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Planning Mechanism Design and Benefit Analysis of Electric Energy Substitution: A Case Study of Tobacco Industry in Yunnan Province, China

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ABSTRACT The problem of fossil energy shortage and pollution has become increasingly prominent. In China, government-led electric energy substitution projects are being carried out in nationwide, aiming at the end of energy consumption links, using electricity instead of coal-fired and oil-fired energy consumption, in order to optimize the energy structure and achieve the goal of energy conservation and emission reduction. Aiming at the planning and benefit sharing of electric energy substitution project, this research first designs the planning mechanism of electric energy substitution for productive users, analyses distribution network planning, transformation subsidy and so on, and puts forward three schemes. Secondly, based on the cooperative game theory, the benefit allocation model of electric energy substitution project is established. Finally, we take the flue-cured tobacco project about replacing coal with electricity in three areas of Yunnan province as an example to analyze, optimize the game strategy, and put forward three indicators to measure the benefits of the participants in the project. The pollution reduction situation that can not be converted into economic benefits is counted. The modeling results show that the density of users geographically will directly affect the cost of the distribution network transformation. The coal flue-cured tobacco heat loss and serious pollution, after optimization, power grid enterprises can quickly recover investment.

INDEX TERMS Electric energy substitution, mechanism design, benefit analysis, tobacco industry.

I. INTRODUCTION

With the excessive consumption of global fossil energy, the problem of energy shortage and environmental pollution is becoming increasingly prominent. The Paris Accord sets a target for global CO2 reduction of carbon emissions, which is the European national system. A timetable for the withdrawal of fuel-fired vehicles from the market has been set [1]. The Chinese government has pointed out that the proportion of electricity in terminal energy consumption should reach about 27% by 2016-2020 [2]. In response to the relevant policies of the Chinese government, the State Grid Corporation of China has launched in recent years the concept of ''Replacing coal with electricity, replacing oil with electricity, and using clean electricity'' as the core concept of electric energy substitution work [3]. Electric energy substitution refers to the energy consumption mode of substituting electric energy for fossil energy such as coal, oil, natural gas and conventional terminal energy in the end energy consumption link [4].

Nowadays, China is actively carrying out electric energy substitution projects. In the whole year of 2018, 38,000 electric energy substitution projects have been completed. The additional electricity generated by substituting other energy sources amounts to 135.3 billion kW·h, which is equivalent to reducing 75.77 million tons of coal combustion, 135 million tons of carbon dioxide emissions and 430 million tons of sulfur dioxide, nitrogen oxides and dust emissions, the economic and environmental benefits of this project are remarkable [5]. Electric energy substitution emphasizes that priority should be given to energy consumption through technological innovation. In order to reduce the consumption of fossil energy, the project encourages the use of various types of electric

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products and facilities, such as traditional coal-fired boilers, coal burners, residential heating and cooking, to reduce coal consumption [6].

In fact, similar projects have already begun in other countries. The United States began rural electrification [7] in the last century and used ground heat pump technology [8]. Japan levied a tax on fossil fuels at the rate of 2400 yen per ton to promote the rise of electricity consumption [8]. European countries are actively expanding electric heating [9]. Simultaneously, most countries in the European Union are opening up the power market, implementing self-pricing mechanism, and accelerating the speed of substituting electric energy for other energy sources [11]–[13]. In addition, electric transportation, including electric vehicles, is supported by different countries all over the world [14], [15]. Although similar projects have been carried out in some countries, it is necessary to further study the project in light of Chinese energy consumption characteristics and policy background.

In recent years, related research has focused on energy efficiency and power demand forecasting. The energy-GDP elasticity coefficient is used to measure the change of energy use when GDP changes by 1%. Csereklyei and Stern pointed out that the growth of per capita energy use has been primarily driven by economic growth [17] in the medium and long term. Li and Tao summarized four main energy efficiency evaluation methods [18]. Bukarica and Tomsica designed an energy efficiency market model and compares it with market conditions [19]. Chen and Chen evaluated the energy use of construction industry in 28 major cities in northern China, and pointed out that electric heating is more adaptable than steam heating in rural areas of China [20]. In Malaysia with abundant hydropower, Bello *et al.* studied uses ridge regression method and runoff generation function to estimate the parameters, which verifies that hydropower can be used in this country, feasibility of replacing fossil fuels [21].

Electricity can be substituted with other energy sources. The substitution effect is an important factor driving the power consumption intensity. The decrease of capital price and energy price will lead to the increase of power consumption intensity [22], [23]. Akay and Atak introduced dynamic into grey forecasting model and tracked and predicted Turkey's long-term electricity demand for the whole society and industrial sector [24]. German buildings currently use electric heating, and by 2040 the German electric power sector will gain an additional 260 TW·h of electricity demand [10]. Yongxiu *et al.* used particle swarm optimization combined with in-depth learning to predict China's electricity demand, and measured the impact of driving factors on electricity demand by correlation degree, it revealed the direction of action of driving factors on electricity demand [25]. There is a relationship between electricity demand and season. A seasonal grey model (SGM) is proposed, which is based on the cumulative operator generated by seasonal factors, can effectively predict seasonal power demand fluctuations in the primary industry [26].

Electric energy substitution can be divided into two categories from the economic point of view: production behavior and non-production behavior. Some users mainly use electric energy to replace other energy sources to improve their quality of life, mainly residential users, such as electric heating [49], electric cooking [50]. While the other users with production behavior use electricity, they can replace other energy sources to carry out production activities, e.g. electrolytic aluminium [29], [31], electrolytic copper [30], and electric boiler [31]. In other words, electric energy is one of the means of production of such users, who use electric energy to carry out production activities.

The electric energy substitution project has been carried out on a large scale in China, but the planning mechanism has not been designed in the existing research, which can not guide the actual development of such projects. Therefore, this paper studies the issue. The first part is about the design of the planning mechanism of electric energy substitution, and subsidy strategies are formulated for users and power grid enterprises (PGE). The second part establishes the benefit distribution model of electric energy substitution based on cooperative game theory. The third part introduces the solution algorithm. In the fourth part, the strategy of replacing coal by electricity for flue-cured tobacco in Yunnan province was analyzed. The fifth part discusses the environmental benefits of the flue-cured tobacco project. Finally, the sixth part draws relevant conclusions.

II. MECHANISM DESIGN OF ELECTRIC ENERGY SUBSTITUTION

A. USER CLUSTERING PHENOMENON

In the actual electric energy substitution project, when the number of users reaches a certain scale, there is scale benefit, so the government and PGE are willing to promote the development of this project. The potential substituted objects are various, involving all energy users, possibly industrial users, residential users, agricultural users, etc. When these users are ready to use electric energy as power to carry out production activities, the primary problem they face is how to connect these users to the power grid, when the number of users reaches a certain scale. These productive users are often located in the production of raw materials, e.g. flue-cured tobacco barns around tobacco planting areas. From the point of view of distribution network planning, these users have the phenomenon of "clustering" geographically. Figure 1 shows the phenomenon of users clustering in the distribution network.

The unconnected users in Figure 1 are potential objects of electric energy substitution. This paper defines these users as User Clusters (UC) that has a certain distance between them and connected users. Combining with the GIS system of distribution network, the UC are classified into three types according to the dense degree: dispersed, medium and dense. Equivalent, the characteristics of dispersed UC are that they

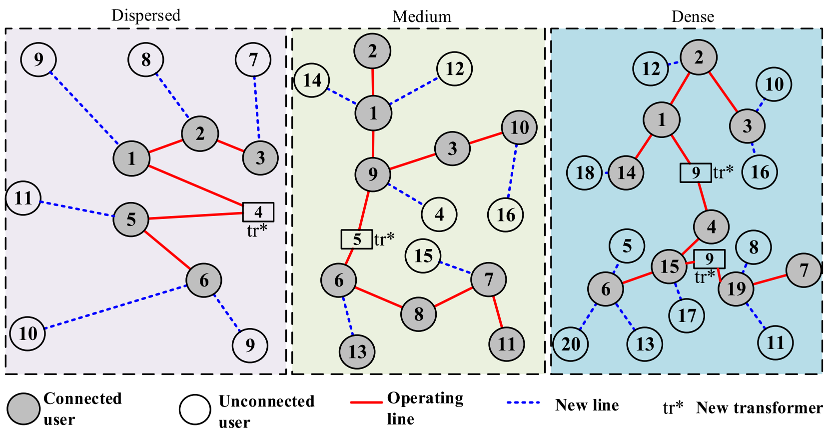

FIGURE 1. Classification of user clusters dense degree.

are far away from adjacent operational lines or connected users, while a small number of users need a longer length of new lines, The characteristic of dense UC are that they have a shorter distance from the users have access to the distribution network, so new lines need to be shorter in length. The density of UC directly affects the length of lines with different voltage levels that need to be built and the number of transformers that need to be added. Through the above statistical classification, it is very important for the next practical project to complete the preliminary data research work of electric energy substitution. In order to further quantify the denseness index, in section II.B of this paper, the denseness coefficient of UC is calculated by classifying statistics and weighting method of five categories of users, which can represent the dense degree of user distribution in a certain area in the distribution network layer.

B. DESIGN OF ELECTRIC ENERGY SUBSTITUTION PLANNING MECHANISM

The promotion of electric energy substitution projects can not be separated from effective incentive and reasonable planning mechanism. At present, there is no design of this mechanism for electric energy substitution. The projects that have been carried out in China generally have period of three years, the longest is not more than 8 years. However, there is no systematic method to guide the project planning. At the same time, there are no reasonable economic incentive measures on the user side. Therefore, we take into account the size of the UC, the degree of psychological acceptance and the cost of distribution network transformation. Consideration has been given to the formulation of planning mechanism as shown in the following figure:

As shown in Figure 2, the objects of electric energy substitution constitute a cluster. Because of the large number of users in the project, it is impossible to make them participate in the project all at once, and the project needs to respect the wishes of users. Considering these factors, we will design the substitution mechanism as shown in Figure 2. Firstly, the UC are classified according to the number of users, the psychological acceptance of electric energy substitution projects and the cost of distribution network transformation.

1) NUMBER OF USERS

From the experience of electric energy substitution projects, the number of potential users directly determines the project cycle. The higher the number of users, the longer the project cycle will be. Through the post-survey of such projects, the number of users is in the order of 100 and 1000, giving priority to short-term substitution. The number of users in the order of 10,000 can consider medium-term substitution, while the number of users is higher than 50,000, long-term substitution needs to be considered.

2) PSYCHOLOGICAL ACCEPTANCE OF USERS

The biggest characteristic of the electric energy substitution project on the user side is voluntary participation. Influenced by many factors such as industry energy structure and user's energy consumption behavior, the user's acceptance of the use of power production or life varies. Therefore, it is necessary to conduct user acceptance survey before carrying out such projects. In this paper, users' psychological willingness is investigated by questionnaires. Questionnaires are designed by Likert scale and Fuzzy Language Scale [27], [28], as shown in Table 1. If a user chooses "uncertain", the scale value $\kappa = P_{\rm li} \cdot P_{\rm FL}$, $\kappa_{uncertain} = 3 \cdot 10\% = 0.3$, and the user has a neutral attitude to the project.

Through acquiring the data of potential users' psychological willingness and classifying the users according to their acceptance degree, Lead users are more likely to participate in the project and play a leading role in the UC. Neutral users hold a wait-and-see attitude, while stubborn users are less motivated to participate in the project, and even refuse to make it happen.

3) COST OF DISTRIBUTION NETWORK TRANSFORMATION

Now, the vast majority of electric energy substitution projects only involve the transformation of distribution network, and there is no need to build new transmission network or

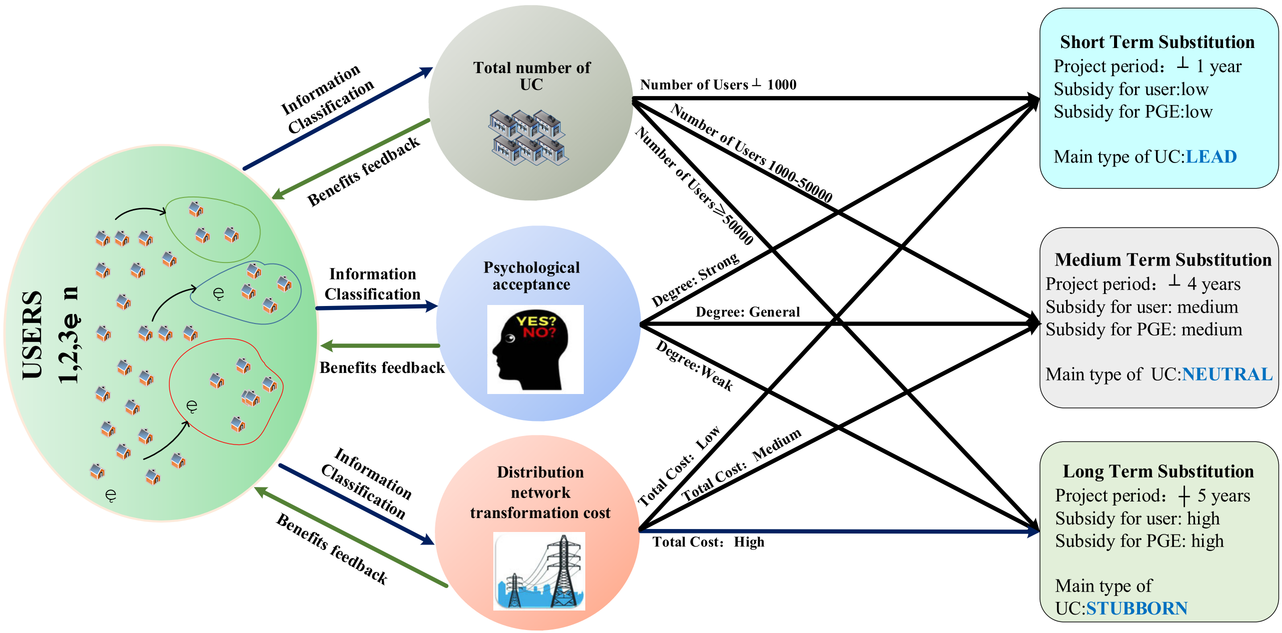

FIGURE 2. Design of planning mechanism for electric energy substitution.

TABLE 1. Likert and fuzzy language scale.

Scale Type	Strongly Disagree	Disagree	Uncertain	Agree	Strongly Agree
Likert	1	2	3	4	5
Fuzzy Language	0%	0%	10%	70%	20%
Type (κ)	Stubborn (κ=0)	Stubborn (κ=0)	Neutral ($\kappa \leq 1$)	Lead ($\kappa \geq 1$)	Lead ($\kappa \geq 1$)

transform higher voltage level lines, e.g. 110kV and 220 kV. Therefore, we estimate that the cost of distribution network transformation mainly considers the situation of adding 10kV, 0.4kV line length and the number of new transformers. Combining the Part II A of UC density, we define the following UC density coefficients:

$$\xi = \sum_{p}^{p=5} \eta_p \mu_p \tag{1}$$

In formula (1), the user-dense factor covered by each distribution station in a certain area, and also reflects the new construction of 10kV, 0.4kV lines and transformers in a certain distribution network area. The smaller the value of ξ, the more dispersed the distribution of users, the higher the cost of distribution network transformation in a certain area may be. η_p is the proportion of the number of users in the whole cluster within the number of p-type users. Assuming that $\eta_5 = 30\%$ represents more than 50 users in the distribution area where 30% of the users are located, and that μ_k is the corresponding weight factor of η_p, the weight of η_p and the grading of distribution network transformation such as Table 2 are adopted by expert weighting method [33].

TABLE 2. Classification of distribution network transformation based on density.

n	1-10	11-20	21-20	31-50	$\geq$50
η_p	η_1	η_2	η_3	η_4	η_5
μ_k	1.1	1.05	1	0.95	0.9

On the basis of the above three evaluation indicators, and combined with our investigation on a large number of completed projects, we design three substitution schemes:

A Short-term Substitution

Assuming that the number of potential users in a certain area is small, the number of Lead-type users accounts for a large proportion of the total number of users, and the cost of distribution network transformation is low, this type of UC and PGE are more suitable for short-term substitution. Government's subsidies for users and PGE need not be too high, and appropriate incentives can be pushed forward. The project cycle can be designed for one year when the project is launched.

B Medium-term Substitution

Assuming that the number of potential users in a certain area is medium, the number of Lead-type and Neutral-type users accounts for a large proportion of the total number of users, and the cost of distribution network transformation is not high, this type of UC and PGE are more suitable for medium-term substitution. The government's subsidies for

UC and PGE can be referred to benchmark. The period of design was 2-4 years.

C long-term Substitution

Assuming that the number of potential users in a certain area is huge, the number of Stubborn-type users accounts for a large proportion of the total number of users, and the cost of distribution network transformation is high, this type of UC and PGE are more suitable for long-term substitution, and government total subsidies for UC need to be increased by a large margin. The design period of the project is 5 years or more.

The three substitution plans can support government and PGE on schematization, but it is not suitable for area with complex energy consumption.

C. SUBSIDIES FOR ELECTRIC ENERGY SUBSTITUTION

How to calculate the subsidy cost is extremely important for the government. It also involves whether it can stimulate the PGE and UC, and play the role of economic leverage in the process of the project.

1) SUBSIDY FOR UC

When the function Y has a sinusoidal relationship, there is:

$$\begin{aligned} S^{\text{odd}}_{\text{UC}\cdot i\cdot k} &= \omega_k \cdot S^{\text{base}}_{\text{UC}\cdot i} \\ S^{\text{base}}_{\text{UC}\cdot i} &= (\varepsilon \pm \Delta\varepsilon) \times C_{\text{equ}} \end{aligned} \tag{2}$$

$S^{\text{odd}}_{\text{uc}\cdot i\cdot k}$ is the subsidy for individual k–type users in the i-th year, and $S^{\text{base}}_{\text{uc}\cdot i}$ is the benchmark subsidy issued by the government in the i-th year. The smaller the value of the psychological willingness coefficient of k-type users, the easier it is for users to participate in electric energy substitution projects. ω_k is calculated by appendix Table 7 and appendix Formula A1. C_{equ} is the cost of equipment generated by the user when replacing energy, ε is the ratio of subsidy, and $\Delta\varepsilon$ is the floating range of subsidy rate. Every user receives a subsidy only in the first year when he participates in the electric energy substitution project, i.e. the subsidy is one-time, and the same user cannot get the subsidy repeatedly.

2) SUBSIDY FOR PGE

$$\begin{aligned} S_{PGE\cdot i} &= \xi \cdot S^{base}_{\text{PGE}\cdot i} \\ S^{base}_{PGE\cdot i} &= (0 \sim 5\%) \cdot C^{i}_{D} \end{aligned} \tag{3}$$

$S_{\text{PGE}\cdot i}$ is the government's subsidy for PGE in the i-th year, $S^{\text{base}}_{\text{PGE}\cdot i}$ is the benchmark subsidy for PGE issued by the government in the i-th year, and C^{i}_{D} is the capital invested in the transformation of PGE in the i-th year. The government may flexibly subsidize PGE according to the tax situation generated by the project. The meaning of ξ is consistent with that of this paper II B.

III. BENEFIT GAME OF ELECTRIC ENERGY SUBSTITUTION

After the development of electric energy substitution projects, there will be multiple benefits, which will inevitably lead to conflict of distribution. Essentially, it can be summed up as game problems. It should be noted that UC, PGE and government must form a partnership, otherwise, none of them will get the benefits of this project, and this kind of relationship is just in line with the characteristics of cooperative game. The relationship between all participants in the game and benefit conflict are expressed as follows.

As shown in Figure 3, because of the different roles played by UC, PGE and government in the distribution of electric energy substitution benefits among different subjects, and the different goals pursued by the corresponding subjects, the game behavior of the interests of each subject is generated when the project is carried out. The objectives of the UC in Figure 3 include reducing energy costs and increasing the ratio of energy to economic benefits. PGE expect to increase electricity consumption in the end energy consumption, the proportion of electric energy expands, but also need to consider the safe and economic operation of transmission and distribution network, and PGE will contribute tax revenue to the government. The government is more concerned about the environmental benefits of electric energy substitution, reducing the emissions of various pollutants through electric energy substitution, and the government will stimulate UC and PGE to participate in the projects in the form of economic subsidies, thus promoting the change of energy consumption structure.

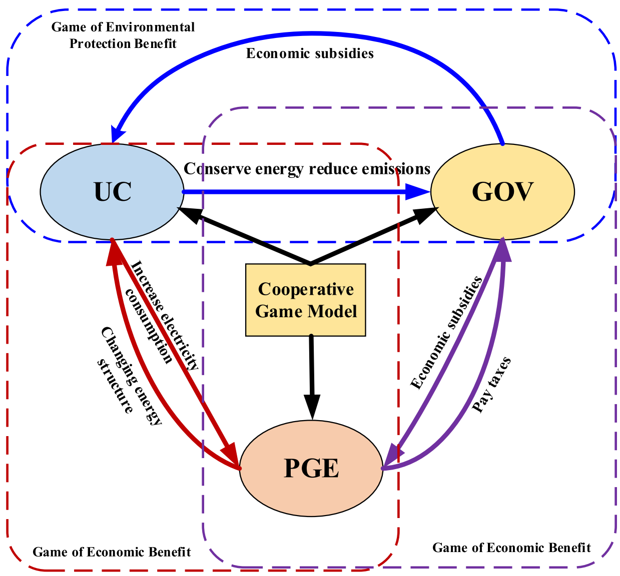

FIGURE 3. Benefit game in electric energy substitution project.

The game pattern of government, PGE and UC should be in a cooperative state. From the point of view of information exchange, cooperative game shows that all participants understand each other's objective function. From the perspective of game benefit, the game points between UC and government focus on environmental benefits, while the game points between PGE and UC, PGE and government focus on economic benefits. Only by objectively analyzing the benefit contradiction of electric energy substitution for each participant can we effectively coordinate the benefit distribution of each game subject and fully tap the potential of electric energy substitution.

A. MODEL ASSUMPTIONS OF ELECTRIC POWER SUBSTITUTION

The electric energy substitution takes cooperative game as the background, and cooperative game emphasizes the rationalization of group decision-making, i.e. under the condition of dynamic information exchange and satisfying constraints, all participants can realize the reallocation of resources through cooperation to improve the overall efficiency. Therefore, cooperative game mainly studies how to optimize the allocation of resources, and through the solution of cooperative game and payment transfer to achieve global optimization [45]. The following assumptions are made according to the actual electric energy substitution projects:

Assumption 1: Electric energy substitution projects are carried out under the cooperative mode. The government, the PGE and UC form cooperative relationships to provide benefits for the society, while the private sector can also obtain reasonable profits.

Assumption 2: PGE and UC are self-interested, i.e. to maximize their own interests.

Assumption 3: Each batch of substituted users forms a consortium, which gives priority to maximizing cluster interests in the game process.

B. DECISIONS OF GAME PARTICIPANTS

The government makes decisions on subsidies. Their decision variables for the project are as follows:

Ω_{GOV} is a set of government decision variables, including UC's subsidy (S_{UC}) and PGE's subsidy (S_{PGE}). $S^t_{\mathrm{UC}\cdot k}$ is the government subsidy fee for each k-type substitution user in t-th year. k_{Lead}, k_{Nerural}, k_{Stubborn} represent lead users, neutral users and stubborn users respectively. S^t_{PGE} is the government's subsidy to PGE in t-th year. X_1 and X_2 are two kinds of subsidy fees.

$$\Omega_{GOV}\left\{\begin{array}{l} S_{UC}\left|\begin{array}{l} S_{UC}=\sum\limits_{t=1}^{n}\sum\limits_{k=1}^{3}S^t_{UC\cdot k},\ S^t_{UC\cdot k}\in X_1,\\ \forall t\in\{1,2,3\cdots n\},\\ k\in\{k_{Lead},k_{Netrual},k_{Stubborn}\}\end{array}\right.\\ S_{PGE}\left|\begin{array}{l} S_{PGE}=\sum\limits_{t=1}^{n}\sum\limits_{k=1}^{3}S^t_{PGE},\ S^t_{PGE}\in X_2,\\ \quad\forall t\in\{1,2,3\cdots n\}\end{array}\right.\end{array}\right. \tag{4}$$

The UC constructs its set of decision variables as follows:

$$\Omega_{UC}=\left\{q_{UC}\left|\begin{array}{l} q_{UC}=\sum\limits_{t=1}^{n}\sum\limits_{k=1}^{3}q^t_k,\ q^t_k\in X_3\\ \forall t\in\{1,2,3\cdots n\},\\ k\in\{k_{Lead},k_{Netrual},k_{Stubborn}\}\end{array}\right.\right\} \tag{5}$$

Ω_{UC} is the set of decision variables of UC in electric energy substitution project, q_{UC} is the total number of UC, $q^{\mathrm{t}}_{\mathrm{k}}$ is the number of k-type users who accept substitution in the t-th year, and X_3 is the set of substitution users.

PGE makes decisions on electricity price in the project, and the decision set is constructed as follows:

$$\Omega_{PGE}=\left\{I_p\left|\begin{array}{l} I^t_{p\cdot k}\in X_4,\ \forall j\in\{1,2,3\cdots n\}\\ \forall t\in\{1,2,3\cdots n\},\\ k\in\{k_{Lead},k_{Netrual},k_{Stubborn}\}\end{array}\right.\right\} \tag{6}$$

Ω_{PGE} is a set of decision variables for PGE in the electric energy substitution project. The decision variables are electricity price (I_{P}). $I^{\mathrm{t}}_{\mathrm{P}\cdot k}$ is the fee charged by PGE to k-type substitution users in the t-th year, and X_4 is the price set.

C. GAME MODEL OF ELECTRIC ENERGY SUBSTITUTION BENEFIT

Quantifying the benefits of each participant is the key to the game model. Based on the actual electric energy substitution project, this paper pays attention to the income and cost of each participant in the game, and considers the discount rate of funds and the operation cycle of the project, we take the tobacco industry as an example to model. By analyzing and observing the decision variables of each participant in the game, the problem is summed up as a mixed integer programming problem (MILP) [46], and the following game model is constructed.

■ The revenue function and constraints of government

$$\text{Max } F_{GOV}=E_{carbon}-S_{UC}-S_{PGE}+\Delta R_{tax} \tag{7a}$$

$$E_{carbon}=P_{ETS}\sum_{t=n}^{n}\sum_{k}^{k=3}(q^t_kL^t_{carbon\cdot k}),\quad n=1,2,3,4,5 \tag{7b}$$

$$S_{UC}=\sum_{t=n}^{n}\sum_{k}^{k=3}(\omega_{PI\cdot k}q^t_kS^t_{UC\cdot k}),\quad n=1,2,3,4,5 \tag{7c}$$

$$S_{PGE}=\xi\sum_{t=1}^{n}S_{PGE\cdot t},\quad n=1,2,3,4,5 \tag{7d}$$

The government's objective function is formula 7a. F_{GOV} is composed of four parts (E_{carbon}, S_{UC}, S_{PGE}, ΔR_{tax}). E_{carbon} is the government's carbon income, the reduction of carbon emissions by users is converted into economic benefits. P_{ETS} is the carbon price under Emission Trading Scheme (ETS) [47]. $L^t_{\mathrm{carbon}\cdot k}$ is the reduction of carbon emissions by k-type users in the t-th year. S_{UC} is the government's total subsidy expenditure to users during the project cycle to compensate for the cost of purchasing energy equipment when users change their energy use patterns. $S^t_{\mathrm{UC}\cdot k}$ is the subsidy cost to k-type users in the t-th year; $\omega_{\mathrm{PI}\cdot k}$ is the psychological willingness coefficient of k-type users to the project, the lower its value is, indicating that the more enthusiastic such users are to participate in the project, and it same as ω_k of this paper section 2.

$$\Delta R_{tax} = \Delta R_{power}^{tax} + \Delta R_{production}^{tax} \tag{7e}$$

$$\Delta R_{power}^{tax} = \mu_{power}^{tax} \sum_{t=n}^{n} \sum_{k}^{k=3} (q_k^t I_{p\cdot k}^t) \tag{7f}$$

$$\Delta R_{production}^{tax} = \sigma_{production\cdot i}^{tax} (R' - R) \sum_{t=n}^{n} \sum_{k}^{k=3} (q_k^t \Delta M^t) \tag{7g}$$

Formula (7e)-(7g) denotes the change of tax revenue caused by the change of energy use. ΔR_{tax} is the total change of tax revenue. It includes the increment of electric energy tax ($\Delta R_{\text{power}}^{\text{tax}}$) and the increment of product tax ($\Delta R_{\text{production}}^{\text{tax}}$). $\mu_{\text{power}}^{\text{tax}}$ is the tax payment rate of PGE. $\sigma_{\text{production}}^{\text{tax}}$ is the tax rate of flue-cured tobacco levied by the government on tobacco farmers [48], ΔM^{t} is the annual incremental yield of flue-cured Tobacco. For the annual increase of the output of flue-cured tobacco, R' the price per unit mass of electric flue-cured tobacco (¥/kg), and R is the price per unit mass of coal flue-cured tobacco (¥/kg).

Formula (8a-8c) is the constraints of equality and inequality in government objective function:

$$\begin{aligned} &\textit{subject to}: S_{PGE} \\ &= (\Gamma \pm \Delta\Gamma)\xi \sum_{t=1}^{n} S_{PGE\cdot t}, \quad n = 1, 2, 3, 4, 5 \end{aligned} \tag{8a}$$

$$S_{UC\cdot k}^t \geq 0,\ S_{UC\cdot k}^t \text{ is integer variables.} \tag{8b}$$

$$S_{UC\cdot k}^t = \Gamma \pm \Delta\Gamma \times C_{equ} \tag{8c}$$

Formula (8a) is the equation constraint of distribution network transformation subsidy. Γ is the benchmark subsidy ratio for distribution network transformation and $\Delta\Gamma$ is the floating ratio based on Γ. Formula (8b) is the integer constraint of subsidy cost. C_{equ} is the equipment cost when using other energy converts to use electric energy. Formula (8c) is the equation constraint of subsidy when users change the type of using energy.

■ The revenue function and constraints of UC

$$\text{Max } F_{UC} = E_{income} + S_{UC} - C_{COST}^{power} - C_{UC}^{equ} \tag{9a}$$

$$E_{income} = (R' - R) \sum_{t=1}^{n} \sum_{k}^{k=3} (q_k^t \Delta M^t)$$

$$\Delta M^t = M' - M, \quad n = 1, 2, 3, 4, 5 \tag{9b}$$

$$C_{COST}^{power} = \frac{Q_i}{M'} \sum_{t=1}^{n} \sum_{k}^{k=3} I_{p\cdot k\cdot t} q_k^t, \quad n = 1, 2, 3, 4, 5 \tag{9c}$$

$$C_{UC}^{equ} = C_{equ} \sum_{t=1}^{n} \sum_{k}^{k=3} q_k^t, \quad n = 1, 2, 3, 4, 5 \tag{9d}$$

The objective function of UC (F_{UC}) is formula (9a), which includes four parts: E_{income} is output income, $C_{\text{COST}}^{\text{power}}$ is the cost of electricity consumption for the whole UC in the project cycle, $C_{\text{UC}}^{\text{equ}}$ is the total cost of equipment for the whole UC to bake tobacco leaves in electric oven, Q_i is the corresponding annual power consumption (kW·h) when the production quantity is M', M is the production quantity of using original energy.

$$\begin{aligned} &\text{subject to: } q_{k\cdot t} \geq 0 \\ &\text{and } q_{k\cdot t} \text{ is integer variables.} \end{aligned} \tag{10a}$$

$$C_{UC}^{equ} = C_{equ} \sum_{t=1}^{n} \sum_{k}^{k=3} q_k^t, \quad n = 1, 2, 3, 4, 5 \tag{10b}$$

$$q_{UC} = \sum_{t=1}^{n} \sum_{k}^{k=3} (q_k^t), \quad n = 1, 2, 3, 4, 5 \tag{10c}$$

$$q_{UC} = q_{k\in Lead} + q_{k\in Netrual} + q_{k\in Stubborn} \tag{10d}$$

$$q_{Lead} = \sum_{t=1}^{n} q_{k\in Lead}^t, \quad n = 1, 2, 3, 4, 5 \tag{10e}$$

$$q_{Netrual} = \sum_{t=1}^{n} q_{k\in Netrual}^t, \quad n = 1, 2, 3, 4, 5 \tag{10f}$$

$$q_{Stubborn} = \sum_{t=1}^{n} q_{k\in Lead}^t, \quad n = 1, 2, 3, 4, 5 \tag{10g}$$

Formula (10a-10g) is the constraints of equality and inequality in the objective function of UC. Formula (10a) is the integer constraint of the number of users participating in the project every year. Formula (10b) is the equality constraint of the total number of UC. Formula (10c-10g) is the equality constraint of different types of users.

■ The revenue function and constraints of PGE

$$\text{Max } F_{PGE} = R_{GRID} + S_{PGE} - C_{GRID}^{COST} - \Delta R_{power}^{tax} \tag{11a}$$

$$R_{GRID} = C_{COST}^{power} \tag{11b}$$

$$C_{GRID}^{COST} = C_{line\cdot tra}^{new} + C_{\cos t}^{operation} \tag{11c}$$

As shown in (11a), the objective function of PGE (F_{PGE}) is composed of four parts. R_{GRID} is the revenue from the increase of electricity consumption, which is equal to the $C_{\text{COST}}^{\text{power}}$ of the UC, S_{PGE} is the total subsidy cost of distribution network transformation, C_{GRID}^{COST} is the construction and operation cost of distribution network transformation, and the definition of $\Delta R_{\text{power}}^{\text{tax}}$ is same as (7f).

$$C_{\text{line}\cdot\text{trans}}^{\text{new}} = (P/F, r, t-1)(\sum_{x=1}^{N_L} \text{c}_x l_x + \sum_{s=1}^{N_{\text{tra}}} \text{c}_s)$$

$$(P/F, r, t-1) = (1+r)^{-t} \tag{11d}$$

$$\begin{aligned} C_{\cos t}^{operation} &= (P/F, r, t-1) \sum_{t=1}^{n} C_{\cos t\cdot t}^{repair}, \\ n &= 1, 2, 3, 4, 5 \end{aligned} \tag{11e}$$

In formula (11d), $C_{\text{line}\cdot\text{trans}}^{\text{new}}$ is the cost of new 10 kV, 0.4 kV lines and new transformers, $(P/F,\ r,\ t\text{-}1) = (1+r)^{-t}$ is the compound present value coefficient,c_x is the unit length of line construction cost (¥/km), l_x is the length of line x, and N_{l} is the number of new lines. c_s is the unit price of new transformer and N_{tra} is the total number of new transformers. $C^{\text{repair}}_{\text{cost}\cdot t}$ is the operation and maintenance cost of the distribution network covered by the UC in the t-th year.

$$\text{subject to: } 0 \le I^{t}_{\text{p}\cdot k} \le I_{\text{p max}} \quad \text{and } I^{t}_{\text{p}\cdot k} \text{ is non-integer variables} \tag{12a}$$

$$N_L \le N_{L\cdot\max}, N_L = \sum_{g=1}^{m} N_g, \forall g \in \Omega^+ \tag{12b}$$

$$N_{\text{tra}} \le N_{tra\cdot\max}, N_{tra} = \sum_{v=1}^{z} N_v, \quad \forall v \in \Pi^+ \tag{12c}$$

$$C^{repair}_{\cos t\cdot t\cdot base} \le C^{repair}_{\cos t\cdot t} \le C^{repair}_{\cos t\cdot t\cdot \max} \tag{12d}$$

Formula (12a)-(12d) constraints for PGE, Formula (12a) denotes that the decision variable price of PGE is a non-integer variable, and Formula (12b) shows that N_g is the number of 10kV lines to be built in the distribution area g, while the number of distribution areas to be reconstructed in this area is m, Ω^+ is a set of newly added lines. N_v is the number of new lines to be built in the distribution area v. The number of transformers is z, Π^+ is a new set of transformers, moreover, line operation and maintenance costs must be higher than benchmark maintenance costs ($C^{\text{repair}}_{\text{cost}\cdot t\cdot\text{base}}$), but it is not be higher than the upper limit of the maximum maintenance cost ($C^{\text{repair}}_{\text{cost}\cdot t\cdot\text{base}}$).

The final decision variables of the three game participants will determine the benefit allocation of the project.

$$\underset{GOV,UC,PGE}{MAX\ \arg} \begin{cases} P^*_{GOV} = \underset{GOV}{\arg\max}(S^*_{UC}, S^*_{PGE}, q_{UC}, I_p) \\ P^*_{UC} = \underset{UC}{\arg\max}(S_{UC}, S_{PGE}, q^*_{UC}, I_p) \\ P^*_{PGE} = \underset{PGE}{\arg\max}(S_{UC}, S_{PGE}, q_{UC}, I^*_p) \end{cases} \tag{13}$$

In formula (13), the government, UC and PGE make decisions on their respective decision-making quantities and then get the balanced strategy of maximizing the tripartite revenue. Max arg () is a set of variables that maximize the value of the tripartite income function. All equality and inequality constraints must be satisfied for the above optimal equilibrium strategies.

IV. SOLUTION OF GAME MODEL OF ELECTRIC ENERGY SUBSTITUTION BENEFIT

Based on the above analysis of the game pattern of electric energy substitution projects, the game problem is summed up as a multi-objective optimization problem. At present, the main algorithms for solving multi-objective problems are MOEA [51], SPEA [52], NSGA-II [41], NSGA-III [42], [43]. Deb proposed NSGA-III with reference point selection strategy in 2014. However, the algorithm uses predefined structured reference point set and lacks preference information, which often leads to premature solution space harvest when dealing with practical optimization problems. So we design a PNSGA-III algorithm as shown in the Figure 4:

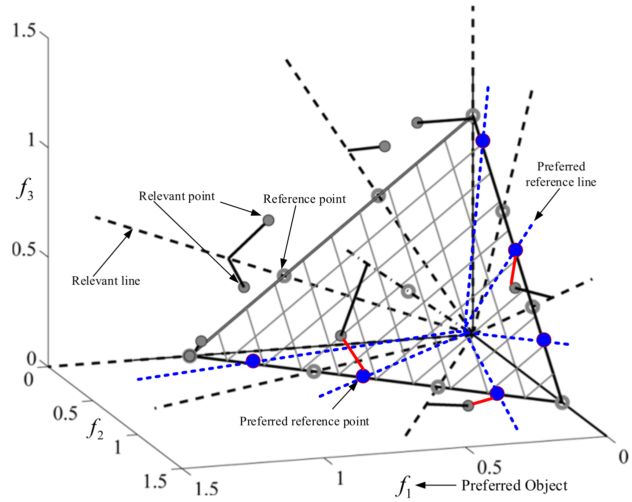

FIGURE 4. Relevant selection with preferences.

Figure 4 is based on the distribution of s in the target space. After adaptive normalization of each target, it is necessary to associate the individual population with each reference point. In order to realize the association between individual population and reference point, reference line is defined here, i.e. in the hyperplane, the line formed by connecting reference point and coordinate origin becomes the reference line of each reference point. Then the vertical distances between the individual and the reference line in population s are calculated. Individuals with the smallest vertical distance from the reference line in the hyperplane are associated to the corresponding reference points. Suppose we have a one-level preference for Goal 3, then we add a preference reference point between each original reference point in the direction of f_3, i.e. the blue point in the Figure 4. We can see that some of the relevant points will be re-connected to the new reference line, i.e. the red line representation. The two-level preference needs to be added reference point between the reference points of the one-level preference. Three to N-level preferences operate on the same principle.

The more the preference points increase, the stronger the relevance of the direction of the target. In practical problems such as uneven distribution of benefits of one party or artificial need to take care of one participant's benefits when the objective function conflicts, the search of solution space is guided from the level of algorithm. In this paper, in the game of electric energy substitution, because PGE will invest more funds, the objective function of the relevancy selection is preferred to PGE, with one-level preference.

V. CASE STUDY

In this paper, the tobacco industry in Kunming, Baoshan and Wenshan, Yunnan Province, China, is taken as an example. Firstly, the tobacco farmers are planned to connect to the distribution network. On the basis of obtaining the distribution network planning data, the Pareto plane is found by

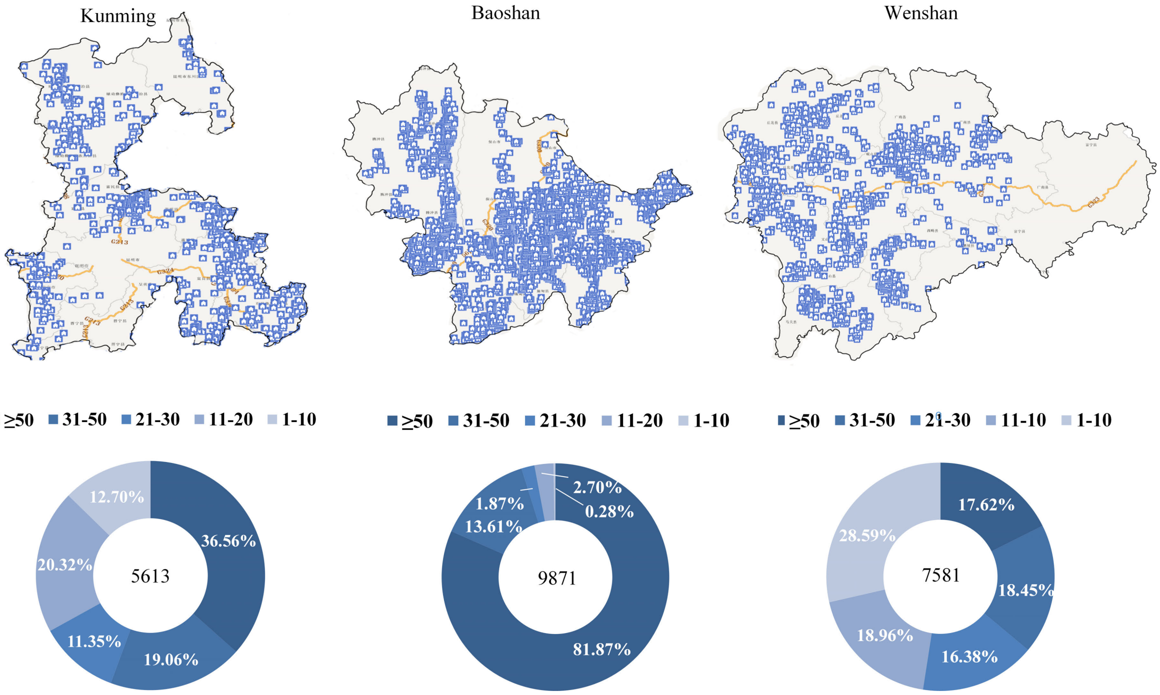

FIGURE 5. Density of tobacco barns in Kunming, Baoshan, and Wenshan areas.

PNSGA-III algorithm, and the optimal tripartite strategy is obtained under Nash equilibrium. To analyze the benefits of government, UC (This refers to the cluster of tobacco farmers) and PGE participating in such projects more concretely, the benefit evaluation indicators are proposed for different participants. Relevant data and questionnaire results of user types in three areas are given in the appendix Table 8 and Table 9.

A. DISTRIBUTION NETWORK PLANNING ANALYSIS

In order to obtain the complete distribution network data of the three areas, we use the GIS system of the PGE and the GPS information of the flue-cured tobacco barn to connect. According to the following steps, we can count the distribution network planning data of the three areas.

i. By using the flue-cured tobacco geographic information system of China Tobacco Yunnan Company, the flue-cured tobacco barns which are not connected to 10 kV lines at present are screened out, and the GPS data of this part of the flue-cured tobacco barns are imported into the power grid GIS system.

ii. Use the power grid GIS system to find out the 10 kV transformer nearest to each flue-cured tobacco barn, so that each flue-cured tobacco barn is connected with the 10 kV transformer of the power grid.

iii. Calculate the length of 10 kV and 0.4 kV lines that need to be added in a certain area.

$$L_{\mathrm{n}} = \sum_{v=1}^{g} l_{v\cdot s} \tag{14}$$

In formula (14), L_{n} adds 10 kV line length, v is the v-th flue-cured tobacco barn, g is the number of flue-cured tobacco barns connected to 10 kV line, and $l_{v\cdot s}$ represents the new line length of flue-cured tobacco barn v from transformer s. The length of the new 0.4kV transmission line is calculated according to the average of about 20m per flue-cured tobacco barn.

Figure 5 reflects the density of flue-cured tobacco barns in Kunming, Baoshan and Wenshan, which have not yet been connected to the 10kV distribution network. Simultaneously, the ratio of five types of users to all users in this area is counted. The distribution of flue-cured tobacco barns in Baoshan is very concentrated, 81.87% of which are located in the distribution network area, the number of flue-cured tobacco barns is more than 50, only 0.28% of flue-cured tobacco is distributed in the distribution network area with less than 10. The distribution of flue-cured tobacco barns in Wenshan is relatively scattered, and only 17.62% of the barns are located in more than 50 barns in the distribution network area. Distribution density of flue-cured tobacco barns in three areas is different, and different density will affect the next distribution network planning.

It can be seen from the Table 3 that although the total number of flue-cured tobacco barns in Baoshan is large, in fact, there are not many flue-cured tobacco barns that need to be connected to 10 kV. The length of new 10 kV and 0.4 kV lines in Baoshan is relatively short, and the number of new transformers is the least. Although the number of flue-cured tobacco barns in Wenshan is less than that in Baoshan, the density of flue-cured tobacco barns in this area

TABLE 3. Distribution network planning of Tobacco barns in three areas of Yunnan province.

Item	New 0.4 kV Line Length (km)	New Number of Transformers	New 10 kV Line Length (km)	Number of Tobacco Barns Unconnected to 10 kV	Number of Tobacco Barns
Kunming	112.26	1113	1075.93	5613	16018
Baoshan	197.42	748	232.69	9871	32139
Wenshan	151.62	1673	1689.12	7581	27180

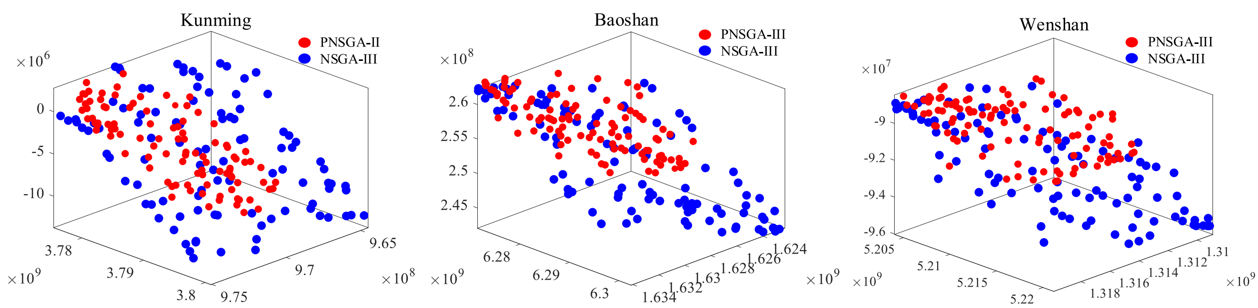

FIGURE 6. Pareto plane.

is low. Therefore, the number of new transformers needed in this area is as high as 1673, and the length of new 10 kV and 0.4 kV lines totals 1840.74 km. It can be seen that the transformation of distribution network in Wenshan requires a relatively large investment. The cost of distribution network transformation in Kunming is medium, and the number of flue-cured tobacco barns in Kunming is the smallest among the three areas.

B. NASH EQUILIBRIUM ANALYSIS

On the basis of the mathematical model of electric energy substitution established in section III, the game model is solved by NSGA-III and PNSGA-III algorithms. The two algorithms generate 100 populations at the same time and iterate 500 times. The Pareto of the three areas is shown as Figure 6:

In Figure 6, f_1, f_2 and f_3 represent the objective functions of the government, the UC and the PGE respectively. There are conflicts among the benefits of the three participants on the Pareto plane. None of the non-dominated solutions can satisfy the requirements of maximizing the benefits of the three parties at the same time. Compared with NSGA-III, PNSGA-III has a preference for the objective function of PGE by introducing preferential association selection, so the distribution of non-dominant solutions in space is more concentrated. Especially in Kunming and Wenshan, both the local PGE are in loss. However, because of the preference association operation of PNSGA-III algorithm, more non-dominant solutions are searched in solution space, which make the loss of PGE smaller. Obviously, these solutions have more practical value to guide the decision-making of all participants, and at the same time, they maintain better diversity. It can be seen that PNSGA-III has better optimization effect than NSGA-III.

C. OPTIMAL STRATEGY

Finding an exact solution on the Pareto is very essential for the participants, so Nash equilibrium solutions need to be screened out, i.e. the optimal compromise solution. We use PNSGA-III algorithm to obtain the following optimal strategies:

In Table 4, the optimal strategy of flue-cured tobacco UC listed by area, type of UC and time. The optimal solution satisfies the constraints of the number of UC (the proportion of different types of users in different areas). To optimize the benefits of all participants, we suggest that the number of UC per year should not be generalized, but be precise to a single digit, which will achieve better benefits for all participants in the game. In terms of time planning, it is enough to ensure that all types of users can be replaced in the project cycle. However, if the number of substituted users varies greatly in different years, for example, the number of substituted users is too large in a certain year, which results in a huge amount of work for the distribution network transformation in that year, and causes a large workload for the PGE. This kind of strategy is not desirable, so we need to reconsider the optimization strategy.

TABLE 4. **Optimal strategy of UC.**

	Lead Number of Tobacco Barns (n/year)			Neutral Number of Tobacco Barns (n/year)			Stubborn Number of Tobacco Barns (n/year)		
	1^{st}	2^{nd}	3^{rd}	1^{st}	2^{nd}	3^{rd}	1^{st}	2^{nd}	3^{rd}
Kunming	3000	666	507	2996	2830	502	2970	2043	504
Baoshan	3858	3951	3695	3890	3701	3332	3846	3866	2000
Wenshan	3810	3327	2719	2541	2555	3512	3676	2540	2500

TABLE 5. **Optimal strategy of government.**

	Lead Carbon Subsidies (¥/ barn·year)			Neutral Carbon Subsidies (¥/ barn·year)			Stubborn Carbon Subsidies (¥/ barn·year)			Distribution Subsidies (¥/ year)		
	1^{st}	2^{nd}	3^{rd}	1^{st}	2^{nd}	3^{rd}r	1^{st}	2^{nd}	3^{rd}	1^{st} r	2^{nd}	3^{rd}
Kunming	6530	6786	6769	8040	8864	8502	10073	10000	10995	7719083	8812817	10000000
Baoshan	6956	6697	6317	8716	8895	8257	10907	10798	10773	533629	2099271	6000000
Wenshan	6450	6515	6629	8849	8707	8891	10385	10260	10160	19082148	17105062	15000000

TABLE 6. **Optimal strategy of PGE.**

	Lead Electricity Price (¥/ kw·h)			Neutral Electricity Price (¥/ kw·h)			Stubborn Electricity Price (¥/ kw·h)		
	1^{st}	2^{nd}	3^{rd}	1^{st}	2^{nd}	3^{rd}	1^{st}	2^{nd}	3^{rd}
Kunming	0.3960	0.3749	0.3884	0.4460	0.43822	0.4128	0.5292	0.5494	0.4510
Baoshan	0.3733	0.3605	0.3970	0.4337	0.4469	0.4389	0.5499	0.4778	0.5361
Wenshan	0.4087	0.3855	0.3968	0.4722	0.4750	0.4800	0.5382	0.5497	0.5625

The Table 5 gives the optimal strategies of three local governments:

There are two main types of government decision variables: carbon subsidies and distribution network subsidies. As for carbon subsidy, the cost of carbon subsidy does not need to be too high for Lead-type tobacco farmers. Such users are willing to participate in the project. In the three-year project cycle, the cost of carbon subsidy for lead tobacco farmer in all three areas is less than 7,000 ¥per year, for Neutral-type tobacco farmers, the cost of carbon subsidy is between 8,000 and 9,000 ¥per year. Stubborn users are reluctant to accept electric energy substitution and need higher carbon subsidy fees to attract them to participate in the project. In the three areas, the same types of users have little difference in the cost of carbon subsidies. In terms of distribution network subsidy, Baoshan district has the lowest cost of distribution network transformation and the lowest corresponding optimal cost of distribution network subsidy. However, Wenshan district government needs to give higher subsidy cost to local PGE, because the cost of distribution network transformation will be high.

The Table 6 gives the optimal strategies of three local PGE:

Electricity price charged by PGE for three types of UC should be cascaded. By solving the game model, the feasibility of cascaded electricity price in the game is confirmed. For Lead users, their participation in electric energy substitution is high. The corresponding PGE should lower the price charged to them, but for stubborn users, they should adopt the strategy of increasing electricity price to respond to their low enthusiasm of participating in electric energy substitution. Among Lead users and neutral users, the fluctuation range of electricity price charged by PGE is not too large, while for stubborn users, PGE can bid in a larger range. In different areas, there are also differences in electricity prices. Difference between Kunming and Baoshan is not big, while Wenshan charges users higher electricity prices. It can be seen that the level of distribution network costs will also lead to fluctuations in electricity prices.

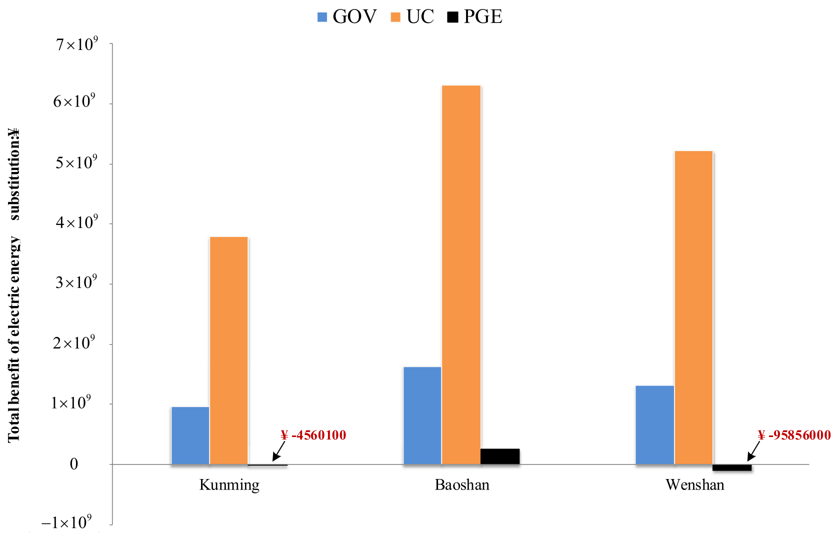

FIGURE 7. The revenue of participants in three areas.

D. BENEFIT ANALYSIS OF OPTIMAL SOLUTION

We get the optimal strategy through the PNSGA-III algorithm. This section will analyze the revenue of the government, tobacco farmers and PGE under the optimal compromise solution. After the project cycle is over, the cumulative total revenue of the three participants shown as Figure 7:

As can be seen from Figure 7, the benefits of the three participants are quite different in different areas when the flue-cured tobacco project of replacing coal with electricity is carried out. The cumulative total revenue of government and tobacco farmers in the project cycle is positive in all three areas. Only the total income of PGE in Baoshan is positive, and the PGE in Wenshan and Kunming areas are in a loss state. Among them, the loss of PGE in Wenshan area is larger in the project cycle. The fundamental reason is that the distribution of flue-cured tobacco barns in Wenshan area is dispersed, which greatly increases the cost of distribution network transformation. While in Kunming area, the number of tobacco farmers is less than that of other two areas, and the new electricity generated by substituting users is not enough to support the PGE to recover the cost of distribution network transformation, so the PGE in Kunming also suffer a slight loss.

In order to further analyze the specific benefits of each participant in the project, we listed three indicators from the perspective of three participants: carbon repay rate, unit heat cost and distribution network cost recovery time.

1) THE CARBON REPAY RATE

For measuring the revenue of the government in the game, we define the carbon repay rate as an index to measure the profit of the government's carbon compensation behavior.

$$\rho = \frac{R_{carbon}^{\mathrm{tax}}}{C_{\mathrm{carbon}}^{\mathrm{cost}}} \times 100\%,$$
$$R_{\mathrm{carbon}}^{\mathrm{tax}} = \Delta R_{\mathrm{carbon}}^{\mathrm{tax\cdot elec}} + \Delta R_{\mathrm{carbon}}^{\mathrm{tax\cdot tocaboo}} \quad (15)$$

In formula (15), ρ is the carbon repay rate, $C_{\mathrm{carbon}}^{\mathrm{cost}}$ is all fee of carbon compensation, and $R_{\mathrm{carbon}}^{\mathrm{tax}}$ is the tax revenue from the project, which includes two parts: $R_{\mathrm{carbon}}^{\mathrm{tax\cdot elec}}$, $R_{\mathrm{carbon}}^{\mathrm{tax\cdot production}}$, $R_{\mathrm{carbon}}^{\mathrm{tax\cdot elec}}$ is tax of new electricity consumption, and $R_{\mathrm{carbon}}^{\mathrm{tax\cdot production}}$ is the tax, which comes from the increase in production that electricity replaces other energy.

In Figure 7, the three local governments are profitable in general, but in fact, to analyze whether the carbon compensation behavior of the three local governments is profitable, it needs to be measured according to the index of carbon repay rate, after the three local governments have made carbon compensation for tobacco farmers, the corresponding carbon repay rate is shown in Figure 8. In the process of carbon compensation, the governments of all three regions have not received 100% return. It can be seen that in the process of carbon compensation, the government has not been able to get full return. Considering that the electrical energy substitution project is still in the early stage of promotion, and other environmental benefits generated by electric energy substitution can not be converted into economic benefits, e.g. ammonia nitrogen compounds. So we

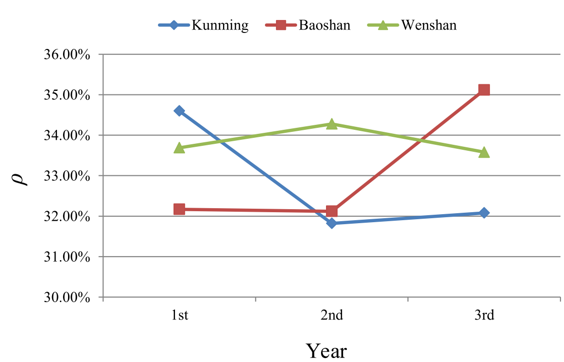

FIGURE 8. The carbon repay rate in three areas.

think it is reasonable that the government's carbon compensation behavior has a certain loss in the initial stage of the project.

The carbon repay rate of the three areas is all in the range of 30%-40%. However, the average carbon repay rate of Wenshan in three years is higher than those of the other two areas. The reason is that the average electricity price of Wenshan in three years is higher than that of the other two areas, which leads to tax growth and thus improves the carbon repay rate of Wenshan. Therefore, the government has a higher level of electricity price, carbon compensation in the area will get better benefits. The carbon repay rate of Baoshan shows an increasing trend, Wenshan area has a relatively stable carbon return rate, Kunming has a downward trend, resulting in fluctuations in carbon repay rate in different years due to fluctuations in annual electricity prices. Of course, carbon prices also have an important impact on carbon returns, but in order to ensure fairness, carbon prices are the same in the three areas.

2) THE UNIT HEAT COST

Lignite is the main coal used in flue-cured tobacco in Yunnan Province. The comprehensive efficiency of traditional flue-cured oven boilers is 0.8, the yield is 0.9, and the average coal consumption is 2.5 kg/kg (dry tobacco). The corresponding calorific value of coal combustion can be calculated to be about 13600 kJ/kg. According to calorific value conversion, the lignite is about 0.37 tons of standard coal per ton, and the price of lignite in Kunming, Baoshan and Wenshan is given in appendix Table 8. Based on the relevant data and game results, we calculate the average electricity price in three areas, and calculate the unit heat cost of coal-fired tobacco and electric-fired tobacco in three areas, which is expressed as Figure 9:

Under the same production capacity, the unit heat cost of coal-fired tobacco is about 100 times higher than that of electric-fired tobacco. It can be seen that the cost of coal-fired tobacco is too high. The basic reason is that the heat loss released after coal combustion is serious in the process of roasting tobacco. The heat of roasted tobacco leaves only accounts for a small part of the heat released by coal combustion. Utilization rate is extremely low, while the electric flue-cured tobacco has a very high heat utilization rate, most of the heat is used for flue-cured tobacco, so the heat loss is less. In three areas, for coal flue-cured tobacco, the change trend of unit heat cost is similar to that of coal price. After using electric flue-cured tobacco, the unit heat cost of electric flue-cured tobacco is higher than that of the other two areas in Wenshan, where the distribution network investment is larger than that of electric flue-cured tobacco. For users, the index of unit heat cost can effectively compare and analyze the difference of economic cost between the two energy consumption modes, and help users understand more intuitively the efficiency and economy of using electric energy.

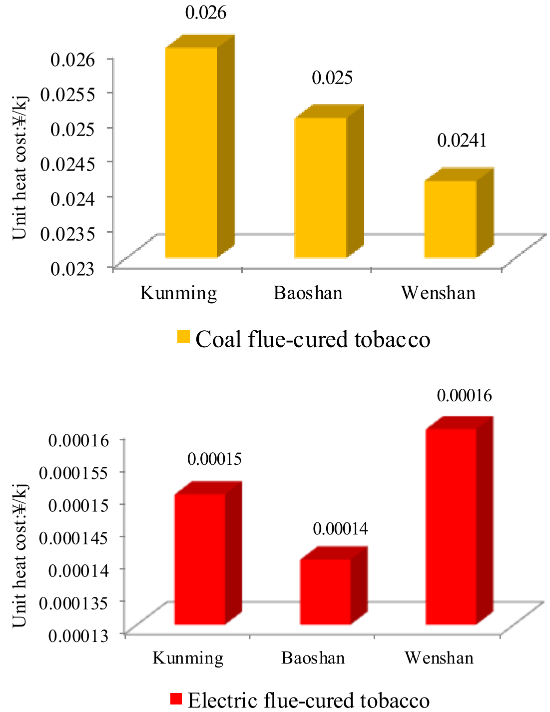

FIGURE 9. Unit heat cost of coal-fired tobacco and electric-fired tobacco.

3) THE DISTRIBUTION NETWORK COST RECOVERY TIME

In Figure 10, only Baoshan recovered the cost of distribution network transformation and realized profit in the project cycle. The project invested high cost in the stage of distribution network transformation, while the PGE concerned about how long they would take to recover the cost of transformation.

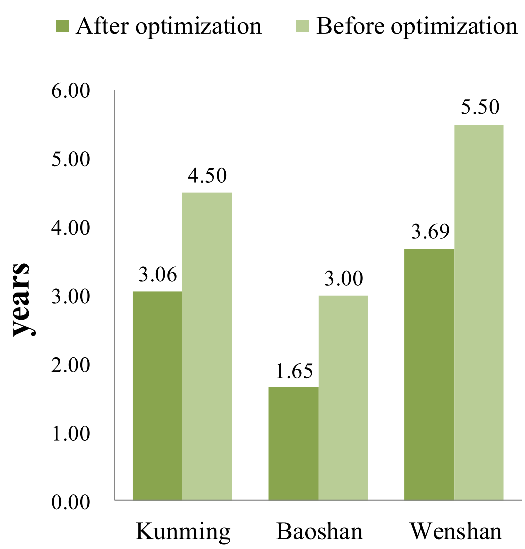

FIGURE 10. Distribution network cost recovery time.

After game optimization, compared with the forecast of the Yunnan PGE, the cost recovery time of distribution network in three areas is obviously shortened. Baoshan recovers the cost of distribution network transformation within half of the estimated time of PGE. PGE in Kunming and Wenshan can not recover the cost of distribution network transformation within three years, but in the first year after the completion of the project, the PGE in Wenshan and Kunming can achieve profits. It is worth noting that although the cost of distribution network transformation in Wenshan is high, compared with Kunming, it can also make profits in the fourth year, and the profits of the PGE in Wenshan will be much higher than that in Kunming every year after that. After all the tobacco farmers are using electricity, the new electricity consumption in Kunming is about 190 million kW·h/year, while that in Wenshan is about 320 million kW·h/year. It can be seen that the number of users has played a dual role in the income of PGE. On the one hand, it causes the cost of distribution network transformation to rise, the cost recovery period to extend, On the other hand, after cost recovery, new electricity consumption increases sharply, which brings considerable profits to the PGE.

VI. DISCUSSION OF EMISSION REDUCTION

A. BENEFITS OF ATMOSPHERIC EMISSION REDUCTION

In the electric energy substitution project, when tobacco farmers used coal to bake tobacco, carbon emission is the main emission reduction index, but in this process, some other atmospheric pollutants cannot be converted into economic benefits, but it should not be ignored.

We collected lignite used by tobacco farmers in three areas. Through the analysis of the components of coal samples, we found that there was little difference in the composition of lignite in the three areas. The main components of lignite are shown in the appendix Table 10.

As shown in Figure 11, from the point of view of atmospheric pollution, the electric energy substitution will effectively reduce the emissions of greenhouse gases e.g., CH_4 and N_2O [34], [35]. The important precursor of photochemical pollution, NO_X [36], also reduces emissions. At the same time, SO_2, the key reactive gas forming acid rain, also reduces

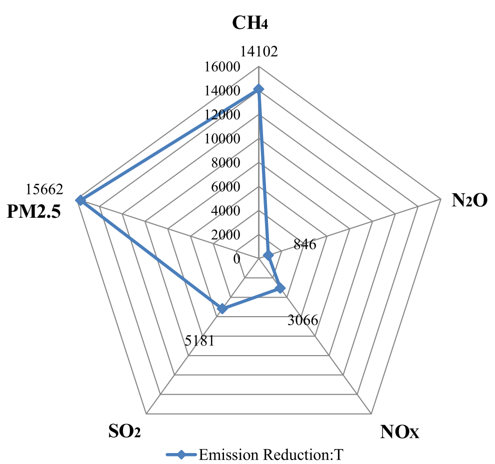

FIGURE 11. Emission reduction of air pollution.

emissions greatly [39]. In addition, the emission reduction of PM2.5, the primary pollutant affecting atmospheric quality, is also very large. Another point of view is that the lignite used by tobacco farmers now does not use such purification measures as desulfurization [37], [40], denitrification [38], and dust removal, plus the large number of flue-cured tobacco farmers, the air pollution caused by burning coal to bake tobacco leaves every year can not be ignored.

B. BENEFITS OF HEAVY METAL EMISSION REDUCTION

About heavy metal pollution (see Figure 12 and Figure 13), the project will reduce Zn emissions very high, followed by As and Cd.

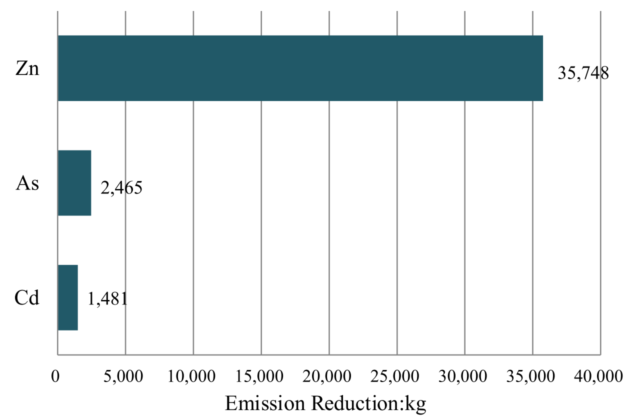

FIGURE 12. Emission reduction of heavy metal.

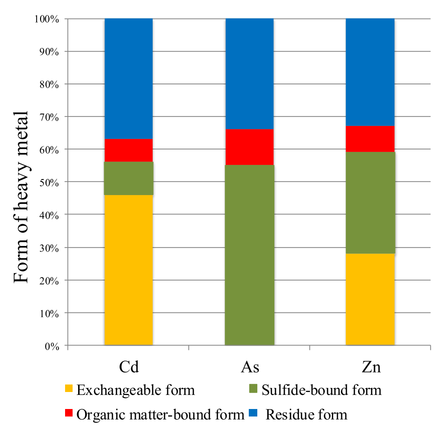

FIGURE 13. The form of heavy metal.

There are mainly four forms of heavy metals in coal: exchangeable form, sulfide-bound form, organic matter-bound form and residue form. It is generally believed that the exchangeable form has a high mobility in the ecosystem. Heavy metal elements in coal are also often found in sulfide-bound form and organic-bound form. The migration of these two forms is relatively small, the heavy metals in the organic matter-bound form are more volatile during combustion, the heavy metals in the sulfide-bound form are decomposed at high temperature, and the heavy metals in the residual form are stable. Therefore, in order to solve the problem of

TABLE 7. User acceptance weight.

Weight	W_{Lead}	$W_{neutral}$	$W_{stubborn}$
Weight value: w_x	0.95	1	1.05

heavy metal pollution caused by electric energy substitution, the emission reduction brought by the change of energy use mode mainly comes from the exchange form of heavy metals, sulfide-bound form and organic matter-bound form. Residual form should not be included in emission reduction, because heavy metals in residual form are still concentrated in natural soils even if tobacco leaves are not baked by coal combustion. In other words, the emission reduction of heavy metals should not be able to analyze the total amount of heavy metals in coal, but should consider the amount of heavy metals migration caused by human use of energy, which will do harm to the environment.

VII. CONCLUSION

This research designs the actual development mechanism of electric energy substitution project. From the point of view of distribution network planning, we put forward the ‘‘user clusters phenomenon’’, and quantifiy the phenomenon as one of the evaluation indicators of the project. Meanwhile, we design liker scale to investigate the willingness of users to accept electric energy substitution. Three types of indicators correspond to different substitution. In addition, on the issue of government subsidy, targeted subsidy measures have been formulated for UC and PGE. These subsidy measures constitute closed-loop feedback, for providing reference for the government in formulating relevant subsidy standards and schemes.

This paper establishes an optimization model of electric energy substitution decision-making based on cooperative game theory, and abstracts this engineering problem into a multi-objective optimization problem with mixed integers. A preferential optimization algorithm (PNSGA-III) is proposed to solve this problem. Nash analysis was performed on Pareto. The problem of finding the optimal compromise solution among many non-dominant solutions is solved.

In the case study, three areas of Yunnan Province in China, namely Kunming, Baoshan and Wenshan, are selected for the upcoming flue-cured tobacco project of replacing coal by electricity. Firstly, through the analysis of distribution network planning, the density geographically of UC directly affects the cost of distribution network transformation. Secondly, Nash equilibrium solution shows that UC need to accurately make sure the number of users participating in the project every year. According to the different objects of subsidy, there must be obvious difference between the two kinds of governments’ subsidy. Similarly, PGE should also charge different electricity prices for different types of users. In addition, PGE should raise the electricity price appropriately in areas with high cost of distribution network transformation.

This paper also defines three indicators: carbon return rate, unit heat cost and distribution network transformation recovery time. The three indicators reflect the specific benefits of the three participants. Moreover, the amount of pollutant emission reduction that cannot be quantified as economic benefits is also counted. The research shows that the flue-cured tobacco industry without environmental protection technology actually produces serious air pollution, which is of great environmental significance for the industry to carry out electric energy substitution. In the analysis of heavy metal emissions reduced by electric energy substitution, we should consider the amount of heavy metal migration caused by human use of energy, rather than the total heavy metal content of fossil fuels.

TABLE 8. Case data.

	ξ	Annual flue-cured tobacco output (T/year)	Cost of electric flue-cured tobacco oven (¥/station)	Price of coal-fired tobacco (¥/kg)	Price of electric flue-cured tobacco (¥/kg)	Lignite price (¥/T)	Distribution network maintenance costs (¥/year)	New 10 kV line cost (¥/km)	New 0.4kV line cost (¥/m)	New transformer cost (¥/tra)
Kunming	0.956	5.5	30000	15	25	650	300000	200000	50	40000
Baoshan	0.917	5.5	30000	15	25	625	400000	200000	50	40000
Wenshan	1.011	5.5	30000	15	25	600	500000	200000	50	40000

TABLE 9. Questionnaire results and factors of user types in three areas.

Item	Lead	neutral	stubborn	ω_k
Kunming	4173	6328	5517	1.008
Baoshan	11504	1093	9412	0.992
Wenshan	9856	8608	8716	0.995

TABLE 10. Composition and corresponding calorific value of lignite in Yunnan.

Component	%
Mar	37.47
Aar	11.91
Car	35.37
Har	2.39
Nar	0.84
Sar	1.76
Oar	10.23
As	2.38mg/kg
Cd	1.43 mg/kg
Zn	34.51 mg/kg
Low heat value (kJ/kg Qnet,ar)	13614.13

We hope attract attention of engineers, and help apply optimization theory in the project. Call for more countries and regions to use clean energy.

APPENDIX

$$\omega_k = \sum_{x=1}^{3} w_x \cdot m_x, m_x = \frac{m_x}{m},$$
$$m_x \in \{m_{Lead}, m_{Neutral}, m_{Stubborn}\} \tag{A1}$$

ωk is same as define of this paper, w_x is weight of x type, m_x is Percentage of x type users, m is total number of users, users are classified by acceptance, which includes lead, neutral and stubborn.

The value of $\sigma^{tax}_{production}$ is 0.2.

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