Optimal Benefit Strategy of Clean Energy Consumption Based on Transmission Channel Constraints

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Abstract. With the continuous development of social economy, energy and environmental issues deserve more and more attention. In order to improve the new energy’s consumption, this paper proposes an optimized social income strategy for clean energy consumption based on transmission channel constraints. The main method combines the method of cooperative game to maximize the value of social income, so as to determine the optimal combination of power generation, then taking into account the constraints of transmission channels and other issues, and then solving the problem of cross-regional clean energy trade with the goal of maximal social benefits. At the same time, the proceeds from the cooperative game can be distributed to each power transaction entity through the method of nuclear solution.

Keywords: Cooperative Game, Clean Energy Consumption, Double-Layer Model

1. Introduction

With the rapid development of the economy, the problems of energy shortage and environmental pressure are increasingly serious. Today, China has a long-standing problem of uneven distribution of energy resources. Clean energy resources are mainly distributed in northern, western China, while the high-power demand center is mainly concentrated in the central and eastern parts of the country. Therefore, through cross-provincial clean energy transactions, that is, a large amount of clean energy in western China will be transported to the provinces with high electricity consumption in the central and eastern regions. Not only can it improve the environmental pollution problem, but also reduce the abandonment of wind and light rate in a high proportion of clean energy provinces, and make full use of natural resources while promoting the economic development of these provinces.

In recent years, with the country's emphasis on clean energy consumption, research on the cross-regional transactional consumption of clean energy has made great progress. Literature [1-2] compares and analyses three models of European multinational power market: node pricing model, ATC model, FBMC model, it can be used for reference for the model mechanism of cross-provincial electricity market in China. Literature [3] studies particle swarm optimization (PSO) algorithm in constrained optimization problems. Literature [4] studies a generic algorithm based on Ant Colony
Optimization to solve multi-objective optimization problems. Literature [5] studies the problems of photovoltaic generators in a power distribution network. Literature [6] studies multi-terminal alternating current and direct current hybrid transmission technology in the integration and transmission of large-scale wind power. Literature [7] studies the integration of wind power generators with the power grid, and the enhancement of profit by means of optimal allocation of SVC. Literature [8] studies the energy storage deployment and innovation in clean energy transition. Literature [9] explores the future of transportation in sustainable clean energy. Literature [10] studies micro grids using renewable clean energy to help lower greenhouse gas emissions. Literature [11] studies the factors of the adjustment of the tie line plan and increases the consumption of new energy.

However, it is well known that one of the important features of the power system is that the power supply needs to meet the real-time balance, and the power cannot be stored in large quantities. None of the above articles has optimized the different combinations of purchasing and selling electricity. Therefore, according to the existing inter-regional energy demand problem, this paper proposes an optimized social income strategy model for clean energy consumption based on transmission channel constraints for the problem of large-scale clean energy consumption, aiming to promote more Clean energy and new energy power plants reach deals with users.

2. Cross-Regional Trading Entities and Trading Methods

In cross-regional transactions, the main players of the transaction include clean energy generation, grid companies and various power load users. In the inter-regional transaction process, the clean energy sellers generate electricity by selling different types of clean energy to obtain profits. The grid company obtains revenue through transmission and distribution, and the power load user pays the clean energy manufacturer the cost of purchasing electricity.

In this paper, it is proposed that the clean energy sales vendors declare the electricity and electricity prices to be sold at various times, and the power users declare the electricity purchases and electricity purchase prices at various times. When there are multiple clean energy sales vendors to trade with multiple power users, a combination of multiple transactions will be formed. According to the basic idea of cooperative game, this paper performs matching transaction calculation through the electricity and electricity price information provided by both parties. The purpose to be achieved is: The social gains obtained by the final determined transaction portfolio alliance are the highest. Finally, comprehensively calculating the transaction combination method corresponding to the largest comprehensive function value, so that while obtaining the maximum social benefits, it can also transform more electricity, that is, it is also more conducive to the reliability and safety of clean power grid connection.

According to the calculated function value of the comprehensive value, the best transaction combination method can be determined. Then, through the proceeds of the matching transaction obtained through the cooperative game, the distribution of the nucleophile of each transaction entity is carried out, and the gains of all parties are obtained. The schematic diagram of cross-region multi-subject transaction of clean energy is shown in Fig. 1.

Figure 1 Schematic diagram of multi-agent transaction of clean energy across regions
3. Cross-Regional Purchase and Sale Cooperation Game Trading Model

In order to study the purchase and sale of electricity by multi-party entities in electric energy trading, a cooperative game theory-based approach can be applied for modeling analysis. Due to the cross-provincial consumption to promote clean energy, there is a binding agreement between the parties involved in the multi-party transaction to be conducted. Therefore, it is possible to construct a cooperative game model between multiple types of purchase and sale parties. Then, a trading mechanism is designed to fully interact with the electricity purchaser and the electricity seller and finally determine the price of the electricity transaction and the number of transactions.

It is assumed that in the current clean energy power market transaction process, the electricity seller and the electricity purchase user are required to conduct transactions, and the respective power generation information is disclosed or disclosed to each other through the manager. Therefore, different electricity sellers and power purchase users can analyze in the energy trading by setting up a cooperative game model. In addition, since the additional income obtained by the cooperation can be distributed among the participants, it can also be called a payment-transferable cooperative game.

For cooperative games, the result is a kind of collaborative alliance. In the pursuit of maximizing individual interests, it also ensures that the overall interests are greatest. Using the idea of cooperative game, fully consider the possibility of combination matching between various clean energy power plants and various power users, and establish a transaction model between clean energy power plants and power users. In order to analyze the process of making a purchase and sale decision, a cooperative game model N can be constructed, which represents a limited set of total number of clean energy sellers and power users participating in the transaction.

3.1. Cooperative Game Optimization Model Based on Electricity Curve

3.1.1. Upper-Layer Optimal Purchase and Sale Combination Model

1) Objective function

The mathematical function model of the cross-region cooperation game is established as follows:

$$\max F = \sum_{i=1}^{h} U_i(w), i \in I$$

In the formula, since the combination method in the combination alliance should contain at least the two parties of the purchase and sale, and all transaction entities should be able to conduct transactions, the determination of the total number of possible combinations of the alliances in the model is determined by the permutation combination. Methods as below:

$$I = (C_1^1 + C_1^2 + \ldots + C_i^r) \times (C_j^1 + C_j^2 + \ldots + C_j^s) + C_i^r C_j^s$$

Where F is the objective function and it represents the value of the comprehensive adaptation function; w is expressed as a sub-group combination in the general league; \( U_i(w) \) represents the power usage gain function; h is the matching logarithm in the combination; \( r \) is the number of electricity purchasers participating in the general league \( N \); \( s \) is the number of sales quotients participating in the general league \( N' \); \( r/2, s/2 \) takes an integer greater than 0.

\( U(w) \) in the objective function represents the income function corresponding to the combined alliance w of different clean energy power producers and power users. The objective function of the cooperative alliance income in the form of a combined alliance of w is:

$$U(w) = \sum_{i=1}^{s/2} \sum_{j=1}^{s/2} \Delta P_{a,b,i,j} \cdot x_{a,b,i,j}$$

Where \( \Delta P_{a,b,i,j} = (q_{a,b,i} - q_{a,b,j}) \) is the condition that the transmission path is not considered,
Representing the difference in quotation between power load user $A$ (or clean energy power plant $A$) and clean energy power plant $B_j$ (or power load user $B_j$) during $t_i$ period, $q_{i,t,\alpha}$ is the purchase price of the electricity purchase node $k$ at time $t_i$; $q_{i,t,\beta}$ is the electricity price for the power plant node $l$ at the time $t_i$; $x_{s,t,i,j}$ represents the transaction power of the electric load user $A$ (or the clean energy power plant $A$) and the clean energy power plant $B_j$ (or the electric load user $B_j$) during the $t_i$ period; $x_{s,i,j}$ represents the amount of electricity demanded by the user $B_j$ (or the power generation amount of the clean energy power plant $B_j$) during the $t_i$ period; $B$ is a collection of $B_j$.

2) Constraints

a. Constraints of clean energy output and power user load power

\[
G_i^\text{max}(t) \leq G_i(t) \leq G_i^\text{min}(t)
\]  

(4)

\[
L_i^\text{max}(t) \leq L_i(t) \leq L_i^\text{min}(t)
\]

(5)

Equation (4) represents the upper and lower limits of the power output of the clean energy power plant. Where $G_i^\text{min}(t)$ represents the minimum power output value of a new energy power plant; $G_i^\text{max}(t)$ represents the maximum power output value of a new energy power plant; Equation (5) represents the upper and lower limits of the load of each power user. Where $L_i^\text{max}(t)$ represents the minimum power load of a power user; $L_i^\text{min}(t)$ represents the maximum power load of a power user;

b. Constraints on the trading power of the main body of the purchase and sale of electricity

\[
\sum_{s,\alpha} x_{s,t,i,j} \geq x_{s,i}
\]

(6)

\[
x_{s,t,i,j} \leq x_{s,i}
\]

(7)

The above formula (6) indicates that the amount of electricity traded by the market trading entity $A$ and the corresponding trading object cannot be less than its own maximum demand (or pre-sale) electricity; Equation (7) indicates that the transaction volume of the market transaction entity $B$ and the market transaction entity $A$ cannot be greater than the maximum pre-sale (or demand) power of $B_j$.

c. The quotation and quotation difference of the main body of the purchase and sale of electricity

\[
q_{i,t,\alpha} \leq q_{i,t,\beta} \leq q_{i,t,\alpha}
\]

(8)

\[
q_{i,t,\beta} \leq q_{i,t,\beta} \leq q_{i,t,\alpha}
\]

(9)

\[
\Delta P_{s,t,i,j} > 0
\]

(10)

Equation (8) indicates the upper and lower limits of the quoted price of clean energy power producers. $q_{i,t,\alpha}$ represents the minimum price of the electricity purchase user in a certain period of time, $q_{i,t,\beta}$ represents the maximum price of the electricity purchase user in a certain period of time; The upper and lower limits of the power user's quotation are expressed in equation (9), $q_{i,t,\beta}$ represents the minimum quoted price of a clean energy power producer for a certain period of time, $q_{i,t,\alpha}$ represents the maximum price quoted by a clean energy power producer for a certain period of time;
The constraint condition (10) indicates that the price of the electric load user in the two parties involved in the cross-regional clean energy transaction needs to be greater than the sum of the quotation of the clean energy power producer and the transmission line network loss, that is, the price difference is greater than zero.

3.1.2. The Lower Layer Function Considers the Cross-Region Path and Channel Constrained Transaction Model

1) Objective function

After determining the best purchase and sale of electricity trading portfolio through the aforementioned income function model, the mathematical function model considering the constrained transaction with cross-regional channel is established as follows:

\[
\max f(w) = \sum_{t \in T} \sum_{a,b} \Delta P_{a,b,t}^{w} x_{a,b,t}
\]

(11)

Where \( \Delta P_{a,b,t}^{w} = \sum_{q \in Q} (q_{a,t} - r_{a,b} - q_{b,t}) \) is the difference between the price of the electric load user \( A \) (or clean energy power plant \( A \)) and the clean energy power plant \( B_j \) (or the electric load user \( B_j \)) during the \( t \) period. Taking into account the transmission channel, \( q_{a,t} \) is the purchase price of the electricity purchase node \( k \) at time \( t \); \( r_{a,b} \) is the network loss discount of the transmission line \( (a,b) \); \( q_{b,t} \) is the electricity price of the electricity supplier's node \( l \) at the moment \( t \); \( x_{a,b,t} \) represents the transaction power of the electric load user \( A \) (or the clean energy power plant \( A \)) and the clean energy power plant \( B_j \) (or the electric load user \( B_j \)) during the \( t \) period; \( x_{a,b,t} \) represents the amount of electricity demanded by the user \( A \) of the electric load during the \( t \) period (or the amount of power that can be generated by the clean energy power plant \( A \)); \( x_{b,t} \) represents the amount of electricity demanded by the user \( B_j \) (or the power generation amount of the clean energy power plant \( B_j \)) during the \( t \) period; \( Q \) is a set of paths \( q \); \( B \) is a collection of \( B_j \).

2) Constraints

Except for the aforementioned constraint conditions (5) ~ (11), considering the physical constraints of the transmission path are:

\[
0 \leq x_{q,a,b} \leq X_{q,a,b}
\]

(12)

\[
X_{q,a,b} = r_{a,b} X_{q,a,b}
\]

(13)

Equation (12) represents the capacity constraints of the transmission channel. Where \( x_{q,a,b} \) represents the amount of electricity passing through the \( (a,b) \) line in the \( q \) path; \( X_{q,a,b} \) represents the upper limit of the amount of electricity passing through the \( (a,b) \) line segment in the \( q \) path; Equation (13) represents the line maintenance plan constraint, \( r_{a,b} \) indicates the maintenance factor. When the value is 1, it indicates that the line is not inspected. When it is 0, it indicates that the line is overhauled. Since the method considered here is mainly to optimize the transaction path problem, the DC network flow method is used for modeling, regardless of the voltage of the network node.

In summary, by calculating the feasible pairing methods in each combination, the alliance income \( U(w) \) is optimal, that is, the function \( F \) takes the largest value, then consider the transmission path constraint problem in the actual transmission, and calculate the optimal social benefit in the
cross-regional clean energy transaction problem, that is, the function of takes the largest value.

3.2. Income Distribution Based on Cooperative Game Kernel Solution

Through the comparative analysis of the above calculation results, the best pairing combination method can be obtained. Then the allocation of cooperative income should be considered. Since the solution to the cooperative game is always present and unique, the kernel method is used to distribute the cooperative income.

The idea of nucleophilic solution is to create a solution that maximizes the satisfaction of members of the alliance. At this point, the income distribution method $x^*$ is the nucleolus solution for this cooperative game. From the foregoing, $w$ is any subset of the union $N (n,v)$, and it can be known that the satisfaction degree of the obtained income distribution method $x$ is $e(w,x)$:

$$e(w,x) = V(w) - z(w)$$

(14)

Where $z$ is the sum of the actual gains of each participant in $w$. $V(w)$ is the expected benefit of the alliance $w$ participating in the cooperative game. It can be seen from the above formula that the transition vector $e(w,z)$ is the difference between the gain of the union $w$ participating in the cross-regional transaction and the sum of the gains available to each individual in the alliance. It can be used as a representation of the satisfaction of the union won the income distribution $z$, the smaller the value, the higher the satisfaction. The model based on the nucleolar solution is:

$$\text{min } e$$

(15)

$$s.t. V(w) - \sum_{i\in w} z_i - e \leq 0$$

(16)

$$V(N) - \sum_{i\in N} z_i = 0$$

(17)

$$z_i - V(N) \leq 0$$

(18)

Equation (15) represents the minimum dissatisfaction of the required objective function; Equation (16) represents a constraint that minimizes the maximum dissatisfaction value; Equation (17) indicates that the sum of the income distributions of all the transaction entities is the value of the cooperative income in the general alliance $N$; Equation (18) indicates that the distribution income of each subject $z_i$ should be less than the total revenue of the alliance.

4. Case Analysis

This paper uses the clean energy source based on transmission channel constraints to optimize the optimal social income strategy model. In the upper optimization algorithm, considering the social benefits of different combinations to comprehensively select the optimal combination; After the calculation of the upper layer function, the corresponding optimal purchase and sale power combination is transmitted to the lower layer mathematical function model containing the transmission path and the constraint, to calculate the solution considering the constraints of the transmission channel, at the same time, the maximum social income can be calculated and the distribution income and contract price of each transaction subject can be calculated.

It is now considered that a total of 5 market entities located in the eastern region of China and the southwestern region B will conduct electricity trading. The two power purchase users B1 and B2 in the east purchased clean electric energy from the three clean energy power plants A1, A2 and A3 in the west of China.

Table 1. Electricity and Electricity Price Information of Both Parties Involved in the Transaction
Purchase and Sale of Electricity and Electricity Price Information

| Time slot | Price ¥/kWh | Electricity kWh | Price ¥/kWh | Electricity kWh | Price ¥/kWh | Electricity kWh | Price ¥/kWh | Electricity kWh | Price ¥/kWh | Electricity kWh |
|-----------|-------------|----------------|-------------|----------------|-------------|----------------|-------------|----------------|-------------|----------------|
| 1         | 0.327       | 9580.999       | 0.297       | 4255           | 0.345       | 2254.353       | 0.441       | 6552           | 0.449       | 5067           |
| 2         | 0.301       | 9588.99        | 0.367       | 3674           | 0.345       | 2254.353       | 0.437       | 6562           | 0.449       | 5139           |
|           |             |                |             |                |             |                |             |                |             |                |
| 24        | 0.324       | 2516.147       | 0.278       | 3088           | 0.329       | 2817.941       | 0.414       | 6535           | 0.439       | 5244           |

(1) According to the transmission channel constraint-based clean energy consumption optimization model, we first obtained the optimal social income strategy to obtain the optimal purchase and sale combination.

The electricity price data to be input is shown in Tab 1. By writing a MATLAB program and calculating various feasible combinations, the feasible trading results are shown in Tab 2 below.

**Table 2.** Transaction results of various combinations of alliances

| Combined Alliance W | Portfolio Union Revenue \( V(W) \) (¥) | Abandoned Rate | Combined Union Function Value \( f(W) \) |
|---------------------|----------------------------------------|----------------|----------------------------------------|
|                     | Matching Income | Total Income | Matching Abandonment Rate | Average Abandonment Rate |
| (A1, B1)            | 12522.2        | 25511.0      | 0.20                        | 0.2                        | 37560.9       |
| (A2+A3, B2)         | 12988.8        |              | 0.19                        |                            |                |
| (A1, B2)            | 12971.5        | 26430.7      | 0.36                        | 0.18                       | 28469.7       |
| (A1+A2+A3, B1+B2)   | 26899.1        | 26899.1      | 0.20                        | 0.20                       | 14693.4       |

It is known from the comparison of the combined function values obtained by the above-mentioned final combination alliance, the composite function value comparison size: combination 1> combination 2> combination 3. Therefore, the combination 1 is determined to be the optimal combination of the transaction. And, compared with directly purchasing all the electricity purchasers and the seller, the mode of combination 1 (ie, the wind, the light or the water rate) is reduced.

**Figure 2.** Power curve image of the combination (a) A1 and B1 and (b) A2, A3 and B1
Fig 2(a) ~ Fig 2(b) above is the determined purchase and sale power curve of the optimal purchase and sale of electricity, Fig 3 shows the purchase and sale of electricity curves without matching combinations. According to equations (17) ~ (21), the best benefits based on the cooperative game nuclear solution are shown in Tab 3.

(2) Calculate the results of each path transaction with channel constraints

According to the results of the optimal purchase and sale of electricity obtained by the optimization of social income strategy based on the clean energy of the transmission channel constraints, the detailed transaction results of each path with channel constraints are further calculated.

According to the grid structure, the transmission path is obtained according to the depth-first search algorithm: there are two ways for the transmission path from the ground to the ground, namely: B-A (recorded as path 1), B-C-A (recorded as path 2), as shown in Fig.4 below.

Table 3. Income of each trading entity

| Transaction Subject | Income (¥) |
|---------------------|------------|
| A1                  | 7336.5     |
| A2                  | 3602.2     |
| A3                  | 3602.2     |
| B1                  | 6391       |
| B2                  | 5969       |

Table 4. Clean energy transmission line information

| Line   | Network Loss | Line Capacity(Kwh) |
|--------|--------------|--------------------|
| B—A    | 0.007        | 6400               |
| B—C    | 0.002        | 7200               |
| C—A    | 0.005        | 3400               |

The relevant parameters of the line parameter query are as follows: the loss rate of the line to the line A is 0.007, the line loss rate of the line B to the line C is 0.002, and the line loss rate of the line C to the line A is 0.005. The upper limit of the transmission capacity of the clean energy transmission in this example: the line capacity of B to A is 6400 kWh, the line capacity of B to C is 7200 kWh, and the line capacity of C to A is 3400 kWh, as shown in Tab 4. (The data is converted into the transmission capacity of kW in 1kW, in kWh). The solution results are shown in Tab 5 below:

Table 5. Transaction results of various combinations of alliances

| Determined Combinations | Electricity And Total Electricity Transferred By Each Path(Kwh) | Social Benefits Of Trading Portfolio Paths And Total Trading In Portfolio(¥) |
|-------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
|                         |                                                               |                                                               |
| [A2+A3, B2]             |                                                               |                                                               |
| path 1                  | 56743.93                                                     | 5017.68                                                       |
| path 2                  | 68000.07                                                     | 7651.65                                                       |
| [A1, B1]                |                                                               |                                                               |
| path 1                  | 94853.98                                                     | 7334.74                                                       |
| path 2                  | 61629.02                                                     | 5803.86                                                       |
|                         |                                                               | 25807.94                                                       |
5. Conclusion

In the reality that China's energy distribution and high-power load are reversely distributed, this paper focuses on the optimization of the combination of clean energy power producers and power users in the inter-provincial consumption for large-scale clean energy. Through the calculation results of the transaction model in the above subsection, the optimal social income strategy based on the transmission channel constraint-based clean energy consumption can be selected initially, and the best purchase and sale transaction portfolio can be selected initially. Then carry out constrained transaction calculations, while maximizing social benefits, increasing transaction volume, appropriately reducing the rate of abandonment.

The constraints in the model established in this paper are less than the actual constraints in reality. Therefore, in the subsequent optimization improvement, the corresponding constraint conditions can be increased according to the corresponding limiting factors, so that the function model has better practicability. Thereby making the model more conducive to the purpose of clean energy consumption.

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