Benefit and cost competitiveness analysis of wind and solar power inter- continent transmission under global energy interconnection mode

Xiaoxia Wei1, 4, Jian Ding2, Jie Liu3, Tiezhong Wei3
1. State Grid Energy Research Institute, Guangyi Building A1206, Guangyi Street 5#, Xicheng district, Beijing, China
2. Beijing Haitong Tiancheng Information Technology Co.Ltd., China
3. Heilongjiang Power Company, China
E-mail: 20583853@qq.com

Abstract. Relying on the global energy interconnection, considering the energy implementation, carrying out clean energy alternative is mainly to use the clean energy to take place of fossil energy. Under the green development scenario, this research gives the global energy interconnection development model, makes the Arctic and the Equation as the connection points, gives the Northern hemisphere interconnection model and equator interconnection model unite the whole world energy. This research also identifies the factors effecting the transmission changes cost, including generation cost, transmission cost and landing cost. And take two continents connection as the prediction example, estimate these two continents cost benefit and variable power-jointed scheme cost competitiveness. It showed that under the global energy interconnection mode, the trans-continent mode had better benefit, and the landing cost is good to be used, can solve the pollution and energy restriction.

1. Introduction
Global energy supply is constrained by resource reserves and rising supply costs. To the amount, fossil energy reserves are limited, non-renewable, large-scale development and utilization will lead to depletion of resources [1, 2]. To the layout, the world's energy resource and consumption are reverse distribution; energy exploitation is centralizing to a few countries. At present, the supply costs of fossil and clean energy is showing a "one rising and one dropping". With the rapid development of clean energy technology, the cost will decrease [3].

The global energy environment is affected by global warming and the ecological environment destruction. The Fossil fuel combustion is the main source of global greenhouse gas emission, which can directly affect land reduction, species extinction, food supply, human health. Sulfur dioxide and other pollutants are leading acid rain and other environmental pollution. In addition, a large number of fossil fuels in mining, transportation, use of the various aspects of the water quality, soil, water and other environmental pollution [4].

The global energy efficiency needs to enhance energy development, configuration and utilization efficiency. At present, the world average oil recovery rate of only 34%; coal recovery rate is from 65% to 70%; the world average level of thermal power coal consumption is about 330 g standard coal / (kilowatt hour), the German average thermal power coal consumption of 290 g standard coal / (kilowatt hour), while some countries coal power is up to 370 g standard coal / (kilowatt hour). Energy
efficiency of developed countries is higher than developing countries; per unit GDP of OECD countries are only about 25% of the non-OECD countries [5, 6].

2. Global energy interconnection development model

According to the analysis of global clean energy demand, expected 2050, the electricity delivered amount of the Arctic channel will reach 3 trillion kilowatt-hour/year, and that of the equatorial region will reach 9 trillion kilowatt-hour/year. Electricity accounts for 16% of global electricity demand. In addition, there is a certain proportion of trans-continental power exchange, access to peak load, complementary resources, sharing of spare networking benefits.

2.1. Northern hemisphere interconnection model

Northern Hemisphere Interconnection model is mainly based on the Arctic power transmission channel. On the one hand, it is carrying the Greenland, Norway, Barents Sea, Kara Hai, Bering Strait, while on the other hand, it is a global energy Internet strategy platform connecting Arctic wind power base for electricity delivery needs, on the other hand, it can realize northern hemisphere three continents connection, forming the global energy interconnection strategy platform. This connection can give full play to great grid connection; give many benefits of peak and valley regulation, mutual backup, cross-complementarity. In addition, making use of the time difference between the continents, send the Arctic wind power to other continents, meet the day peak load needs, and improve Arctic wind power utilization efficiency, showed in Table 1.

| Connection          | Sending and receiving                                                                 | Line setting                                                                 | 2050 transmission capacity                                    |
|---------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------|---------------------------------------------------------------|
| Arctic to North east Asia | The Kara Sea wind power base of the Arctic to North China.                           | Adopt overhead lines ± 1100 kV HVDC transmission technology to China's power transmission channels, | Transmission capacity is 1.2 trillion kilowatt-hour / year, channel capacity is 240 million kilowatts. |
| Arctic to Europe     | Bering Strait wind power base to North China, Japan and South Korea.                 | Adopt UHV DC submarine cable to Japan, South Korea.                          | Transmission capacity is 0.8 trillion kilowatt-hours / year; channel capacity is 160 million kilowatts. |
| Arctic to North America | Greenland wind power to the north of England.                                        | Adopt UHV DC submarine cable connecting Green land South wind power base to Iceland, then leading to the north of England. | Transmission capacity is 1 trillion kilowatt-hours / year, channel capacity is 200 million kilowatts. |
|                     | Offshore wind power in the Norwegian Sea and the Barents Sea can be sent to Europe via the land channel. |                                                                               |                                                               |
|                     | Bering Strait wind power base to the western United States load center.              | Adopt ± 1100 kV HVDC transmission technology from Quebec to New York          |                                                               |
|                     | Southern Greenland wind to the east coast of Canada, then the eastern United States to the central load Ottawa. |                                                                               |                                                               |
2.2. Equator interconnection model
Equator Interconnection model, is considering the equatorial power transmission channel, carrying North Africa, East Africa, the Middle East, Australia, South America and other equatorial regions of the solar power base of electricity delivery, can achieve the northern hemisphere, the southern hemisphere interconnect the main communication channel. Through the equator Interconnection model, not only can solve the equatorial solar power delivery problems, also can make the southern and northern hemisphere interconnect into realization. Because of the large gap of these continents in the time zone, solar radiation intensity and load have certain simultaneity. The peak time of North Africa sunshine in Europe is the same with Europe load peak. This can make the benefit of solar power generation, showed in Table 2.

| Connecti   | Sending and receiving | Line setting                                                                 | 2050 transmission capacity                                                                 |
|------------|-----------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| North Africa to Europe | Solar power base of Morocco, Algeria, Tunisia, Libya, Egypt and other countries of North Africa to the South of Europe | Adopt ± 1100 kV HVDC transmission technology                                      | Transmission capacity is 1.5 trillion kilowatt-hours / year; channel capacity is 300 million kilowatts. |
| The Middle East to South Asia | Solar power base of the Middle East, Saudi Arabia, Oman, the United Arab Emirates in South Asia to the western of India | Adopt UHV DC submarine cable connecting the Strait of Hormuz to reach Iran, then by land UHVDC from Pakistan to the western India Mumbai load center | Transmission capacity is 2.5 trillion kilowatt-hours / year; channel capacity is 500 million kilowatts. |
| Australia to Southeast Asia | Australian northern solar power base using high-voltage submarine cable cross-sea landing in Indonesia, and then through a short cross-sea distance through Singapore to Thailand | Adopt ± 1100 kV HVDC transmission technology                                      | Transmission capacity is 1 trillion kilowatt-hours / year; channel capacity is 200 million kilowatts. |

2.3. Wind, Solar and Other Renewable Energy Transmission Efficiency Model
Global energy interconnection can guarantee the energy supply of economic and social development. Relying on the global energy interconnection, can guarantee the long-term stable energy supply, by widely distributed large potential of clean energy. From now on, if wind and solar power grow at 12.4% per year, by 2050, the non-fossil energy will reach 80% of the world total energy consumption. By then, wind and solar energy will become the leading energy, but its development is less than 5% of the total resources.

Global energy interconnection can reduce energy supply costs. Take Asia and Europe interconnection as example, Asia is the sending area (Xinjiang Province of China, Kazakhstan, the Russian Siberian region and Mongolia) which is compiling natural gas, wind and solar and other clean energy, using ± 1100 kV HVDC transmission technology, sending power to Germany. The channel using hour of DC is 5500 comparing with Germany’s receiving offshore wind, the program of the Asia and Europe inter-connection through Russia St.Peterburg relaying transmission is cheaper 30.4% than Germany offshore wind. The maximum power cost is 0.3648 yuan/kW·h. If we adopt the nonstop transmission of Asia and Europe, the maximum power cost is 0.526 yuan/kW·h, which is cheaper 43.8% than Germany offshore wind power. Through the implement of Asia and Europe inter-connection, this connection can reduce Germany power supply cost; the benefit of intercontinental connection is obvious.
Transmission efficiency is mainly to compare the landing cost with generation cost of sending area, analyse its economic efficiency. Considering the development mode of the global energy interconnection, the research on transmission benefit identification is divided into four levels, showed in Figure 1.

![Diagram](image)

**Figure 1.** Analysis process of transmission efficiency

3. **Identify the factors effecting the transmission changes cost**

| Policy tool | Country example | Impact on SV |
|-------------|-----------------|--------------|
| Grid codes that require advanced capabilities | Participation of wind in balancing the grid in Denmark and Spain | By providing system services from renewable energy, more thermal generation can be turned off during times of abundance |
| Advanced design of system services markets | Integrated planning in Brazil | Siting renewable energy generation in locations |
| Integrated planning of grid infrastructure and generation | Mexican auction system; differentiation of FIT levels in China | |
| Location of deployment | Locational signals in remuneration schemes | |
| Technology-specific auctions that reflect the value of each technology as determined in long-term planning | Technology mix | Deploying a mix of technologies can lead to a more stable VRE profile and reduce periods of VRE excess, hence boosting SV |
| System Value reflected in multi-technology auctions | Integrated planning in South Africa | |
| Economic design criteria | Partial exposure to market prices via premium systems | Investors are encouraged to choose a technology that generates during times of high electricity prices |
| Integrated planning, monitoring and revision | An integrated long-term plan for VRE and flexible resources, updated regularly | Aligned deployment of VRE and flexible resources enhances SV; regular update of the long-term path allows reaping the full benefit of technology innovation |
3.1. The generation cost of renewable energy
The sending area’s generation cost, is considering renewable energy generation cost and different energy delivery compound mode. (1) Considering the characteristics of resources in each region, identify the trend of the renewable energy base construction and transportation cost. (2) Considering the development trend of power generation technology, identify the trend of various power generation internal and external costs. (3) Identify the costs of different electricity generation, such as hydropower, gas and coal, according to unit cost, coal price, gas price, utilization hours, tax rate, operating period, power consumption rate, annual operation and maintenance cost, and hydropower station submerged compensation. (4) Identify the synthetic generation cost under different power combing scheme, considering the proportion capacity of wind power and solar energy, hydropower regulatory capacity of the flood season, the regulation of gas and electricity capacity.

3.2. The cost trend of wind and solar development
Wind and solar power generation can affect the system cost through solving programs; it is mainly focusing on some certain aspects, showed in Table 3.

In 2015, wind and solar power generation amount accounts 90% to total new power increased. Between 2008 and 2015, the land wind power’s average cost decreased about 35%. While the solar power generation cost decreased about 80%. In Figure 2, more evidence showed that, the nest generation wind and solar power generation technique will be more mature, and much more economy, which can push the wind and solar into the widely usage. The Figure gives, costs refer to global average of levelised cost of electricity (LCOE) with country specify assumptions on investment costs and cost of financing. Different costs per country are averaged weighted by annual capacity additions. The sending area’s renewable energy bases, established in the area of wind and solar energy, facing the energy bundling sending out, its cost will decrease gradually. The solar energy LCOE will decrease from 0.13dollar/kw·h of 2015, to 0.055dollar/kw·h of 2025, the decreasing ratio is 59%. The onshore wind cost will drop to 0.053dollar/ kw ·h of 2025, affected by wind tower, generator, wind farm development and other factors. Consider the renewable energy cost trend, the energy persistence, fast impact the coal, gas and other fossil energy. In the future, the solar and wind power sending costs will have more advantage.

![Figure 2. 2008-2015 wind and solar power generation cost curve](image)

![Figure 3. Under scheme two/1 analyse the landing cost and cost competitiveness](image)

3.3. Transmission cost of transmission channel
Transmission costs of transmission channels depend on how to select transnational power transmission mode, the corresponding project cost and the cost of fluctuations in different countries, line loss and the cost of electricity in different countries and settlement changes in the situation and other issues.

(1) The choice of power transmission type, consider power supply and demand of inter-continent and inter-country, analyse the advantage of choosing direct or continuous transmission mode, analysis characteristics of UHV DC transmission project, transmission channel characteristics, utilization hours and its supporting power supply, including the grid to provide the price of transmission services.

(2) Engineering cost, combined with the above project planning to estimate the static cost of construction, project cost fluctuations, the relevant technical costs of the project cost-related.

(3) The line losses cost, should be calculated on the basis of the principle of tariff balance. It is assumed that the cost of landing is the settlement price of the grid companies that provide transmission.
services and grid companies in the receiving areas, which is equivalent to the cost of local power purchase.

\[ C_{\text{line loss}} = C_{\text{generation}} \times K / (1 - K) \]  

(1)

\( C_{\text{line loss}} \) is line loss cost, \( C_{\text{generation}} \) is generation cost, \( K \) is line loss.

3.4. The receiving area landing cost

The receiving area landing cost refers to the receiving area getting the sending renewable energy adds the transmission cost.

\[ C_{\text{landing}} = C_{\text{generation}} + C_{\text{line}} (C_{\text{line loss}}) + T_{\text{tariff}} \]  

(2)

\( C_{\text{landing}} \) is landing cost, \( C_{\text{line}} \) is transmission cost, \( T_{\text{tariff}} \) is tariff.

(1) Landing Cost should be calculated according to the cumulative principle of cost. Power transmission projects across continents, need to consider cross-border tariffs generated by different countries when electricity imports. Each transit country should be a link, based on DC lines, converter stations and supporting exchange projects in the country's investment were calculated transmission costs and line loss costs, the country's landing costs and based on the country's tariff rate. The resulting tariffs are added together as the cost of the next country's electricity generation.

(2) There are relay points in some countries. In the landing cost calculation, the DC cost of the before relay point and the cost of electricity generated by the surplus electricity are taken as the DC generation cost, which can be used as after the power-weighted average of the respective country.

3.5. The landing cost competitiveness

The landing cost competitiveness is to analysis and comparison, under the basic and global interconnection scenarios, the use of different energy combinations in the form of energy transmission area, compared with the cost of receiving electricity in the renewable energy power generation. The lower the landing cost, the more competitive the corresponding price will be, and it will have the better economical, the transmission efficiency will be obviously.

\[ P = (1 - C_{\text{landing}} / C_{\text{generation}}) \times 100\% \]  

(3)

\( P \) is the landing cost competitiveness.

4. Prediction

Taking the most feasible connection of Asia and Europe as example, make up six intercontinental transmission schemes on two continents, which are estimated according to the investment of DC transmission project. According to the transmission cost, estimate wind and solar energy generation cost, transmission cost, landing cost, showed in Table 4.

4.1. The prediction of power generation cost

The generation cost and power usage hour Consider the proportion of wind and solar capacity, hydropower flood season adjustment, gas power adjustment; it can get different power generation cost, showed in Table 5.

4.1.1. Tariff China's tariff rate ranges from 0% to 35%, Poland ranges from 0% to 15% (average 4.2%), and Germany ranges from 5% to 17%. By the end of 2011, Russia, Belarus, Kazakhstan, the three countries jointly created the Eurasian Economic Commission, on September 1 of 2014, the weighted average tariff rate fell to 7.1%. In this research, it chooses the rate can be seen by Table 6.

4.1.2. The loss rate prediction ± 800, ± 1100 kilovolt converter station power loss is generally between 0.5% to 1%, this research make the value as 0.75%.
Table 4. The investment of sending side power (Million kilowatts, yuan / kWh)

| Project design | Channel introduction | Capacity | Wind power | Solar power | Hydropower | Gas power | Generation price | Utilization hour | Total investment |
|----------------|----------------------|----------|------------|-------------|------------|-----------|------------------|-----------------|-----------------|
| pure wind power | power connection at Xinjiang | 1100 1700 800 | 0.510 | 4400 | 1052.8 | 37 |
| Wind+solar | Power connection at Siberian | 1100 800 1100 | 0.590 | 5700 | 786.93 | 5 |
| Siberian hydropower and Xinjiang wind power | Power connection at Siberian | 1100 800 200 1100 | 0.593 | 6100 | 825.29 | |
| Siberian gas, Xinjiang wind power and Mongolia solar | Power connection at Ekibastuz | 1100 1200 200 1100 | 0.452 | 6600 | 2056.6 | 71 |

Table 5. The cost analysis of sending side power-jointed program design

| Program design | Synthesized generation cost (yuan/kWh) | Synthesized hour (h) |
|----------------|----------------------------------------|----------------------|
| 1 | Kazakhstan gas / hydro + China Xinjiang wind power | 0.4601 | 6000 |
| 2 | Kazakhstan gas / hydro + China Xinjiang + Mongolia solar wind power | 0.4978 | 5800 |
| 3 | China Xinjiang wind power + Russia Siberia hydropower | 0.4962 | 5900 |

Table 6. Tariffs along the lines

| Country | Calculation tariff (%) |
|---------|------------------------|
| China   | 17                     |
| Kazakhstan | 7.1                |
| Russia  | 7.1                    |
| Belarus | 7.1                    |
| Poland  | 4.2                    |
| Germany | 11                     |

4.2. The transmission cost prediction

According to the transmission scheme and power-jointed program mentioned above, and combine with basic usage hour, can get the relative transmission cost, showed in Table 7.

Table 7. The corresponding transmission cost (yuan/kWh)

| Transmission cost | one/1 | one/2 | two/1 | two/2 | three/1 | three/2 |
|-------------------|-------|-------|-------|-------|---------|---------|
| 1                 | 0.126225 | 0.140363 | 0.135270 | 0.149710 | 0.185018 | 0.201080 |
| 2                 | 0.078844 | 0.081095 | 0.079444 | 0.081095 | / | / |

4.3. The landing cost

According to the relative basic usage hour and its calculation method, can get each transmission scheme landing cost and cost competitiveness, showed in Table 8.
Table 8. The relative landing cost and competitiveness analysis (yuan/kWh , %)

|                  | one/1 | one/2 | two/1 | two/2 | three/1 | three/2 |
|------------------|-------|-------|-------|-------|---------|---------|
| Landing cost     | 0.9905| 1.0566| 0.9121| 0.9699| 1.0768  | 1.1694  |
| Cost competitiveness | 17.46 | 11.95 | 24.00 | 19.17 | 10.27   | 2.55    |

In Table 8, the landing cost of two/1 is lowest, and cost competitiveness is highest. While the landing cost of three/2 is highest, and cost competitiveness is the lowest. This showed that the relative landing cost of scheme two is higher than the scheme one. The relay transmission program’s landing cost is lower than the direct transmission program. The power scheme two is higher than scheme two and three. So scheme two’s line loss cost is lower than other two schemes.

While the scheme one and three covers one more country than scheme two. And because of China is the DC original point, considering the tariff of covering countries, offset the making Kazakhstan as the original point scheme’s transmission loss affection. So the landing cost of scheme one and three is higher than two. And the tariff of scheme three is obvious high. Cost competitiveness of direct scheme can not get the same affection with relay scheme. The landing cost of scheme one and two is lower than scheme three.

Figure 3 gives the 2015-2050 landing cost and cost competitiveness. Considering all kinds of factors, as the jointed power basement reset power proportion of the scheme one and two is the same, the after generation power cost of scheme one is higher than scheme two. We can get the result is that; the lower of generation cost, the landing cost affected by generation cost will be great.

5. Conclusion

The global clean energy resources are rich, water resources are more than 10 billion kilowatts, wind energy resources exceeds 1 trillion kilowatt, and solar energy resources exceed 100 trillion kilowatts, surpassing the human society. This research gives the global energy interconnection development model, through the northern hemisphere interconnection model and equator interconnection model can unite the whole world energy. It also identifies the factors effecting the transmission changes cost, including generation cost, transmission cost (line loss) and landing cost. And take Asia and Europe connection as the prediction example, estimate these two continents cost benefit and variable power-jointed scheme cost competitiveness. The research showed that under the global energy interconnection mode, the trans-continent mode had better benefit, and the landing cost is good to be used, can solve the pollution and energy restriction.

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