Research on optimal investment path of transmission corridor under the global energy Internet

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Abstract. Under the background of the global energy Internet, the investment planning of transmission corridor from XinJiang to Germany is studied in this article, which passes through four countries: Kazakhstan, Russia, Belarus and Poland. Taking the specific situation of different countries into account, including the length of transmission line, unit construction cost, completion time, transmission price, state tariff, inflation rate and so on, this paper constructed a power transmission investment model. Finally, the dynamic programming method is used to simulate the example, and the optimal strategies under different objective functions are obtained.

1. Introduction

Today's traditional fossil energy resources are getting dried up, environmental pollution and climate change are becoming more and more serious. In the consumption and production of the primary energy, clean energy is becoming more and more important, which will set off a new global energy revolution. It has become very urgent to solve the energy and environmental problems as well as break through the bottleneck of economic and social development.

On a global scale, clean energy reserves are plentiful, in which the resources of hydropower, land wind energy and solar energy are more than 10 billion kilowatts, 1 trillion kilowatts, 100 trillion kilowatts, respectively, far more than the total energy demand of human society\cite{1}. But clean energy base often far from load center, there will usually be a vast distance between the countries with huge energy demand and the countries with abundant energy. Taking the time differences into account, we can see that the unbalanced situation between demand and distribution exists either in space or time. So it has a great significance to realize the construction of the global energy Internet.

However, the world’s existing power allocation capacity and scope is limited, it cannot meet the future need of a global configuration of clean energy. In order to solve the problem, an efficient global power configuration platform should be accelerated construction \cite{2}, and that's why the research on optimal investment path of transmission corridor is necessary and critical importance for the scientific development of global energy Internet. The experts and scholars at home and abroad have studied the related problems in the early stage: Literature \cite{3} has introduced the basic characteristics and connotation of the new energy power system and discussed the related research direction worthy of further attention; Literature \cite{4} takes the minimum cost of investment and operation as the objective function, established the planning model of space power grid considering the substation location; The
relationship between transmission planning and geographical environment is analyzed in literature [5], in addition, it proposed the decision method of power transmission route considering environment information; Literature [6] evaluated the financial feasibility of the Eurasian energy transmission program based on the existing measurement principle of electricity price and the characteristics of transmission projects across many countries; The current status and challenges of the European Super grid is discussed in literature [7]; Literature [8] studied the potential of outgoing power in the sending end area of Asia-Europe power transmission project; Taking the inter European clean energy power transmission as an example, the feasibility of the Eurasian intercontinental transmission technology is studied in literature [9]. The design of transmission line is the premise of power grid construction, and the path selection is related to the investment amount and operation reliability of the power engineering [10]. These studies have preliminarily demonstrated the necessity, feasibility, economy and technology of the power transmission in the Eurasian continent, provide a reference for further research, but there is no specific study on the investment in the transmission corridor.

This paper aims to study the optimal investment path of transmission corridor for the transportation of clean energy from Xinjiang to Germany. In this article, the subsection investment cost calculation model and price competitiveness model are constructed, firstly. Then through using the dynamic programming method, taking the countries along with the transmission route as stages, and the area of each country as the state, all possible path planning can be counted out as a strategy set. After that, fuzzy membership function is used to process the multi-objective problem. Finally, a simulation example is given to obtain the optimal investment path decision under different objective functions.

2. The research of transmission corridor optimization

From China to Germany will pass through Kazakhstan, Russia, Belarus and Poland, it can be obtained that this is the shortest arc length between the beginning and end of the transmission project. Figure 1 shows that each intermediate country is divided into three areas, only adjacent areas can be interconnected between two countries, and the feasible lines are indicated by arrows. The passing country is represented by \(i\), the divided area is represented by \(j\).

![Figure 1. Investment model of transmission corridor](image)

2.1. Calculation model of subsection investment costs
(1). Project investment cost \(CP_{ij}\)

\[
CP_{ij} = CH_{ij} + CX_{ij} \cdot L_{ij}
\]

(1)

\[
CP = CP_{ij}(1+i)^n \left[\left((1+i)^n - 1\right)\right]
\]

(2)

Where \(CH_{ij}\) represents the cost of the converter station in the area \(j\) of country \(i\), \(L_{ij}\) represents the length of the line from country \(i\) to country \(i+1\), \(CX_{ij}\) indicates the unit construction cost of the line, and \(i\) is the discount rate.

(2). Waiting cost \(CD_{ij}\)
Not all countries complete the construction at the same time, countries that have completed the construction in advance need to wait for others, thus resulting in a waiting cost.

\[
CD_{i,j} = CP_{i,j} \left[ \left(1 + l_{i,j}\right)^{CN_{i,j}} - 1 \right] \tag{3}
\]

Where \( CN \) denotes the total length of construction duration, \( CN = \text{MAX}_{i,j} \), \( l_{i,j} \) denotes the storage interest rate of the local bank, \( n_{i,j} \) denotes the construction time of country \( i \) to country \( i+1 \).

(3). Downtime cost \( CT_{i,j} \)

Some countries need to stop construction in the extreme weather, such as extreme heat or cold circumstances. The devaluation of the currency during the downtime produces the cost.

\[
CT_{i,j} = CP_{i,j} \left[ \left(1 + R_{i,j}\right)^{t_{i,j}} - 1 \right] \tag{4}
\]

Where \( R_{i,j} \) is the inflation rate and \( t_{i,j} \) is the length of downtime.

(4). Borrowing cost \( CJ_{i,j} \)

\[
CJ_{i,j} = JD_{i,j} \left[ \left(1 + l_{i,j}\right)^{CN_{i,j}} - 1 \right] \tag{5}
\]

Where \( JD_{i,j} \) and \( l_{i,j} \) are the amount of the loan and the loan interest rate of the local bank, respectively.

(5). Operation and maintenance cost \( CYW_{i,j} \)

\[
CYW_{i,j} = A_{\text{fixed}_{i,j}} \cdot R_{\text{oper}_{i,j}} \tag{6}
\]

Where \( A_{\text{fixed}_{i,j}} \) denotes the original fixed assets value of country \( i \), area \( j \), \( R_{\text{oper}_{i,j}} \) presents the operation and maintenance rate.

(6). Line loss cost \( CXS_{i,j} \)

\[
CXS_{i,j} = P_{r,i,j} E_{\delta,i,j} \left(1 - R_{\text{sum}}\right) \tag{7}
\]

\[
E_{\delta,i,j} = C_{\text{apa}} \delta_{i,j} \% H_{\delta} \tag{8}
\]

Where \( P_{r,i,j} \) denotes the on-grid price after entering country \( i \), area \( j \); \( E_{\delta,i,j} \) denotes the line losses; \( R_{\text{sum}} \) represents the profit rate of power plant; \( H_{\delta} \) represents the use hours of line loss; \( C_{\text{apa}} \) is the rated transmission capacity and \( \delta_{i,j} \) is the line loss rate, respectively.

2.2. Electricity price competitiveness model

The lower the electricity price, which transported by the transmission corridor, the more competitive.

\[
d_{i,j} = P_{r,i,j} + e_{i,j} + c_{i,j} \tag{9}
\]

\[
c_{i,j} = P_{r,i,j} \delta_{i,j} \% \left(1 - \delta_{i,j} \% \right) \tag{10}
\]

\[
P_{r,i,j} = d_{r(i,j)-1} \left(1 + f_{i,j}\right) \tag{11}
\]

Where \( d_{i,j} \), \( e_{i,j} \) and \( c_{i,j} \) denote the electricity price after entering area \( j \) of country \( i \), transmission price and line loss price, respectively; \( d_{r(i,j)-1} \) presents the electricity price before out of country \( i \), area \( j \); \( f_{i,j} \) is the tariff upon entry into area \( j \) of country \( i \).

2.3. Dynamic programming and fuzzy degree of membership function

In the construction of this model, countries in the transmission route are taken as the stages, the areas of each country are the state variables, the possible paths of each stage are used as the decision
variables, and all possible path planning sets are used as the strategies. We use $u_i(s_i)$ to represent the transmission line chosen from country $i-1$ to country $i$. So the strategy of sub-process $k$ can be expressed as:

$$p_{k,i}(s_{k}) = \{u_k(s_k), u_{k+1}(s_{k+1}), \ldots, u_i(s_i)\}$$  \(12\)

Selecting the sum of the all indicators of each stage included in the dynamic programming as an indicator function, which is:

$$v_{k,n}(s_k, u_k, s_{k+1}, \ldots, s_{n+1}) = \sum_{j=k}^{n} v_j(s_j, u_j)$$  \(13\)

Through the dynamic programming, the solution steps are as follows:

1. Determine the length of the transmission corridor, the cost of per unit, tariff, storage interest rate, inflation rate and other information.

2. Only taking the minimum total investment cost as the optimization target, the total investment cost $c'$ and grid access price $G_P'$ are obtained.

3. Only taking the minimum grid access price as the optimization target, the total investment cost $c''$ and grid access price $G_P''$ are obtained.

Let $c^* = c'$, $G_P^* = G_P'$, $\delta_1 = a_1(c' - c^*)$, $\delta_2 = a_2(G_P^* - G_P')$

Here, the value of $a_1$ and $a_2$ range from 0 to 1, depending on the preference of the decision maker.

In this article, there are two goals, one is the lowest price of electricity transmitted to Germany, and another is the lowest cost of the investment. We establish the Degree of Membership of the objective functions to deal with the multi-objective function with fuzzy method.

The Degrees of Membership of two objective functions are:

$$\mu(c) = \begin{cases} 0, & f_1 < f_1^* - \delta_1 \\ \frac{c - c^* + \delta_1}{\delta_1}, & c^* - \delta_1 < c < c^* \\ 1, & c^* < c \end{cases}$$  \(14\)

$$\mu\left(G_P\right) = \begin{cases} 0, & p_G < p_G^* - \delta_2 \\ \frac{p_G^* - p_G + \delta_2}{\delta_2}, & p_G^* - \delta_2 < p_G < p_G^* \\ 1, & p_G^* < p_G \end{cases}$$  \(15\)

Where $c^*$ and $p_G^*$ stand for the theoretical optimal values of the two objective functions, $\delta_1$ and $\delta_2$ are the increments of the investment cost and electricity price in Germany allowed by the decision maker.

Assume that $\mu$ is the minimum of the two Degrees of Membership, which is used to indicate the satisfaction degree of the decision maker.

$$\mu = \min\{\mu(c), \mu\left(P_G\right)\}$$  \(16\)

Thus, the multi-objective optimization problem is transformed into a nonlinear programming problem that satisfies all the restrictions, and $\mu$ be the maximum is the goal.

$$\max \mu$$  \(17\)

subject to

$$-c + \delta_1 \mu < -c^* + \delta_1$$  \(18\)

$$-G_P + \delta_2 \mu < -G_P^* + \delta_2$$  \(19\)
In addition, the system needs to meet the power balance:

\[
P_{(i,j)-1} + P_{(i,j)in} - P_{(i,j)out} = P_{(i,j)+1}
\]

(20)

Where \( P_{(i,j)in} \) and \( P_{(i,j)out} \) stand for the on-grid energy and the electricity consumption of country \( i \), respectively. \( P_{(i,j)-1} \) indicates the transmission power from the previous country, and \( P_{(i,j)+1} \) is the delivery power to the next country.

What’s more, the constraints of the power are:

\[
P_{i,j} \leq P_{\text{max}}
\]

(21)

In the above, \( P_{i,j} \) is the actual transmission power and \( P_{\text{max}} \) is the maximum power allowed by the line.

2.4. Basic data

As it shown in Figure2, this paper selected four intermediate countries: Kazakhstan, Russia, Belarus, Poland, and numbered the transmission corridors. There are 27 viable transmission corridors in total.

![Figure 2. Transmission corridor investment strategy model.](image)

| item                              | China  | Kazakhstan | Russia | Belarus | Poland |
|-----------------------------------|--------|------------|--------|---------|--------|
| Investment of converter station (billion dollars) | 1.29   | 1.26       | 1.64   | 1.85    | 1.73   |
| Operation and maintenance rate (%) | 1.4    | 1.8        | 1.9    | 1.75    | 1.6    |
| tariff (%)                        | 7.1    | 7.1        | 7.1    | 4.2     |        |
| Storage interest rate (%)         | 1.5    | 2          | 10     | 15      | 0.5    |
| Average line length (kilometer)   | 1663   | 2047       | 745    | 691     | 745    |
| Average line investment (Million/kilometer) | 7.9    | 9.28       | 12.22  | 24      | 24     |
| Fastest completion time (year)    | 0.7    | 0.8        | 0.6    | 0.3     | 0.3    |
| Slowest completion time (year)    | 1      | 1.4        | 0.7    | 0.4     | 0.4    |

In this article, the use hours of the transmission project and line loss are chosen as 6000h and 4000h, respectively. Power plant’s profit margin is 8%. PV on-grid price of china is selected as 0.828 dollars/kWh and the investment of the Germany converter station is 1.61billion dollars. In addition, taking into account the cold winter in Russia, this paper chooses 0.3 years of downtime. Moreover, assume that only Poland borrows 3 billion dollars from the bank and its interest rate is 4.2%. The specific parameters are shown in Table 1.
3. Calculation results
The investment cost, downtime cost, operation and maintenance cost and borrowing cost of each transmission corridor are not affected by the construction time of other lines, as it shown in Figure 3 and 4.

![Figure 3. Project investment costs for different transmission lines.](image1)

![Figure 4. Operation and maintenance costs, downtime costs and borrowing costs for different transmission lines.](image2)

It can be observed that the unit construction costs of China-Kazakhstan and Kazakhstan-Russia are relatively low, but the costs of Russia-Belarus, Belarus-Poland and Poland-Germany are higher. As for Poland-Germany, where need to build two converter stations, has a large project investment.

For the same line, different transmission corridor strategies will lead to the waiting cost, line loss cost and on-grid price be different. The calculation results of each line under different strategies are shown in Figure 5 to Figure 7.

![Figure 5. Waiting costs for each line under different transmission corridor strategies.](image3)
The total investment costs can be obtained by combining the costs of investment, operation and maintenance costs, waiting costs and line loss costs under different transmission corridor strategies and the calculation results are shown in Figure 8.

According to Figure 7, it can be observed that the electricity price in Germany will be the lowest of 0.2485 dollars / kWh when choosing the transmission corridor strategy 20, which passes through the transmission line 2-7-14-20-25. Similarly, we can see from Figure 8 that the total cost will be the lowest of 20.464 billion dollars when the transmission strategy is 1-5-13-18-25. Above all, according to the Fuzzy Degree of Membership Function, it can be obtained that the strategy 2-7-13-18-25 is the optimal transmission path, under this circumstance, the electricity price in Germany is 0.2511 dollars / kWh and the total investment cost is 21.1 billion dollars.

4. Conclusions
This paper mainly discusses the optimal investment corridor planning of clean energy transmission from Xinjiang to Germany under the global energy Internet. Taking into account of the specific situation of each country, this article constructed the investment model of transmission corridor as well as the electricity price competitiveness model, and the dynamic programming method is used to simulate the model. Finally, the optimal transmission path is obtained, which is 2-7-13-18-25. It can provide a reference for investment decision-making under the global energy Internet.
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