Multi-Agent Cooperation Mechanism of Hydropower Plants in Central China Based on Raiffa Solution

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Abstract: "Carbon peak" and "carbon neutrality" have been national development strategies in China. The power industry is crucial for achieving the carbon reduction targets. However, the dysfunctional competition of hydropower plants in Central China leads to massively inefficient utilization of clean hydropower, which also has an adverse impact on the consumption of wind power and photovoltaic energy. To solve this problem, this paper proposes the regional hydropower alliance mechanism based on the cooperative game model. By using the Raiffa solution algorithm, the models are performed based on the technical and economic parameters of typical provinces and river basins in Central China. The results demonstrate that the benefit from the hydropower cooperation alliances across river basins and the same river basins in Central China can be feasibly distributed. What's more, the research has vital guiding significance on building an efficient regional power market order in Central China and promoting carbon emission reduction in power generation.

1 INTRODUCTION

Climate change caused by greenhouse gas emissions has been a key issue concerning the destiny of mankind and sustainable development. In 2020, Chinese President Xi Jinping clearly stated that carbon peak and carbon neutrality in China would have been respectively reached by 2030 and 2060 (Wu, 2021). However, the problem of carbon emissions in China is very serious. According to statistics from the U.S. Energy Administration, as the world's largest carbon emitter, China emits more than 10 billion tons of greenhouse gases each year, of which nearly 40% comes from its power generation industry. Therefore, reducing carbon emission in power generation is a key way to speed up the realization of the "dual carbon" strategy in China.

Nowadays, in China, the problems of carbon emissions in power generation mainly come from its reliance upon fossil fuels, and coal power still occupies the main position of the power generation structure (Xiao, 2020). Therefore, it is an important measure to promote carbon emission reduction in China's power generation by replacing thermal power with clean hydropower, wind power, photovoltaic and other forms. In this context, hydropower and clean energy power generation in Central China have developed rapidly, and the proportion of installed capacity has increased significantly. Figure 1 shows the development trend of the power generation installation structure in Central China.

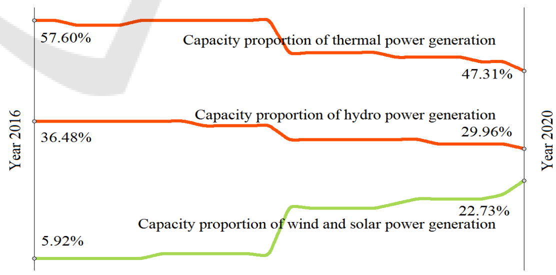

Figure 1: Development trends of power generation installation types in Central China.

Although hydropower, wind power, and photovoltaic power generation in Central China have developed rapidly, the problem that clean energy power generation in Central China is not fully utilized has also been prominent. For example, in 2020, the underutilized hydropower, wind power, and photovoltaic power generation in Central China were 469 million kWh, 292 million kWh, and 2.55 million

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kWh, respectively. The power generation space corresponding to these underutilized clean energy resources is actually filled by coal-fired thermal power, which is detrimental to the realization of carbon emission reduction in power generation and China's "dual carbon" strategic goal.

It is found through field survey that although there are many rivers in Central China, and hydropower has been fully developed, the interest conflicts between power generation and water use still occur along upstream and downstream for many hydropower plants in the same river basin. Meanwhile, the contradiction that hydropower plants across river basins seize market share also appears. What is worse, water conflicts lead to malicious release or closure of power plants in the same river basin, resulting in deficient utilization of water energy and hindering the maximization of power generation efficiency. At the same time, in the cross-basin competition, the rush to generate hydropower in each river basin directly squeezes the grid-connected space of wind power and photovoltaic power generation. What is more, the hydropower game due to competition not only damages the full utilization of water energy in the river basin, but also harms the consumption of wind power and photovoltaic power generation. This game model is not conducive to establishing an orderly and efficient power market and dispatching order in Central China at the micro-level, and also hinders the achievement of carbon emission reduction in power generation and the realization of the "dual carbon" goal at the macro level. Therefore, it is imminent to change the situation of bad hydropower competition in Central China. Based on the cooperative game model, this study builds a hydropower distribution mechanism in Central China to explore the role of this mechanism on promoting carbon emission reduction of power generation in Central China.

2 COOPERATION GAME MODEL CONSTRUCTION OF HYDROPOWER PLANTS IN THE BASIN OF CENTRAL CHINA

For each hydropower plant in the same watershed, the expectation of cooperation rather than malicious competition is that cooperation can make the individual obtain more benefits than the competition (Ambec, 2008). However, the basis of cooperation lies in the reasonable distribution of cooperation income, otherwise, the collapse of the cooperative alliance will damage the income of the alliance, and the relationship that individual returns to competitive will also hurt the income of the individual.

2.1 Construction of Game Model for Hydropower Cooperation in the Same Basin of Central China

It is assumed that there are n_i hydropower plants on each river. I refers to the collection of river basins in Central China, and i is a natural number, which represents the serial number of the river ($i \subset I$). For watershed i, $\mathrm{N}_i = \{1,2,\cdots,\mathrm{n}_i\}$ represents the set of game players of all hydropower plants in watershed i, and $\forall S_i \subseteq N_i, S_i \neq \varnothing$ is called a cooperative alliance, whose characteristic function is $v_i : 2^{n_i} \to R_i$, and $v_i(\phi) = 0$. R_i is the set of real numbers. Moreover, $v_i(S_i)$ indicates the maximum benefit that each participant in the cooperative alliance S_i obtains under the condition forming the alliance, and then $T_i = \{N_i,\ v_i\}$ denotes the game alliance on N_i.

For a single watershed i and the cooperative game $T_i = \{N_i,\ v_i\}$ of hydropower plants on the watershed, if there is a real array $(x_{i,j})_{i\in I, j\in S_i}$, then:

$$\sum_{i\in I, j\in S_i} x_{i,j} = v_i(S_i) \tag{1}$$

$(x_{i,j})_{i\in I, j\in S_i}$ can be called the feasible payment vector of S_i, and the economic meaning of $(x_{i,j})_{i\in I, j\in S_i}$ denotes the share of each individual j allocated from the total income $v_i(S_i)$. When $S_i = N_i$, namely when all individuals participate in the cooperative alliance, if $(x_{i,j})_{i\in I, j\in S_i}$, then:

$$\begin{cases} x_{i,j} \geq v_i(\{\cdots\}), (i\in I), (j\in[1,n_i]) \\ \sum_{j=1}^{n_i} x_{i,j} = v_i(N_i) \end{cases} \tag{2}$$

$(x_{i,j})_{i\in I, j\in S_i}$ will be called a feasible profit distribution solution of the cooperative game. For alliance game T_i, if the set of all individual allocations of hydropower plants in basin i of

Hunan Province is recorded as $E_i(v_i)$, then:

$$E_i(v_i) = \{x_{i,j} \in R_i^{N_i} \mid x_{i,j} \ge v_i, x(n_i) = v_i(N_i)\} \quad (3)$$

Equation (3) is the rational condition for individual j in each hydropower plant. What is more, for the game subject j, if the income gained by joining the single-watershed cooperative game alliance is less than the income gained when j leaves the cooperative alliance and acts alone, j will withdraw from the alliance. Therefore, the collective rationality condition of all hydropower plants in a single basin is based on the super-additivity of Equation (3), which can be derived as follows:

$$\sum_{j=1}^{n_i} x_{i,j} \ge v_i(N_i) \quad (4)$$

At the same time, considering that the total allocated amount of all hydropower plants in a single basin i cannot exceed the total income of the basin, we have:

$$\sum_{j=1}^{n_i} x_{i,j} \le v_i(N_i) \quad (5)$$

According to Equations (4) and (5), it can be known that if the Equation (3) can be satisfied, namely when the individual rationality and collective rationality conditions of a single-basin hydropower cooperative game are met at the same time, it means that all hydropower plants in basin i will completely distribute all the benefits. The remaining question below is what the allocation of each hydropower plant is to achieve $\sum_{j=1}^{n_i} x_{i,j} = v_i(N_i)$. Assuming that the profit of all individuals in the Central China basin i is recorded as B_i, the profit of the remaining $n_i - 1$ parties when no individual j participates is recorded as $v_i(\backslash j) = b_j,\ \ i \in I, j \in [1, n_i]$, while $b_i = [b_{i,1}, b_{i,2}, \cdots, b_{i,n}]$. In addition, the distribution of all cooperation among the parties is marked as $x_i = [x_{i,1}, x_{i,2}, \cdots, x_{i,n_i}]$.

2.2 Construction of Game Model for Inter-basin Hydropower Cooperation in Central China

As is shown in Section 2.1, *I* is used to denote the collection of river basins in Central China. It is assumed that these rivers cooperate in a unified cross-basin optimal dispatch. At this time, the individual participating in the cooperation is basin i. Suppose its cooperative alliance is denoted as TS, and the distribution of cooperative income by each individual is denoted as vector $y = [y_1, y_2, \ldots, y_n]$ (n is the number of rivers in set *I*).

The basis of cross-basin hydropower cooperation is that the benefits obtained by basin i when participating in the cooperation are at least not lower than the benefits when it leaves the cooperative alliance, and the excess profits obtained from the cooperation need to be distributed to each individual participating in the cooperation with a reasonable manner. Besides, hydropower cross-basin cooperative game distribution is the most important concept of cooperative game. To obtain an executable distribution, the distribution formed is classified, forming the core concept, which can be defined as follows:

$$e(TS, y) = v(TS) - \sum_{i \in I} y_i \quad (6)$$

In Equation (6), $e(TS, y)$ reflects the satisfaction of the Hunan Inter-basin Hydropower Cooperation Alliance (denoted as TS) with the allocation plan y. When $e(TS, y)$ is larger, it means that the cross-basin hydropower cooperation alliance is more dissatisfied with the distribution plan y. At this time, the total income of all participating entities in the cooperative alliance (that is, the collection of hydropower in each basin) is far less than the cooperative added value $v(TS)$ generated by it, and the stability of the distribution plan is poor. When A is smaller, it means that the inter-basin hydropower cooperation alliance is more satisfied with the allocation plan y, showing that the allocation plan is more effective.

Obtaining the solution of Equation (6) is equivalent to finding the allocation plan that minimizes the maximum overrun in the cooperative alliance, that is, nucleolus $\widetilde{N}$. What is more, compared with the core that may be an empty set, the nucleolus always exists and contains only one element. First, the core of the cooperative game can be found:

$$\begin{cases} y_i \ge yd_i \\ \sum_{i=1}^{n} y_i = c \end{cases} \quad (7)$$

In Equation (7), c represents the total income obtained by hydropower in different river basins after forming a cooperative alliance. The core of this set of inequalities can be solved as follows:

$$C(v)=\{(c-y_i,y_i):yd_i\le y_i\le c-yd_i\} \quad (8)$$

2.3 Solution Algorithm of Hydropower Cooperation Game Model

The prerequisite for multiple game players to form a cooperative alliance is still individual rationality. If the cooperative alliance damages the interests of the individual without compensation, the subject will have the urge to withdraw from the alliance, and then obtain greater benefits through its own actions or strategies. Therefore, a "fair and reasonable" distribution plan is very important in a cooperative alliance, and the distribution plan is reasonable only when it reaches the rational goals of the participating subjects. Moreover, many scholars in the field of game theory have explored the issue of "fairness of distribution", and representative solution concepts include Nash-Harsanyi negotiation solution, Raiffa value, etc. It can be deduced mathematically that the negotiation solution is equivalent to the Raiffa value (Lozano, 2020), and the method of obtaining the solution of the cooperative game based on the Shapley value is only suitable for the case where the number of individuals in the set is not more than 3 (Eissa, 2021). In this study, there are more individuals in the same and cross-basin cooperative game alliances ($n>3$ and $n_i>3$). Therefore, the Raiffa value is used to solve the solution of the cooperative game distribution mode of hydropower in Central China. The Raiffa value algorithm is carried out in the following steps:

(1) For basin i, according to the profits of the cooperation of n_i and n_i-1 sides, the lower limit of the distribution of all sides, namely $x_{i,j}=\frac{B_i}{n_i}+\frac{1}{n_i}\sum_{j=1}^{n_i}b_{i,j}-b_{i,j}$, is used as the basis of distribution.

(2) When an individual j of basin i joins the cooperation of $n-1$ side without j, the increase in profit, namely the marginal benefit of j, is calculate: $\bar{x}_{i,j}=B_i-b_{i,j}$.

(3) Assign $\bar{x}_{i,j}$ according to two steps. Firstly, the individual j in the basin i and the n_i-1 side hydropower plant without j are equally divided, and then the n_i-1 side hydropower plant is divided equally, namely:

$$x_{i,j}=\frac{\bar{x}_{i,j}}{2},x_{i,k}=\underline{x}_{i,k}+\frac{\bar{x}_{i,k}}{2(n_i-1)},i\in I,j,k\in[1,n_i],k\ne j \quad (9)$$

(4) Taking j as $1,2,\ldots,n$, repeat step (3), and then sum and average, to get the final distribution as:

$$x_{i,j}=\frac{n_i-1}{n_i}\cdot\underline{x}_{i,j}+\frac{1}{n_i}[\frac{\bar{x}_{i,j}}{2}+\frac{1}{2(n_i-1)}\sum_{j\ne k}\bar{x}_{i,k}],j,k\in[1,n_i] \quad (10)$$

Substituting the vector $\underline{x}_i$ and $\bar{x}_i$, Equation (10) can be expressed as:

$$x_{i,j}=\frac{B_i}{n_i}+\frac{2n_i-3}{2(n_i-1)}[\frac{1}{n_i}\sum_{j=1}^{n_i}b_{i,j}-b_{i,j}],i\in I,j\in[1,n_i] \quad (11)$$

Equation (11) is the Raiffa equilibrium solution of the cooperative game.

3 GAME DISTRIBUTION SOLUTION OF INTER-BASIN HYDROPOWER COOPERATION IN HUNAN PROVINCE OF CENTRAL CHINA

In this paper, taking the typical provinces of Central China and the typical river basins of Lishui in Hunan as examples, the quarterly power generation and unit power generation price of each hydropower plant in the river basins of Hunan Province in 2020 are substituted into the hydropower cooperation game model and its solution algorithm in Central China, to obtain the revenue distribution plan of the hydropower cooperation game. In addition, since the value corresponding to this solution can be regarded as value or electricity, the RaiIffa solution is normalized and converted into a proportional value that is the proportion of cooperative game revenue distribution based on the Raiffa solution to avoid unit inconsistency, which is more convenient for practical implementation.

Figure 2 shows the proportion of inter-basin hydropower cooperation distribution in Hunan Province in the Central China by quarter.

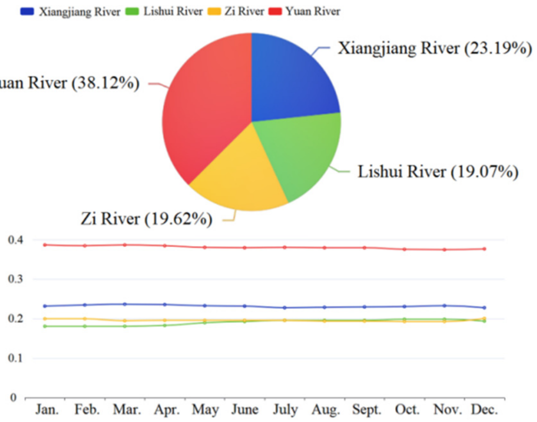

Figure 2: Proportion of income distribution based on multi-year average of Hunan hydropower inter-basin cooperation game.

Table 1: Cooperative game distribution share of power plants in Lishui river basin.

Power plant name	The first quarter	The second quarter	The third quarter	The fourth quarter
Jiang Ya	21.45%	7.48%	24.88%	27.68%
Guan Menyan	7.91%	10.81%	5.68%	6.38%
Changtan River	12.76%	11.24%	5.68%	6.38%
Yu Tan	11.86%	9.93%	15.77%	11.86%
Chalin River	11.41%	11.38%	5.68%	6.38%
Zao City	11.90%	12.26%	19.16%	17.74%
San Jiangkou	13.03%	8.63%	12.64%	12.05%
Yan Zhou	9.67%	28.26%	10.52%	11.53%

It can be seen from Figure 2 that the Yuanshui River Basin has the highest proportion (about 38%), and the Lishui River Basin is the lowest (less than 20%). The Xiangjiang River and Zishui River Basins are approximately equal, which is consistent with the order of hydropower generation value in each basin from high to low, embodying the principle that individuals distribute revenue according to the contribution to the team. Moreover, individuals with a high proportion of power generation value need to reduce the proportion of revenue sharing and give profits to individuals with a low proportion of power generation value to maintain the cooperative alliance.

Based on the profit distribution solution of the cross-basin hydropower cooperation game in Hunan Province, the distribution accuracy of the cooperation revenue can be determined on the hydropower alliances of each basin, further gaining the distribution mechanism in each of the basin hydropower cooperation alliances. Meanwhile, the proportion of each power plant's share of revenue be obtained too. The following obtains the solution of the Lishui Hydropower Cooperation Alliance in a typical river basin, which is listed in Table 1.

It can be seen from Table 1 that the Raiffa value of the hydropower plant cooperative alliance in a single basin has different magnitudes from monthly. Although the difference is small, and the fluctuation range is not more than 2% in most cases, the cumulative difference or cross-quarter difference is significantly larger. The main reason for the difference is that the power plants are different in sensitivity to water regimes and their adjustment capabilities, and there is a certain asynchrony in production during periods of high water, flat water, and low water, which shows that the quarterly Raiffa value distribution method is more reasonable than the annual Raiffa value distribution.

In addition, the cooperative alliance of a single basin hydropower plant is formed to redistribute benefits, which reflects the contribution of each power plant to the single basin cooperative alliance. In other words, power plants that can produce higher electricity value each month account for a larger proportion of the benefit distribution. However, the proportion of profit distribution is not the same as that of the monthly power generation value of each power plant. For power plants with high power generation value, the proportion of profits is lower than that of their power generation value. Conversely, power plants that account for the proportion of power generation value can obtain a higher proportion of revenue in cooperation, which is consistent with the principle of the Raiffa value algorithm considering the "marginal contribution of the team" and "protecting the weak".

4 CONCLUSIONS

Based on the current practical problem that clean energy is consumed inadequately due to malicious competition among hydropower entities in Central China, a hydropower cooperation game alliance in Central China is established in this paper. Moreover, with the help of the Raiffa solution algorithm, the distribution plan of hydropower cooperative game alliances in typical provinces and river basins in Central China is calculated. It is proved that it is feasible to establish a cooperative game alliance of hydropower in Central China, and the distribution plan is reasonable and incentively compatible. What is more, the research methods and conclusions are of practical guiding significance. In addition, the hydropower cooperation alliance in Central China will help regulate the power market and dispatch order, thereby accelerating the consumption of clean energy and promoting the realization of China's power generation carbon emission reduction and "dual-carbon" strategic goals.

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