establish a cross-regional tax levy and administration systems, such as levy policies, standards, objects, and fund management methods. By means of a transfer tax, the model can urge all provinces to give play to their own strengths and jointly promote the completion of energy consumption control targets under the incentive of interest.

In the bi-level model, this study applied the theory of the Stackelberg game, taking the central government as the upper decision maker and the local government as the lower follower, and both of them obtain the equilibrium result through the dynamic game. Compared with previous studies, three novel aspects of this study are as follows: (1) This study creatively applies transfer tax to energy consumption management and establishes an inter-provincial energy consumption transfer tax model to achieve energy consumption control goals flexibly and effectively. (2) Bi-level optimization theory and Stackelberg game theory are applied to construct the ECTTM. An optimization algorithm based on NSGA-II is designed to solve the model and ensure scientific rationality. (3) The study presents the ECTTM's effectiveness and coordination process through empirical research of Shanghai, Zhejiang, Shaanxi and Guizhou and proves its advantages by comparing it with the TMM.

The remainder of the paper is organized as follows: In Section 3, an inter-provincial energy consumption transfer tax model is constructed. Section 4 presents the results of the empirical study, using Shanghai, Zhejiang, Shaanxi and Guizhou as examples. Section 5 discusses the results of the empirical study and analyzes the model's sensitivity. Section 6 provides the conclusions, policy suggestions, and future prospects.

3. Model Development

This study applies a transfer tax to improve China's energy consumption management model. On the premise of ensuring the completion of the overall target, provinces that overfulfil the energy consumption control target transfer their remaining energy consumption quotas to other provinces that fail to meet the target while levying a transfer tax. The tax cost depends on the transferred energy consumption quotas and common transfer tax rate determined by the central government. The central government first develops the energy consumption transfer tax policy as a means of stimulating the energy-saving potential of provinces; then, each provincial government adopts its own strategy to achieve energy consumption control goals at the highest economic benefits of energy consumption. This process can be built as a bi-level decision-making optimization model based on the Stackelberg dynamic game theory with a leader–follower strategy. In a leader–follower game, the leader has a leadership advantage and can take the lead or a favorable position in the game, and the follower must take the game after the leader. In the ECTTM, the central government, as the leader of the game, determines an optimal tax rate to optimize the total socioeconomic benefits of energy consumption under the overall energy consumption control target, and each provincial government, as the follower of the game, attempts to obtain the optimal net benefits of energy consumption according to the observed tax rate. Essentially, this model is a bi-level optimization problem with a generalized Nash equilibrium, and an optimization algorithm based on NSGA-II is applied to determine the optimal solution. Figure 3 presents the model development flow chart, elucidating the ECTTM development's main steps.

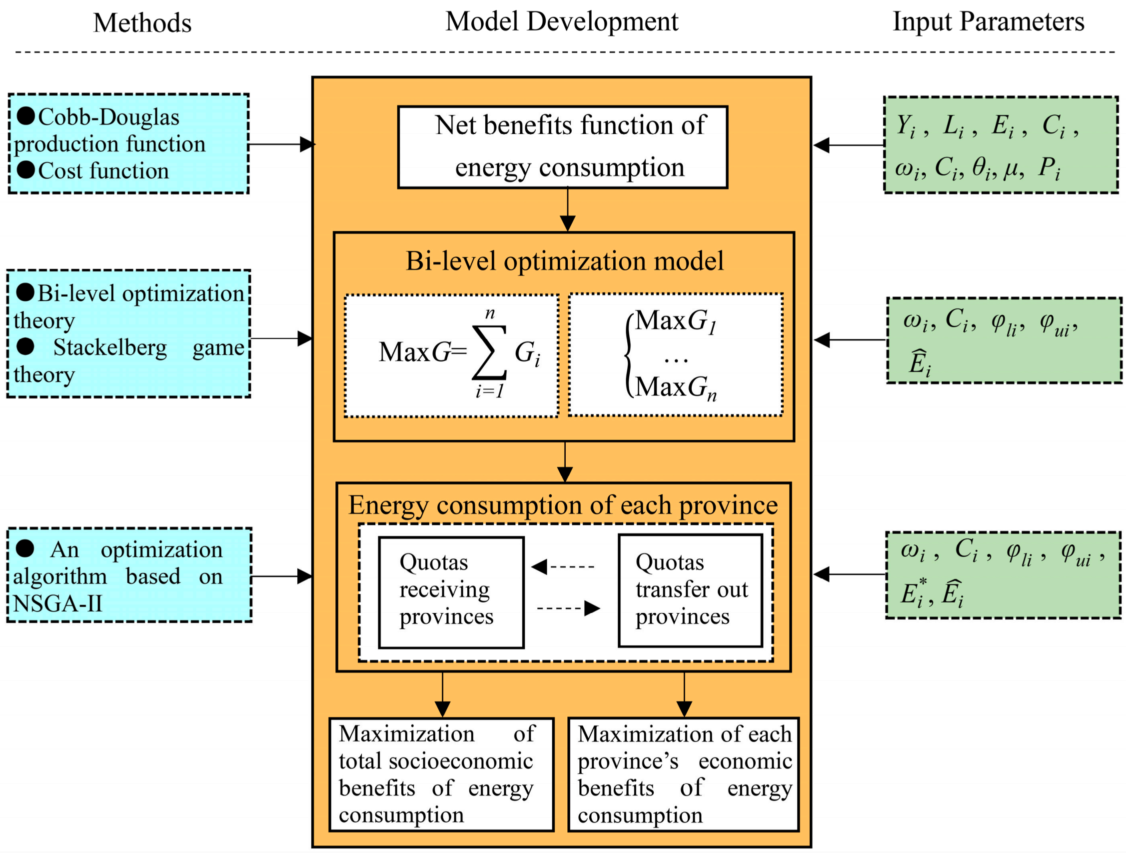

Figure 3. Model development flow chart.

3.1. Construction of Net Benefits Function for Energy Consumption

The net benefits of energy consumption comprise the following three components: gross benefits of energy consumption, energy production cost and transfer tax cost (income) [12,39]. Thus, the function of the energy consumption benefits is:

$$G_i(E_i) = \omega_i(E_i) - C_i(E_i) - t\left(E_i - \hat{E}_i\right),\ i = 1, 2, 3, \ldots, n \tag{1}$$

where E_i is the annual energy consumption of province i, G_i is the annual net benefit of energy consumption in province i, ω_i is the annual gross benefit from the energy consumption of province i, C_i is the annual energy production cost of province i, t is the tax rate of the model, and $\hat{E}_i$ is the total energy consumption quota for province i under the energy consumption control target. The parameters and variables used in this model are presented in Table 1.

Table 1. Variables and parameters.

Variables	Definition	Units	Data Sources
E_i	Annual energy consumption in province i	10^8 kWh	
G_i	Annual socioeconomic benefit of energy consumption in province i under ECTTM	United States dollar (USD) billion	
G_{iTMM}	Annual socioeconomic benefit of energy consumption in province i under TMM	USD billion	
ω_i	Annual gross benefits from energy consumption in province i	USD billion	
C_i	Annual production cost of energy in province i	USD billion	
$\hat{E}_i$	Annual energy consumption quotas in province i	10^8 kWh	
Y_i	GDP in province i	USD billion	China Statistical Yearbook, Provincial Statistical Yearbooks (2002–2020)
L_i	Quantity of employment in province i	10^4 people	China Statistical Yearbook, Provincial Statistical Yearbooks (2002–2020)
K_i	Fixed capital stock in province i	USD billion	China Statistical Yearbook, Provincial Statistical Yearbooks (2002–2020)
p_i	Energy price for end consumers in province i	USD/kWh	
t	Transfer tax rate	USD/kWh	
Parameters	Definition	Units	
θ_i	Annual contribution rate of energy consumption to GDP in province i	-	
μ_i	Cost-to-income ratio of energy producers in province i	-	China Electric Power Yearbook
φ_{li}	Lower limit coefficient of energy consumption in province i	-	
φ_{ui}	Upper limit coefficient of energy consumption in province i	-	

To obtain the annual total socioeconomic benefits of energy consumption for province i, θ_i is defined as the contribution rate of energy consumption to the GDP of province i, and Y_i is the GDP of province i. The function of the annual gross benefits from energy consumption is obtained as follows:

$$\omega_i = \theta_i \times Y_i \tag{2}$$

Referring to the Cobb–Douglas production function in Zeng et al. [9], this paper seeks the mathematical relationship between energy input and economic output and assume the energy consumption (E_i) of province i, technology level (A_i), capital stock (K_i) and labor force (L_i) as input factors of production and GDP (Y_i) as the output:

$$Y_i = A_i \times K_i^{\alpha_i} \times L_i^{\beta_i} \times E_i^{\gamma_i} \tag{3}$$

where α_i, β_i and γ_i are the elastic coefficients of capital stock, labor force and energy consumption, respectively, which represent the impact of the input factors corresponding to them on the value of the output. A_i indicates the rate of technological progress. Subsequently, based on the contribution rate method [42], θ_i can be obtained by:

$$\theta_i = \gamma_i \Delta E_i Y_i / \Delta Y_i E_i \tag{4}$$

Different provinces have obvious differences in energy consumption structure, and their unit average energy cost will also have obvious differences. Based on this, this study refers to the construction of energy production cost in Xue et al. [43] and constructs the following energy production cost function:

$$C_i = \mu_i \times p_i \times E_i \quad (5)$$

where μ_i is the cost-income ratio of the energy producer and p_i is the unit energy price of the end energy consumer in province *i*.

3.2. Construction of the ECTTM

Based on the energy consumption quotas, transfer tax rate and state of economic development, each province chooses the optimal energy consumption strategy to maximize socioeconomic benefits of energy consumption. Therefore, the total annual energy consumption (E_i) of province i is determined as follows:

$$\max G_i(E_i) = \omega_i(E_i) - C_i(E_i) - t\left(E_i - \hat{E}_i\right) \quad (6)$$

To ensure the effective achievement of the target of energy consumption control, according to the relationship between the overall quotas and actual energy consumption, it can be determined that the sum of energy consumption cannot be greater than the sum of the quotas in each province, namely:

$$\sum_{i=1}^{n}(E_i - \hat{E}_i) \le 0 \quad (7)$$

As $t \ge 0$, it can be deduced that:

$$\sum_{i=1}^{n} t(E_i - \hat{E}_i) \le 0 \quad (8)$$

The significance of Equation (8) is that the energy consumption quota is transferred between provinces and that the sum of the transfers is zero when the overall energy consumption reaches the upper limit under the ECTTM. The sum of the fund pool formed by the transfer tax is zero when viewed as a whole.

In fact, the energy consumption in the province is limited. First, to ensure the normal operation of society and economic development, the energy supply of each province must meet the basic production and living energy needs of the province, which is the lower limit of energy consumption in each province. In this study, φ_{li} times $\hat{E}_i$ was selected as the lower limit of energy consumption. Additionally, owing to the existing environmental protection policies and limitations of energy production technologies, there is an upper limit on the provinces' total energy consumption. In this study, φ_{ui} times $\hat{E}_i$ was selected as the upper limit of energy consumption. Consequently, the limit for annual energy consumption in province i can be represented as [12,39,43]:

$$\varphi_{li}\hat{E}_i \le E_i \le \varphi_{ui}\hat{E}_i \quad (9)$$

The central government's goal is maximizing the total national socioeconomic benefits of energy consumption under the constraint of total energy consumption quotas through the ECTTM. The total national socioeconomic benefits of energy consumption are as follows

$$\max\sum_{i=1}^{n} G_i(E_i) = \max\sum_{i=1}^{n}[G_i(E_i, t)] \quad (10)$$

In summary, an inter-provincial energy conservation transfer tax model can be obtained as follows:

The upper model is

$$\max G = \sum_{i=1}^{n} G_i(E_i) = \sum_{i}^{n} [G_i(E_i, t)] \tag{11}$$

The lower model is

$$\begin{aligned} \max G_i(E_i) = \omega_i(E_i) - C_i(E_i) - t(E_i - \hat{E}_i) \\ s.t. \sum_{i=1}^{n} (E_i - \hat{E}_i) \leq 0 \\ \varphi_{li}\hat{E}_i \leq E_i \leq \varphi_{ui}\hat{E}_i \end{aligned} \tag{12}$$

3.3. Solution Approach: An Optimization Algorithm Based on NSGA-II

According to the logic of Stackelberg game theory, both players in the game choose their own strategies based on the possible strategies of the other party, so as to ensure that they can maximize their interests under the strategies of the other party and then achieve Nash equilibrium. As a two-stage complete information dynamic game, the process of the game is sequential, with the leader making their decision first, and the follower making their decision according to the leader's decision [55,56]. As one of the most attractive multi-objective evolutionary algorithms, NSGA-II has a simple structure, high usability and operability, rich application experience and excellent performance [57]. In view of the above characteristics of this model and the superiority of these algorithms, this study designs the optimization algorithm based on NSGA-II to solve the ECTTM to ensure the high operability and performance. The details of the algorithm flow are shown in Appendix A.

4. Results

4.1. Sample Selection and Data Sources

Electricity was selected as the representative form of energy in this study. On the one hand, as a vital component of energy consumption, the importance of electric power resources for social operations and economic development is self-evident. In 2021, electricity consumption accounted for approximately 27% of China's end energy consumption, and some experts predict that this proportion will exceed 70% by 2060 [58]. On the other hand, as the largest sector of fossil energy consumption, controlling the amount of electricity consumption can directly and effectively reduce the consumption of primary energy and carbon emissions [59].

As presented in Figures 1 and 2, evident regional differences exist in electricity consumption and intensity among the provinces in China [60]. This study comprehensively considers the resource endowment, economic development level and energy efficiency of each province and selects Shanghai, Zhejiang, Shaanxi and Guizhou as the samples of empirical research on the ECTTM.

Shanghai and Zhejiang are located on the east coast of China, and the geographical position is superior. Their energy intensity are 1.852 and 2.464 kWh/USD, respectively, which means that they are regions with high energy efficiency. Furthermore, their provincial economy is extremely active, the industrial structure is more reasonable, and the level of development is at the national forefront. Owing to their higher energy efficiency and higher economic benefits per unit energy consumption, these provinces are typical recipients of energy consumption quotas.

Guizhou is located in southwest China, with an energy intensity of 3.871 kWh/USD, with greater room for energy efficiency improvement. The province is rich in mineral and hydraulic resources. Shaanxi, located in the hinterland of northwest China, is an important hub that connects most parts of China. Its economic level is at the national average, and its energy intensity is 3.355 kWh/USD. Shaanxi—having considerable coal and oil reserves—is among China's main provinces for fossil energy supply. Owing to the relatively backward level of economic development and high energy intensity, the two provinces can transfer quotas of energy consumption to other energy-efficient provinces.

These four provinces can basically encompass all the types of regions that exist in the transfer tax mechanism, including the provinces that pay the transfer tax and the provinces that receive the transfer tax. Taking Shanghai as an example, Shanghai represents the economically developed regions such as Beijing and Tianjin, but with a smaller geographical area and poorer resource endowment. Zhejiang represents large energy consuming provinces such as Shandong and Jiangsu, which have a high energy demand, large economies and more adequate energy supply. Guizhou represents provinces such as Yunnan, Jiangxi and other provinces with average economic development and high energy consumption intensity. Shaanxi represents the northwestern region of China, such as Gansu and Shanxi, which are rich in natural resources but have high energy intensity and low level of economic development.

To obtain the gross economic benefit of electricity consumption function and cost function of energy consumption in 2020, this study collects and analyzes data from 2002 to 2020, predominantly collected from the China Statistical Yearbook and Provincial statistical yearbook, among other. The data include information on fixed capital stocks, employment, electricity consumption, regional gross domestic product and so on. Furthermore, from the China Electric Power Yearbook, we collected data on the operation of power generation enterprises in various provinces and electricity price data.

4.2. Net Benefits Function of Electricity Consumption in Each Province

The calculation of the net benefits from electricity consumption in each province includes two components—namely, calculating the income from electricity consumption and calculating the electricity production cost.

The province's annual electricity consumption income calculation is elucidated as follows: First, all variables are put into $LnY_i = A_i + \alpha_i LnK_i + \beta_i LnL_i + \gamma_i LnE_i$ by taking the logarithm of Equation (3); the elastic coefficients are estimated using the EViews 12 (×64) software. The results of elastic coefficients are presented in Table 2. Then, according to Equation (4), the values of θ_i are calculated, as presented in Table 3. Finally, based on the calculation of the above data, the annual gross benefit function of electricity consumption from 2002 to 2020 can be obtained, which represents the corresponding economic revenue of electricity consumption in the four provinces. The results are shown in Table 4.

Table 2. Elasticity coefficient in Equation (3).

Province	Coefficient				Std. Error			
	$lnK(\alpha_i)$	$lnL(\beta_i)$	$lnE(\gamma_i)$	c	$lnK(\alpha_i)$	$lnL(\beta_i)$	$lnE(\gamma_i)$	c
Shanghai	0.668 ***	0.368 ***	0.675 ***	−4.8 ***	0.042	0.094	0.050	0.255
Zhejiang	0.673 ***	0.340 **	0.381 ***	−3.150 ***	0.058	0.136	0.082	0.999
Shaanxi	0.574 ***	2.909 ***	0.195 **	−20.550 ***	0.051	0.393	0.087	2.841
Guizhou	0.641 ***	−1.188 ***	0.364 ***	8.597 ***	0.051	0.169	0.087	1.362

Note: ** $p < 0.05$, *** $p < 0.01$.

Table 3. Value of θ_i for the four provinces.

Province	θ_i
Shanghai	0.428
Zhejiang	0.337
Shaanxi	0.134
Guizhou	0.269

Table 4. Annual gross benefit function for electricity consumption from 2002 to 2020.

Province	ω_i	F-Test	R^2
Shanghai	$12.665exp(0.0016\,E_1)$	1185.32 ***	0.986
Zhejiang	$42.193exp(0.0003\,E_2)$	159.367 ***	0.952
Shaanxi	$6.794exp(0.0008\,E_3)$	95.21 ***	0.929
Guizhou	$6.351exp(0.0011\,E_4)$	107.829 ***	0.956

Note: *** $p < 0.01$.

Based on the electricity consumption data for the four provinces from 2002 to 2020, the unit energy prices of end-users (p_i) and cost-to-income ratios of energy producers (μ_i), the cost function for energy production according to Equation (5) can be fitted, and the results are shown in Table 5 and the parameters are listed in Table 6.

Table 5. Electricity production cost function for the four provinces.

Province	Electricity Production Cost Function
Shanghai	$C_1 = 0.0101E_1 - 0.819$
Zhejiang	$C_2 = 0.0099E_2 - 2.528$
Shaanxi	$C_3 = 0.0079E_3 - 0.716$
Guizhou	$C_4 = 0.0083E_4 - 1.762$

Table 6. Regression results of the electricity production cost function for the four provinces.

Province	Shanghai	Zhejiang	Shaanxi	Guizhou
a_i	0.0101 ***	0.0099 ***	0.0079 ***	0.0083 ***
b_i	−0.819 ***	−2.528 ***	−0.716 ***	−1.762 ***
R^2	0.993	0.991	0.986	0.967
F	2400.924 ***	1800.607 ***	1318.229 ***	538.511 ***

Note: *** $p < 0.01$.

According to the results presented in Tables 4 and 6, the net benefit function of electricity consumption in the four provinces are shown in Table 7.

Table 7. Net benefits function of electricity consumption in four provinces.

Province	Socioeconomic Benefits Function for Electricity Consumption
Shanghai	$12.665exp(0.0016\,E_1) - 0.0101E_1 + 0.819$
Zhejiang	$42.193exp(0.0003\,E_2) - 0.0099E_2 + 2.528$
Shaanxi	$6.794exp(0.0008\,E_3) - 0.0079E_3 + 0.716$
Guizhou	$6.351exp(0.0011\,E_4) - 0.0083E_4 + 1.762$

4.3. ECTTM in the Four Provinces

Based on the energy consumption control targets set by China's central government, we calculate the quotas of annual electricity consumption in Shanghai, Zhejiang, Shaanxi and Guizhou. According to the actual situation of electricity consumption in China, we set the value of the parameter φ_{li} to 0.9, and the parameter φ_{ui} to 1.1. Thereafter, the upper and lower limits of the annual electricity consumption in each province were obtained (Table 8).

Table 8. Electricity consumption quotas for each province in 2020 (unit: 10^8 kWh).

Province	Shanghai	Zhejiang	Shaanxi	Guizhou
Quotas of electricity consumption	1611.620	4810.573	2007.35	1622.286
Lower limit of electricity consumption	1450.458	4329.516	1806.615	1460.057
Upper limit of electricity consumption	1772.782	5291.630	2208.085	1784.515

Therefore, based on the data above and Equations (11) and (12), the ECTTM in the four provinces can be obtained as follows:

The upper model is

$$\max\sum_{i=1}^{n} G_i(E_i) = \max\sum_{i=1}^{n}[\omega_i(E_i) - C_i(E_i)]$$
$$= \max[12.665 exp(0.0016\,E_1) - 0.0101E_1 + 42.193 exp(0.0003\,E_2) - 0.0099E_2 + 6.794 exp(0.0008\,E_3)$$
$$-0.0079E_3 + 6.351 exp(0.0011\,E_4) - 0.0083E_4 + 5.824]$$

$$\text{s.t.}\begin{cases} t \geq 0 \\ \sum_{i=1}^{4} E_i \leq 10051.829 \\ 1450.458 \leq E_1 \leq 1772.782 \\ 4329.516 \leq E_2 \leq 5291.630 \\ 1806.611 \leq E_3 \leq 2208.080 \\ 1460.057 \leq E_4 \leq 1784.514 \end{cases}$$

The lower model is

$$\text{Shanghai}: \ \max G_1 = \max[12.665 exp(0.0016\,E_1) - 0.0101E_1 - t \times E_1 + 1611.620t + 0.819]$$
$$\text{s.t. } 1450.458 \leq E_1 \leq 1772.782$$

$$\text{Zhejiang}: \ \max G_2 = \max[42.193 exp(0.0003\,E_2) - 0.0099E_2 - t \times E_2 + 4810.573t + 2.528]$$
$$\text{s.t. } 4329.516 \leq E_2 \leq 5291.630$$

$$\text{Shaanxi}: \ \max G_3 = \max[6.794 exp(0.0008\,E_3) - 0.0079E_3 - t \times E_3 + 2007.350t + 0.716]$$
$$\text{s.t. } 1806.611 \leq E_3 \leq 2208.080$$

$$\text{Guizhou}: \ \max G_4 = \max[6.351 exp(0.0011\,E_4) - 0.0083E_4 - t \times E_4 + 1622.286t + 1.762]$$
$$\text{s.t. } 1460.057 \leq E_4 \leq 1784.514$$

Using the optimization algorithm based on NSGA-II, the optimal transfer tax rate in 2020 was 0.381 USD/kWh. The annual optimal power consumption of Shanghai, Zhejiang, Shaanxi and Guizhou was 1772.782×10^8 kWh, 5012.374×10^8 kWh, 1806.611×10^8 kWh, and 1460.057×10^8 kWh, respectively. The benefits of electricity consumption are USD 192.675 billion, USD 135.219 billion, USD 22.748 billion and USD 27.420 billion, and the total benefit of electricity consumption is USD 378.062 billion.

5. Discussion

5.1. Comparison of the TMM and the ECTTM

By using the electricity consumption quotas of each province as the actual annual energy consumption, the socioeconomic benefits of energy consumption under TMM can be calculated. As presented in Table 9, the sum of the socioeconomic benefits of electricity consumption under the TMM is USD 329.689 billion, while the optimal total socioeconomic benefits of electricity consumption of the four provinces under the ECTTM is USD 378.062 billion, and the return of the latter increased by USD 48.373 billion, which is 14.67% higher. The socioeconomic benefits of electricity consumption for Shanghai, Zhejiang, Shaanxi and Guizhou increased by USD 41.315 billion, USD 1.464 billion, USD 4.238 billion and USD 1.357 billion, respectively. Additionally, the average electricity energy intensity of the four provinces was 2.659 kWh/USD under the ECTTM, which decreased by 12.8% compared with the TMM.

Table 9. Comparison of results between TMM and ECTTM.

Province	TMM		ECTTM		Increased Benefits (USD billion)
	Quantity of Electricity Consumption (10^8 kWh)	Benefits from Electricity Consumption (USD billion)	Quantity of Electricity Consumption (10^8 kWh)	Benefits from Electricity Consumption (USD billion)	
Shanghai	1611.620	151.360	1772.782	192.675	41.315
Zhejiang	4810.573	133.755	5012.379	135.219	1.464
Shaanxi	2007.350	18.510	1806.611	22.748	4.238
Guizhou	1622.286	26.063	1460.057	27.420	1.357
Total	10,051.829	329.689	10,051.829	378.062	48.373

Table 10 and Figure 4 present the transfer of the quotas of electricity consumption and transfer tax in the four provinces under the ECTTM. The results suggest that Shaanxi and Guizhou transferred power consumption quotas of 200.739×10^8 kWh and 162.229×10^8 kWh to Shanghai and Zhejiang, respectively, and obtained transfer tax benefits of USD 7.654 billion and USD 6.186 billion, respectively. Shanghai and Zhejiang received quotas of electricity consumption of 161.162×10^8 and 201.806×10^8 kWh from Shaanxi and Guizhou, respectively, and paid transfer taxes of USD 6.145 billion and USD 7.695 billion. Therefore, the essence of the ECTTM lies in the reallocation of energy consumption quotas and the redistribution of electricity consumption benefits among the provinces according to the transfer tax rate. Under this model, more energy consumption quotas are transferred to provinces with high energy efficiency and economic efficiency, and the increased economic benefit is redistributed through the transfer tax levied by the government. Through inter-provincial coordination, this transfer tax mechanism can not only better achieve the target of energy consumption control, but also effectively control the impact of energy consumption control on the economy.

Table 10. Transfer direction of electricity consumption quotas and tax to be paid (obtained) in the four provinces under ECTTM.

Province	Electricity Consumption of Quotas (10^8 kWh)	Optimal Electricity Consumption (10^8 kWh)	Direction of Power Quotas Transfer	Quantity of Transfer (10^8 kWh)	Tax of Transfer (USD million)
Shanghai	1611.620	1772.782		161.162	6.145
Zhejiang	4810.573	5012.379		201.806	7.695
Shaanxi	2007.350	1806.611	Shaanxi → Shanghai, Zhejiang	−200.739	−7.654
Guizhou	1622.286	1460.057	Guizhou → Shanghai, Zhejiang	−162.229	−6.186
Total	10,051.829	10,051.829		0	0

Note: In the quantity of electricity consumption transfer, a negative value represents the transfer quantity of the quotas. In the transfer tax, a negative value represents the subsidy received.

The tax rate t is set by the central government, considering the difficulty of achieving energy consumption control targets in each province while paying attention to the response of each province to the tax rate. The value of the tax rate determines the enthusiasm for inter-provincial energy consumption quota transfers. In the ECTTM, provinces consider their own benefits of energy consumption and the economic income obtained (paid) from the transfer of energy consumption quotas under the unified tax rate level. By optimizing their actual energy consumption and transfer quotas, province i can ensure the maximum socioeconomic benefits of energy consumption.

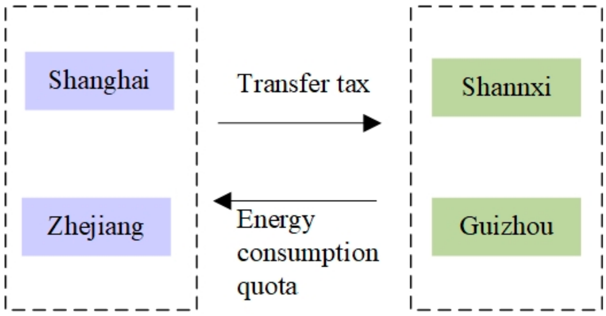

Figure 4. Energy consumption quota flows and transfer tax flows in four provinces.

Compared to the TMM, the ECTTM integrates economic advantages with energy consumption control advantages among provinces and gives full play to the initiative of provinces in energy consumption control. It can be seen that the model is very effective in controlling energy consumption and increasing economic efficiency of energy consumption, and the mechanism of influence is different for different types of provinces. Under the ECTTM, provinces with economic advantages, such as Shanghai, can obtain more energy consumption quotas and produce higher economic benefits of energy consumption. Regions with higher energy intensity receive an economic income higher than their energy consumption's economic benefits, such as Guizhou. With the transfer of energy consumption quotas, economically developed provinces, such as Shanghai, are more likely to rely on its technological and economic advantages, continuously promote technological innovation and constantly improve energy efficiency. For the provinces that have received economic income, taking Guizhou and Shaanxi as examples, the increased economic income can be used to update production technology, gradually phase out backward production capacity, develop and cultivate advanced production capacity, improve regional energy efficiency and reduce energy intensity. In this model, the allocation of resources based on economic means is applied to the field of energy consumption such that the country and provinces can achieve higher socioeconomic benefits of energy consumption and lower energy intensity while fulfilling energy consumption control targets. At the national level, this model can availably reduce the difficulty in achieving China's energy consumption control goals and alleviates the contradiction between energy consumption control and economic growth. In addition, compared with the cooperative and transaction management models mentioned in the previous literature [12,39], this ECTTM, with the authoritative guidance and supervision of the government, has a low management cost, a direct management approach and is more implementable. However, the cooperation or transaction model requires more coordination and transaction costs and is more difficult to supervise and implement due to the imperfect macro-management system and the incomplete construction of the transaction market. Considering the above aspects, the ECTTM exhibits significant advantages in ensuring the realization of energy consumption control targets and promoting economic development.

Under the current dual control policies and regulations, the energy consumption quota gradually becomes a kind of resource. The formation of such resources depends on the energy consumption quota demand formed by each region under the mandatory provisions and constraints of the national dual control target. The mandatory energy consumption quotas allocated by the central government to the provinces can be regarded as the initial allocation of resources. This initial allocation based on the level of regional economic development and the current situation of energy consumption is an allocation model that emphasizes fairness. On this basis, the ECTTM proposed in this study, which uses transfer tax as a means, emphasizes allocation efficiency and can achieve the secondary allocation of energy consumption quotas in a scientific and reasonable way. Compared with the initial allocation, the secondary allocation aims at economic optimization, attaches importance to the coordinated management of energy consumption quotas in various regions during the whole dual controls assessment period, and improves the energy efficiency and economic benefits of energy consumption. Therefore, the ECTTM constructed in this study is an allocation model that takes into account both fairness and efficiency through the combination of the initial and secondary allocation of energy consumption quotas.

5.2. Sensitivity Analysis

To prove the robustness of the ECTTM, conducting a sensitivity analysis is necessary. Table 11 presents the results of the different tax rates and the optimal economic benefits from the energy consumption of the provinces caused by changes in the parameters φ_{li} and φ_{ui}.

Table 11. Results of the sensitivity analysis for the ECTTM (unit: USD billion).

Parameter		Shanghai	Zhejiang	Shaanxi	Guizhou	Tax Rate (USD/kWh)	Total Benefits of Energy Consumption	Increase
Baseline	[0.90, 1.10]	192.675	135.219	22.748	27.419	0.381	378.062	14.67%
Change φ_{li}	[0.80, 1.10]	192.575	138.106	27.980	28.599	0.388	387.259	17.46%
	[0.85, 1.10]	192.575	136.892	25.340	28.638	0.388	383.446	16.31%
	[0.88, 1.10]	192.625	135.829	23.764	27.878	0.384	380.095	15.29%
	[0.93, 1.10]	192.750	134.388	21.328	26.845	0.377	375.311	13.84%
	[0.95, 1.10]	192.775	133.883	20.466	26.553	0.375	373.678	13.34%
Change φ_{ui}	[0.90, 1.05]	170.437	135.579	22.748	26.966	0.381	355.730	7.90%
	[0.90, 1.08]	183.354	135.480	22.779	27.445	0.383	369.058	11.94%
	[0.90, 1.13]	207.778	134.854	22.686	27.369	0.378	392.687	19.11%
	[0.90, 1.15]	218.620	134.601	22.655	27.344	0.377	403.220	22.30%
	[0.90, 1.18]	236.117	134.250	22.624	27.319	0.375	420.310	27.49%
	[0.90, 1.20]	248.631	134.020	22.624	27.319	0.375	432.594	31.21%

The lower-bound coefficient of energy consumption for province i φ_{li} indicates the potential of the province to transfer electricity consumption quotas to other provinces. When φ_{li} is smaller, it suggests that the province has more electricity consumption quotas to transfer to other provinces, and greater socioeconomic benefits of energy consumption may be generated. The data in Table 11 illustrate that when the value of φ_{li} is gradually reduced from 0.95 to 0.8, the total economic benefits of energy consumption tend to increase, and the growth rate of economic benefits increases by 4.12%. When φ_{li} = 0.8, the transfer tax rate is 0.388 USD/kWh, and the economic benefit of energy consumption generated by energy consumption is 17.46% higher than that under the TMM.

The coefficient of the upper limit of energy consumption φ_{ui} indicates the potential of the province to receive energy consumption quotas from other provinces. When φ_{ui} is larger, the province can accept more electricity consumption quotas from other provinces, thus generating higher socioeconomic benefits of energy consumption. By comparison, when the value of φ_{ui} decreases from 1.2 to 1.05, the growth rate of the total economic income indicates a downward trend. With a decrease in the parameter φ_{ui}, the socioeconomic benefits from energy consumption of the four provinces fluctuate stably. In summary, the sensitivity analysis reveals that changes in total socioeconomic benefits of energy consumption remain stable when the parameters are adjusted.

6. Conclusions and Policy Recommendations

Considering the differences in economic development and energy efficiency of different provinces, to further improve the dual controls, alleviate the greenhouse effect and environmental pollution and achieve sustainable development goals, this study applies bi-level optimization and Stackelberg game theories to construct an inter-provincial energy consumption transfer tax model. Under the ECTTM, the central government determines the tax rate to ensure the maximum national benefits of energy consumption, while each province chooses the optimal annual energy consumption to obtain maximum socioeconomic benefits of energy consumption. This article applied this model to an empirical analysis of Shanghai–Zhejiang–Shaanxi–Guizhou. The results suggest that the ECTTM is superior to the TMM regarding socioeconomic benefits of energy consumption and energy efficiency. The total socioeconomic benefits of energy consumption under the ECTTM are 14.67% higher than those under the TMM, the total economic benefit is USD 378.062 billion, and the benefits to Shanghai, Zhejiang, Shannxi and Guizhou increased by USD 41.315 billion, USD1.464 billion, USD 4.238 billion and USD 1.357 billion, respectively. And the electricity consumption per unit of GDP decreased by 12.8%, which indicates that the overall power intensity decreased. Thus, it can be observed that China's provinces can not only flexibility achieve energy consumption control goals but also improve energy efficiency, obtain greater economic benefits of energy consumption than the TMM and achieve a win–win situation of economic growth and energy consumption control under the ECTTM.

Additionally, considering the essential characteristics of transfer tax and the scientific nature of this study, we find that the model has the following advantages in implementation: (1) The ECTTM can enhance the sense of fairness of joint energy consumption control by the central government's management. (2) The determination of the tax rate in the model can effectively avoid the trial-and-error process using scientific methods. (3) Overall, the ECTTM has the authority and binding force of government management and the flexibility and efficiency of economic means.

Although this study is based on China's current problems, the energy consumption transfer tax model proposed in this article has extensive applications. For countries or regions with obvious differences in unit benefit of energy consumption, this model can better achieve energy consumption control goals and maximize economic benefits of energy consumption by optimizing energy consumption between regions. This model is more valuable for developing countries with economic development requirements and carbon reduction goals, such as India, Pakistan and Chile. It is worth noting that in the application of the model, the actual demand and basic conditions of the region or country should be fully considered, and the practical energy consumption benefit function and energy consumption constraint conditions should be constructed, so as to make the setting of the tax rate and the optimal energy consumption results of each region more accurate, real and practical.

To promote the practice of the ECTTM in energy consumption management, we propose the following policy suggestions:

(1) Establishing transfer tax levying and management departments.

It is necessary for the central government to establish or entitle an authoritative department responsible for the administration of inter-provincial quota transfers. This department's functions include formulating a unified inter-provincial quota transfer policy, determining the transfer tax rate, supervising the levying process of the transfer tax, evaluating the performance of the transfer policy's implementation, coordinating the interests among various energy-saving subjects, and dealing with other administrative issues to ensure the system's long-term operation.

(2) Strengthening the process management of transfer tax coordination.

To control the total amount of energy consumption rationally, governments should pay more attention to the process management rather than just the assessment result. In the implementation process of transfer tax, it is necessary to collect and manage related information and data in a unified manner, build the early warning mechanism of energy consumption quotas, and form "positive or negative" feedback of energy consumption control, so as to discover problems in time and formulate targeted and effective measures. In addition, some strategies of transfer tax, such as tax rates, should be adjusted in a timely manner and improved according to the actual situation in the process, to ensure the stable and continuous implementation of dual controls and improve the coordinated operation ability of the central and provincial governments.

(3) Formulating the energy classification system on the supply side.

At the end consumer, the use of renewable energy and traditional fossil energy should be regulated by different tax regimes. Policies are used to encourage the consumption of renewable energy and drive the development of renewable energy through demand. In view of the current inconvenient measurement of renewable energy on the consumption side, it can be calculated by the proportion of renewable energy on the supply side in the total energy consumption.

(4) Adopting a transfer fee as a transition to transfer tax.

Although transfer taxes exhibit evident advantages in terms of the binding force and stability, taxation legislation is a complicated process that takes a long time and is not conducive to the timely resolution of the serious and urgent energy and environmental issues currently facing China. Therefore, transfer fees can be adopted to replace the transfer tax at the early stage of implementation, as the transfer fee system is flexible and easy to implement. The implementation of transfer fees can assess the impact of the implementation of transfer taxes in advance, identify potential problems in time, accumulate implementation experience, contribute to the gradual improvement of the transfer tax system, and achieve a stable transition from transfer fees to transfer taxes. And there is also a need to consider potential challenges and problems, such as insufficient theoretical support and the lack of authority of the institutional framework.

There are still limitations in this study, for example, few considerations of interactions with other policies. Thus, future research on this topic may consider the following improvements. (1) In the setting of the tax rate, in addition to economic benefits, factors such as the ecological environment, social livelihoods and other policies should also be considered. (2) The model should be more carefully demonstrated for a richer sample of districts to enhance the theoretical support. (3) Hierarchical regulation can be considered in the design of transfer tax rates to improve the fairness of the model's redistribution system further. (4) Integration with other policies such as a carbon tax and an emissions tax should be considered to improve research on energy and environmental management policies.

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Appendix A. Solution Algorithm Flow

Step 1: Solve $\sum G_i$ of the upper optimization model using the nonlinear optimization method, get the optimal function values E_i^* and $\sum G_i$, and proceed to Step 2.

Step 2: Input E_i^* into the lower optimization model. Solve the lower optimization model to obtain the Pareto optimal solution set of t by the NSGA-II multi-objective optimization algorithm and proceed to Step 3.

Step 3: Calculate G_i in the lower model by plugging in t and E_i^*, get the set of function values G_i and proceed to Step 4.

Step 4: It is necessary to establish benefits conditions to ensure that the benefits can be increased after optimization. Perform the following operations: Compare G_i with G_{iTMM}, if $G_i \leq G_{iTMM}$, delete t in the corresponding set. If $G_i > G_{iTMM}$, output t, and the result is a set of t that satisfy the benefits condition. Proceed to Step 5.

Step 5: Choose the average value of t in the set as the optimal solution to t^*. The algorithm output t^*, E_i^* and G_i is the satisfactory solution of the ECTTM.

The solution algorithm flow is shown in Figure A1.

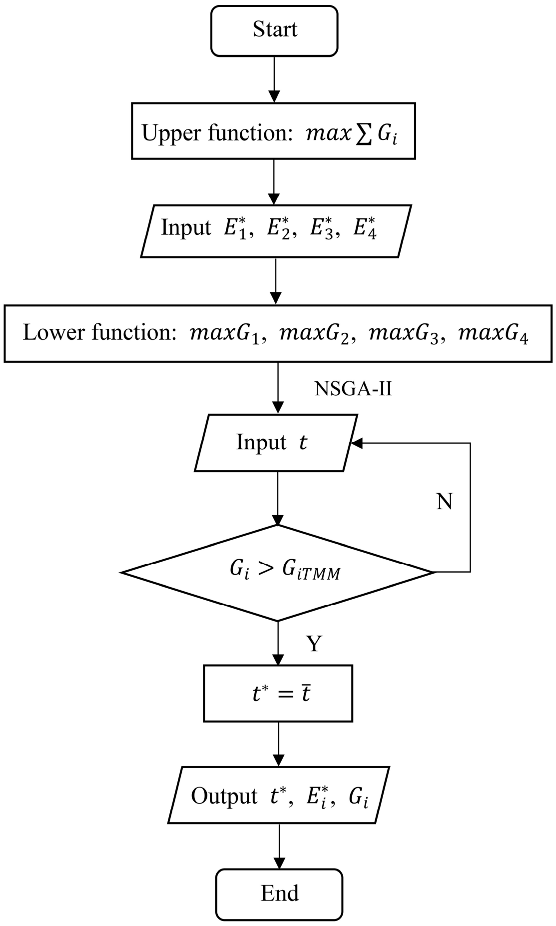

Figure A1. Bi-level multi-objective optimization model algorithm flow.

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