

Study on generation investment decision-making considering multi-agent benefit for global energy internet

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Abstract. This article has studies on the generation investment decision in the background of global energy interconnection. Generation investment decision model considering the multiagent benefit is proposed. Under the back-ground of global energy Interconnection, generation investors in different clean energy base not only compete with other investors, but also facing being chosen by the power of the central area, therefor, constructing generation investment decision model considering multiagent benefit can be close to meet the interests demands. Using game theory, the complete information game model is adopted to solve the strategies of different subjects in equilibrium state.

1. Introduction

Global energy Interconnection is a kind of strong smart grid which is based on the ultra-high voltage grid as backbone and dominated by conveying clean energy [1]. Electricity-centric energy development is a general trend. Therefore, the core of global energy Interconnection must be the grid. The essence of global energy Interconnection is the combination of ultra-high voltage grid as the key, smart grid as the basic and clean energy as the fundamental.

Through the 4.0 dialogue of global energy interconnection with industry, their integration and interaction of different levels in global energy interconnection and the analysis and introduction of individual level, the literature [2] clarifies its emerging commercial operation mode and appreciation potential. Some researches about intercontinental Internet which is a part of global energy interconnection are proposed in relevant literatures. The literature [3] proposed an evaluation model of power transmission potential in sending areas, considering following factors: amount of exploitable resources and local electricity demand, construction cycle, development economy and so on. The literature [4] proposed a feasibility study on transmission losses, ability of voltage support, security and stability of client areas and so on, which used the example of clean energy power transmission between Asia and Europe. An analytical model of the willingness to send out electricity including power delivery areas, receiver areas, and international background have been proposed in the literature [5]. Based on the PSD-BPA computing platform, the literature [6] constructed an electromechanical transient simulation model under the 220kv and above voltage system in German and major connected countries. Then it has calculated and analyzed operational stability issues of 11GW ultra-high voltage direct current access to German power grid. These researches have studied on electric power demand, resources endowment, technical proposal, transmission efficiency and so on. They preliminary



demonstrates the necessity, feasibility, economy and technology of the Asia-Europe continental transmission, which provide the related reference for the further research and building of global energy interconnection.

Investment decision of power system faces a lot of uncertainties, Such as the volatility of electricity price, the randomness of the renewable energy and fluctuation in policy, technology development, diversification of investment subject [7] and so on. Most researches take game theory to solve uncertainty problems of investment decision under the circumstances of power market. First of all, a game model is constructed by research object. And then the equilibrium of the model is solved out to analyze income from investment situation of competitors in different action plans. The option-game theory is a typical example of this kind of method [8], which assessed project value by option pricing theory and was used for scientific decision to project investment. This method doesn't only avoid some disadvantages of the traditional investment decision analysis method, but also solve the contradictions between acquiring option value by waiting in real option theory and acquiring first-move advantage by entering the market firstly in real market [9].

The literature [10] proposed a Nash equilibrium game optimization model to solve power generation investment planning problem. The literature [11] used Black-Scholes option pricing model and took non-cooperative game model to assess deferred investment decision of power generating projects and transmission projects about multiple investment subjects. The literature [12] proposed a model of power generation investment decision and solved investment decision problems when the option price investors faced uncertain factors by option game theory and Barraquand-Martineau option price.

Under the background of global energy interconnection, investments in power generation of clean energy bases may belong to different investors. During the initial planning phase, every investor tends to maximize their profits to determine the optimal capacity. Since the power load centres are located in different countries, the area characteristics will increase absorptive capacity of clean energy, and improve utilization efficiency. Therefore, considering the fact that the power demand of load centres located in different time zones had effect on the decision-making of clean energy bases, characteristics of the generation investment decision under the background of global energy interconnection can be highlighted. Because of the optimization of multi-agent benefits in the investment decision of power generation, game theory can be used to solve the equilibrium strategy of optimal decision-making model for different clean energy bases, which makes different subjects be able to get optimum benefit.

In this paper, after considering the benefit of different power generation subjects, investment decision-making model is established based on game theory and the configuration of power generation capacity in each clean energy base is proposed. The basic idea is that investors in different power clean energy bases and all the load centre purchase parties take the non-cooperative game model of complete competition as participants. Following to this view, after considering the entire life-cycle costs of different investors, power sales revenue, environmental benefits and power purchase cost of electric power and other factors, with the strategy of the investor's investment capacity and the cost of electric power purchase, a non-cooperation game model is established to solve and analyse the Nash equilibrium results.

2. The benefit models of different investment subjects

Under the background of global energy interconnection, there are two types of different investment subject benefits. One is the investment benefit of clean energy base and another is purchase cost in the load centre. The former solves the problem that clean energy can get development and utilization and reduce the pressure to environment as much as possibly in the event of electricity demand in the load centre area. Meanwhile, for the load centres, the power demand may be supplied by different clean energy bases. On the basis of meeting their own load demand they can decide own power purchase plan according to the electricity price and the output force of different clean energy bases. The clean energy bases carries out a comprehensive treatment of the power demand proposed by different load

centres to determine its power generation capacity. Decision framework of power generation investment is shown in figure.1.

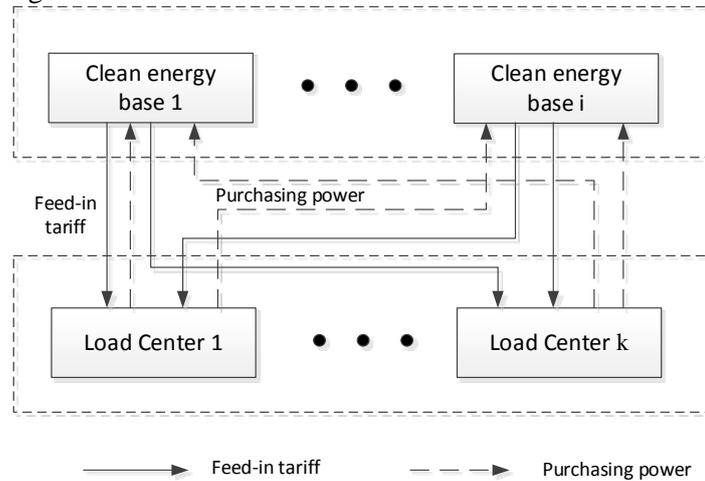


Figure.1 Decision framework of power generation investment.

Load centres located in different time zones determine power purchase plan according to the cost level of power purchase from different power bases. And they feed their demand back to the clean energy bases in order to decide installed capacity of the bases. For this purpose, clean energy bases need take a full consideration output situation of the local clean energy so as to satisfy the demand. Therefore, benefit models of different subjects are proposed.

The objective function of the investment model in the clean energy base can now be formulated as

$$\max B_i = I_{SEL,i} + I_{CDM,i} + I_{D,i} - C_{INV,i} - C_{OM,i} \tag{1}$$

Here, all references belong to clean energy base i . $I_{SEL,i}$ is the annual sales revenue and $I_{D,i}$ is the annual depreciation income of equipment. $I_{CDM,i}$ is the income acquired from carbon market. $C_{INV,i}$ and $C_{OM,i}$ represent annual investment cost and annual maintenance cost.

The annual sales revenue is formulated as

$$I_{SEL,i} = Q_i \lambda_i / (1 + f_i) \tag{2}$$

Q_i , λ_i and f_i correspond to the annual electricity generation, net tariff and export tariff rate, respectively.

The benefit of participation in carbon trading is formulated as

$$I_{CDM,i} = K_{CDM,i} Q_i \alpha \tag{3}$$

$K_{CDM,i}$ stands for the price of carbon in the carbon market. α is the amount of CO₂ produced by unit quantity of electricity from thermal power units.

The annual depreciation income is formulated as

$$I_{D,i} = P_i D_i \frac{r}{(1+r)^{L_i} - 1} \tag{4}$$

D_i is depreciation income of per power unit, r is basic discount rate and L_i is unit life.

The annual investment cost and the annual maintenance cost is expressed by

$$C_{INV,i} = U_i P_i r (1+r)^{L_i} / ((1+r)^{L_i} - 1) \tag{5}$$

$$C_{OM,i} = P_i M_i \tag{6}$$

U_i stands for the unit power cost and M_i represents the unit power maintenance cost.

As far as load centers is concerned, the goal of purchasing electricity is to realize reasonable distribution of purchasing power cost and minimization when the amount of purchasing power is confirmed and every constraint condition is satisfied.

$$\min f_k(Q_{k,i}, c_{k,i}) = \sum_{k=1}^K Q_{k,i} c_{k,i} \tag{7}$$

$Q_{k,i}$ is the amount of purchasing power which load center k bought from base i .

$c_{k,i}$ is the price sent to net from base i to load center k .
the price sent to net can be formulated as

$$c_{k,i} = \lambda_i + \lambda_{k,i} \quad (8)$$

In this equation, $\lambda_{k,i}$ stands for the transmission price from base i to load center k .

In order to ensure the reasonability of the results, the investment decision of power generation should subject to the following conditions.

The constraint of power supply adequacy for load is stated as

$$\sum_i H_i^{max} P_i \geq D \quad (9)$$

H_i^{max} is the annual maximum utilization hours and D stands for total annual electricity consumption of load centers.

maximum and minimum utilization hours constraint is formulated as

$$P_i H_i^{min} \leq Q_i \leq P_i H_i^{max} \quad (10)$$

H_i^{min} is the annual minimum utilization hours.

Maximum installed capacity constraint can be formulated as

$$P_i \leq P_i^{cap} \quad (11)$$

In this inequation, P_i^{cap} represents maximum installed capacity.

The balance of supply and demand constrain is shown as

$$\sum_I P_{i,t,d} = \sum_K L_{k,t,d} \quad (12)$$

$P_{i,t,d}$ is output power in base i on the typical day of d at the moment of t and $L_{k,t,d}$ is the total load power of load center k correspondingly.

According to the output power at every moment on the typical day in different clean energy bases and the duration of typical days, we can get the following equation about total electricity output of clean energy bases in different years and annual power purchase of load centers bought from base i .

$$Q_i = \sum_{d \in \Omega_D} \sum_{t \in \Omega_T} P_{i,t,d} T_d \quad (13)$$

$$Q_{k,i} = \sum_{d \in \Omega_D} \sum_{t \in \Omega_T} L_{i,t,d} T_d \quad (14)$$

T_d is the duration time on the typical day i , Ω_D is set of typical days and Ω_T is set of duration.

The output power limit of units is shown as

$$\delta_i^{min} P_i \leq P_{i,t,d} \leq P_i \quad (15)$$

δ_i^{min} is expressed as minimum unit output level in base i (percentage).

3. A multi-agent benefit equilibrium analysis based on game theory

Although the equilibrium solution got from game theory model cannot guarantee global optimum, the modeling method reflects the behavior pattern of various participants in the investment decision. A game is consist of four essential elements: participants, strategies, value functions and equilibriums. Every load center realizes the minimization of self-purchasing cost according to power purchase plan, and at the same time every clean energy base realizes revenue maximization. This process can be regarded as a multi-agent game. The game reached equilibrium when different subjects could not reach the best interest by adjusting themselves.

Moreover, game theory not only concludes uncertain information, such as illumination and wind speed, but also concludes relatively certain information, such as on-grid price and transmission price of different clean energy sources. For convenience, we can assume the information of game process was totally open. Considering the respective interests of different subjects, this paper belongs to non-cooperative game.

The analysis about multi-agent benefit equilibrium model based on the optimization algorithm of game theory in the literature [12] is shown as follows.

In game theory, for a non-cooperative game with n participants, \mathbf{X}_j is the decision space of participant j . Cartesian product who belongs to decision space of all participants is stated as

$$\mathbf{X} = \mathbf{X}_1 \times \mathbf{X}_2 \times \cdots \times \mathbf{X}_n \quad (16)$$

Revenue function of each participant is $\phi_j(\mathbf{X}_j)$. The Nash equilibrium point \mathbf{x}^* can be defined as

$$\phi_j(\mathbf{x}^*) = \max_{(x_j|x) \in X} \phi_j(x_j|x) \tag{17}$$

Here, $(x_j|x)$ stands for the situation of its strategy x_j of participant j when other participants kept the corresponding strategies in x .

Equation (17) expresses that each participant has achieved optimal benefits when reached the equilibrium, and it can't change its strategy to gain benefits.

According to the approach to solving game equilibrium problem in the literature [10], the normalized Nikaido-Isod function is imported as follows. Nash equilibrium problem will be transformed into optimization problem. The object function is as below.

$$\Phi(\mathbf{x}, \mathbf{y}) = \sum_{j=1}^n (\phi_j(y_j|\mathbf{x}) - \phi_j(\mathbf{x})) \tag{18}$$

Here, y_j is the strategy taken by participant j in the present situation x .

In the state of Nash equilibrium, Nikaido-Isoda function need satisfy the following constraint.

$$\max_{\mathbf{x}^*, \mathbf{y} \in X} \Phi(\mathbf{x}^*, \mathbf{y}) = 0 \tag{19}$$

When equation (19) expressed equilibrium, all the participant couldn't gain their benefits by changing their strategies all alone. At this moment, multiagent equilibrium state has reached.

Iteration searching algorithm is used to solve Nash equilibrium point. The specific process is shown in figure 2.

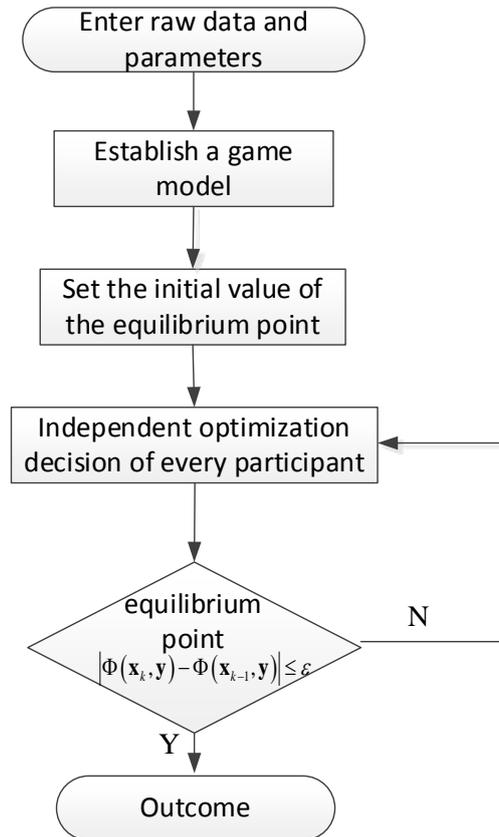


Figure 2. Flow chart of solving equilibrium model of multiagent benefits.

Step 1: Input original data and parameters, including load data, electricity price, discount rate and the parameters needed to calculate the benefit of the participants.

Step 2: Establish the game model as well as the decision-making model of generation investment based on the above modelling idea.

Step 3: Set the initial value of the equilibrium point, which selected randomly from the policy space of the decision variable.

Step 4: Each game participant carries on the independent optimization decision in turn. Mark the optimization results of each participant's in the round m as \mathbf{x}_m , and the optimal policy combination \mathbf{x}_m is obtained by pso, that is:

$$\mathbf{x}_{j,m} = \arg \max \phi_j(x_{j,m} | \mathbf{x}_{m-1}) \tag{20}$$

Step 5: Determine whether the system found the equilibrium point. When each participant gets the Nikaido-Isoda function in the last 2 times and satisfies (20), it is considered that the equilibrium state of the multi-Agent is reached, thus, enter step 6 and output the result. Otherwise, go back to step 4 and continue to seek equilibrium points.

$$|\Phi(\mathbf{x}_k, \mathbf{y}) - \Phi(\mathbf{x}_{k-1}, \mathbf{y})| \leq \varepsilon \tag{21}$$

Where ε is the given threshold.

Step 6: Output the equilibrium point \mathbf{x} of multi-agent benefit model and Calculate the benefits of multi-agents.

4. Result analysis

4.1. basic parameter

Three clean energy bases and load center systems are selected as the example under the background of global energy interconnection to verify the validity of the model, by using 2030 as the base year. Among them, clean energy bases include the North wind power (NP), Russian hydropower (RUS) and Mongolia solar energy base (MGL). Load centers consist of Germany (GER), China (CHN) and Japan (JP). In the base year of 2030, Germany, China and Japan, three load centers, their input power demands are 10GW、25GW and 10GW respectively[13]. The load curve of every load center country has a certain peak effect because of time zones considering two kind of typical load day in summer and winter. GMT+8 time zone in Beijing is taken as the standard. After converting, Germany has 6 hours late in summer and 7 hours late in winter. Japan has 1 hour earlier. Typical daily load curves of three load countries are shown as figure 3 (a)-(b).

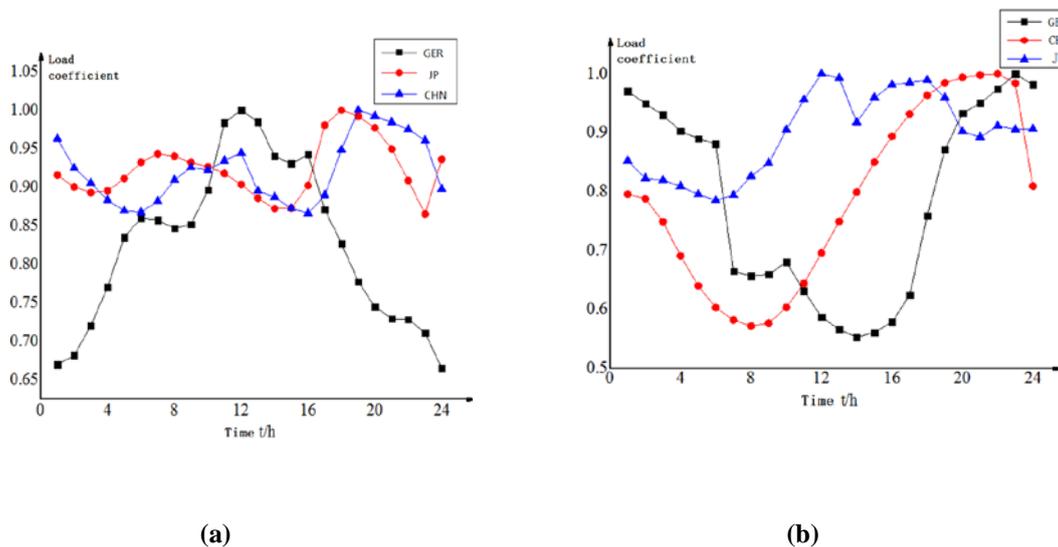


Figure 3. (a) Typical daily load curves in winter (b) Typical daily load curves in winter.

The unit economic parameters of different clean energy bases and other economic related parameters are shown in table1 and 2.

In the literature[11], engineering investment estimation took the calculation method of transmission engineering finance. The transmission price from Arctic to power transmission projects in German is calculated to be about 0.124 yuan. According to the distance from each clean energy base to each load

center, the estimated transmission price of different clean energy bases to each load center is shown in table 3.

Table 1. unit economic parameters.

Unit types	Depreciation unit cost (10k yuan/MW)	Unit power cost (10k yuan/MW)	Unit operation and maintenance cost (10kyuan/MWh)
NP	25	750	0.0035
MGL	30	1150	0.005
RUS	40	1000	0.003

Table 2. other economic parameters.

	customs duty rate (%)	feed-in tariff (yuan/MWh)	Carbon price (yuan/t)
NP	17%	560	30
MGL	17.5%	700	
RUS	7.1%	490	

Table 3. Transmission price from clean energy bases to each load center.

clean energy bases	Load centers	Transmission price (yuan/kWh)
NP	Germany	0.124
	China	0.147
	Japan	0.169
MGL	Germany	0.196
	China	0.038
	Japan	0.105
RUS	Germany	0.08
	China	0.148
	Japan	0.206

In view of the uncertainty of the degree of global power grid interconnection and the price changes of clean electricity in 2030, the following 4 scenarios are set up for analyses.

Scenario 1: The degree of power grid interconnection is lower, and the price of clean electricity is higher. In other words, only the intercontinental power grid realizes inter-connected, and the price and cost is set as a given value to calculate.

Scenario 2: The degree of power grid interconnection is lower, and the same as the price of clean electricity. The cost and price is set as 70% of the given value .

Scenario 3: The interconnection degree of power grid is higher, and the same as the price of clean electricity. Namely, to realize the interconnection of the intercontinental power grid, the clean energy base will be sent to any load center.

Scenario 4: The degree of power grid interconnection is higher, and the price of clean power is lower.

4.2. Result analysis of examples

According to the investment decision models of different subjects, the unit capacity of every clean energy base in four kind of scenarios is shown as figure 4.

As shown in this figure, in 4 different scenarios, the capacity of Arctic wind power took the biggest percentage. The main reason is lower cost of wind power generation in the Arctic. The economic benefits of clean energy bases could have increased when the installed capacity became larger. Compared scenario 1 with 3, the capacity of wind power could be increased further under circumstance of higher degree of interconnection. For Mongolia photovoltaic units who has higher generating cost, the capacity decreased further. In conclusion, the power cost is the key factor to restrict the capacity in the generation investment of global energy interconnection. Therefore, the reduction of the unit generation cost can maintain a strong competitive edge.

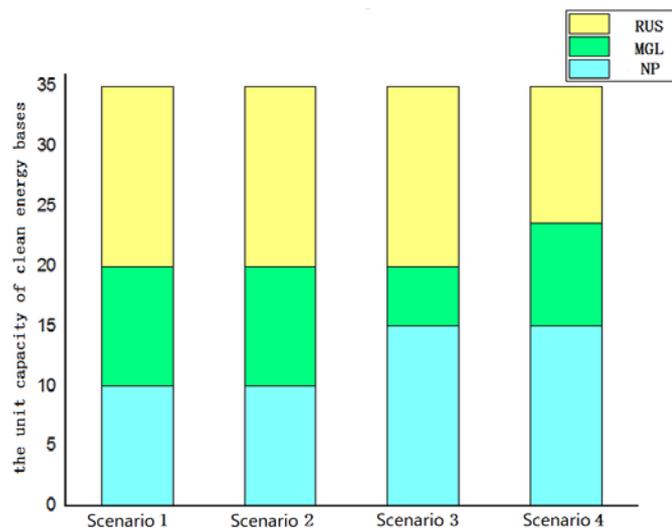


Figure 4. The unit capacity of clean energy bases in different scenarios.

Under circumstance of four different scenarios, table 4 is displaying the analyses of state of equalisation about investment benefits of clean energy bases.

Table 4. the state of equalisation about investment benefits of clean energy bases.

Scenario	Benefit (100M yuan)			Total benefit (100M yuan)
	NP	MGL	RUS	
Scenario1	103.78	72.58	106.93	283.29
Scenario2	76.12	53.88	80.24	210.24
Scenario3	155.66	36.29	106.93	298.88
Scenario4	76.13	46.19	61.14	183.46

According to the table, the total investment benefits of power generation in scenario 3 is the highest. when the degree of power grid interconnection is higher, the investment on wind power bases with lower generation cost can obtain more benefits, which promotes the advantage of wind power. Compared scenario 1 with 2, the decrease of generation cost and price reduced the benefits of every clean energy bases. However, for Mongolia solar energy, the decreasing range of benefits was smaller. It illustrated that reduction of units which have higher generation cost could bring more benefits. Therefore, clean energy bases with higher generation cost need seize the moment with the gradual decline of the cost in other bases to improve the utilization of their own resources and at the same time to gain more benefits.

From the comparison of scenario 1 and 3, when the electricity price had a high level, a wider range of power grid interconnection could enhance the benefits of the Arctic wind power base, thereby increasing total benefit. From the above, the interconnection could promote the absorption of clean energy in a wide area to increase the general economic benefit.

The equilibrium state of power purchase cost in the areas of load centers is shown as figure 5. Compared scenario 1 with 2, it is obvious to find that power purchase cost in every load center is lower. It is because of the decrease of the cost in clean energy bases and the price factor. From the comparison of scenario 2 with 4, there is a conclusion that higher degree of power grid interconnection could be advantageous to reduce the cost of power purchase in load center areas and increase the electric power absorption in delivery areas. In scenario 3, China and Japan had the highest purchase cost, which is because that the optimal value of purchase cost in each load center is calculated, not minimum, when considering the equilibrium state of power purchase cost in different load centers.

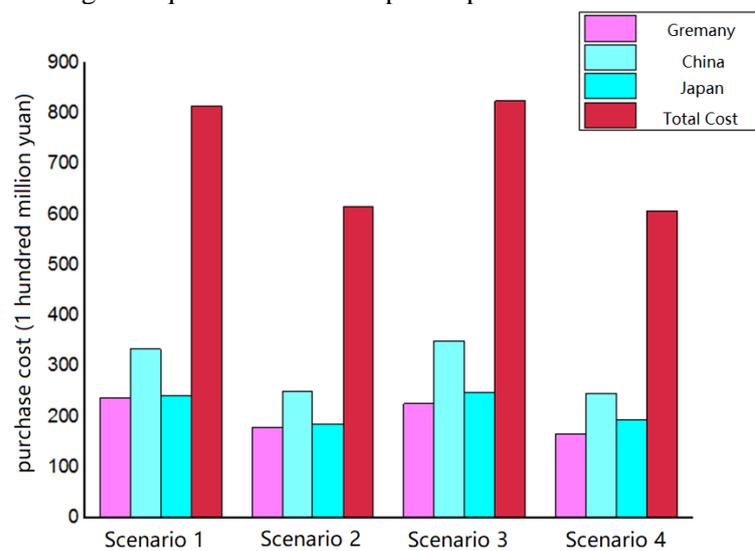


Figure 5. Purchase cost of each load center in different scenarios.

5. Result analysis

This paper have described some dynamic behaviors of different investors in the process of generation investment decision-making under the background of global energy interconnection and achieved modelling about the benefits of different subjects respectively after considered the relationship about their benefits. On the basis of game theory, the strategies of different subjects have been studied and proposed the optimal strategies when all parties got optimal benefits. According to the analyses of all parties benefits in different scenarios, we have come to the conclusion that the investors could obtain better returns with higher degree of power grid interconnection and lower price of clean energy, which highlighted the superiority of the interconnection.

Take into account that the focus of this paper is to explore a idea of investment decision based on the game theory, this paper assume that all information are open and transparent in order to simplify the problem. Therefore, this paper is to solve the model in a complete information environment, which is a simple and feasible processing method. In the paper, multiple subjects in the investment decision models which we considered are not comprehensive. In the future, we will discuss the addition of transmission investors as a type of investment subject. Moreover, we will study on how to balance the benefit of three different and further study on the game types under incomplete information condition to further improve the completeness and reasonability of research content.

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