Optimal location for large-scale wind farms in China

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Wang Jiayang*

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Abstract

Chinese government enacted the Renewable Energy Law and started the full-scale introduction of renewable energy power generation in 2006. The Chinese government has put particular effort into the spread of wind power generation, and the installed capacity of wind power generation in China surpassed that of the United States to become the world's largest in 2011. However, most of China's wind farms were built in the northwest where land prices are cheaper and wind resources are abundant. These areas are far from the eastern coastal areas, which have a high demand for electric power, and a strong power transmission network is required to utilize the electric power in the eastern coastal areas. But the wind power plant output was curtailed since the power transmission network was not sufficiently developed.

It is too costly to transmit the wind power generated in the northwest to the eastern coastal area using the existing 220kV transmission lines. Therefore, this study examined the economic efficiency of power transmission at a high voltage of 750 kV. As a result, it was found that the point with the lowest cost became far from the metropolitan area (expanded from about 120km to about 500km), and it was found that the economic efficiency of power transmission from the northwest to the capital district (Beijing and Tianjin area) was secured.

Keywords

renewable energy, wind power, optimal location, power curtailment, ultra high voltage

Abbreviation

NDRC	National Development and Reform Commission
NEA	National Energy Administration
UHV	ultra high voltage
SGCC	State Grid Corporation of China
SPC	State Power Corporation

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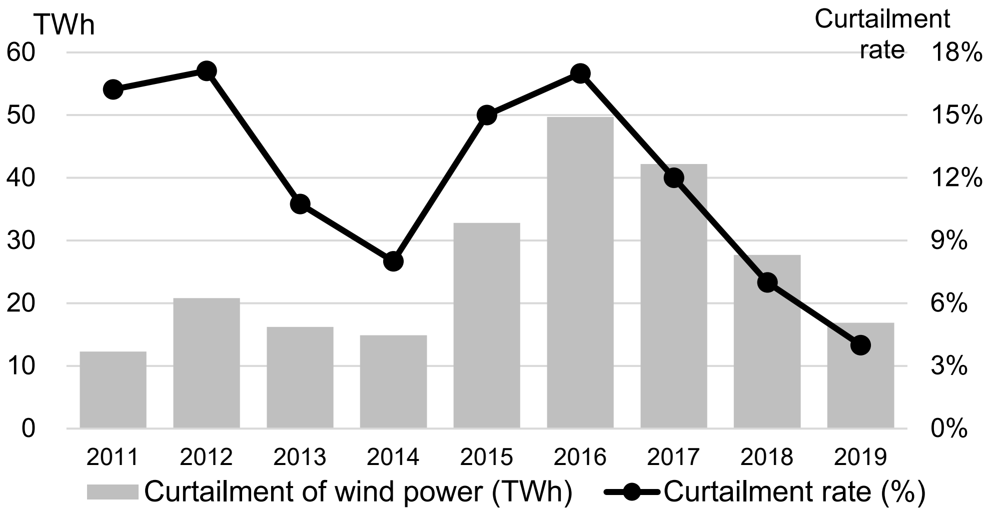
1. Introduction

In 2006, the Chinese government enacted the “Renewable Energy Law” and began to introduce renewable energy power generation in earnest. Special efforts have been made to promote wind power generation, and between 2006 and 2010, the annual growth rate of installed wind power capacity exceeded 100%. As a result, in 2011, China's installed wind power capacity base surpassed that of the United States, to become the largest in the world.

While, on one hand, wind power generation installations are spreading rapidly, a curious phenomenon has occurred: wind power output is being suppressed. The reasons for this are as follows: Most wind farms in China have been built in the northern and western regions of the country where land prices are low and there is an abundance of wind resources. However, these regions are far from the eastern coastal regions, where electricity demand is high, and a strong power grid is needed to utilize the power in the eastern coastal regions, and so the development of the power grid has not kept up with the rapid growth of wind power plants.

Figure 1 shows the amount of wind power curtailment since 2011 and its ratio to the generated capacity (power curtailment ratio), which was quite high at 16.2% and 17.1% for wind power in 2011 and 2012, respectively. It then dropped temporarily due to the efforts of the grid operators to adjust supply and demand, but because of the limits to their abilities to do so, it reached 17% again in 2016. Since then, the power curtailment rate has been on a downward trend.

Figure 1 Power curtailment amount and rate of China's wind power



Source: Created by the author based on data from the NEA (each year)

On a regional basis, wind power development was concentrated in the northwestern and northern regions, and this made it difficult to adjust the supply-demand balance within the region. As shown in Table 1, the high rate of wind power output curtailment in Gansu, the Xinjiang Uyghur Autonomous Region, Jilin Province, Heilongjiang, and Inner Mongolia is a result of this.

Table 1 Power curtailment rate of China's wind power by regional (%)

Regional	2013	2014	2015	2016	2017	2018
Gansu	31.0	11.0	39.0	43.0	33.0	19.0
Xinjiang	4.3	15.0	32.0	38.0	29.0	22.9
Jilin	15.7	15.0	32.0	30.0	21.0	6.8
Heilongjiang	11.5	12.0	21.0	19.0	14.0	4.4
Inner Mongolia	15.2	9.0	18.0	21.0	15.0	10.3

Note: Data for 2014-2017 are only available in integer values.
Source: Created by the author based on data from the NEA (each year)

A renewable energy policy assessment conducted by the European Commission (Ragwitz et al., 2007) pointed out that immature promotion schemes are potentially a major risk affecting the spread of renewable energy generation and concluded that more emphasis should be placed on the stability and reliability of the system as a whole. In fact, the introduction of feed-in tariffs in Europe has been criticized repeatedly by the Federation of Electric Power Companies of Europe and others for concentrating wind power generation projects in remote areas with low economic activity, land prices, and population density, and imposing unnecessary cost on consumers (Kainou (2008)).

The total cost of supplying electricity from large-scale renewable energy power plants can be divided into two categories: power generation cost and transmission cost (Kainou (2009)). The power generation cost include the construction and operation cost of power plants, and the major difference between regions is the cost of expropriating land for the construction of power plants. The cost of land acquisition declines as the location of the power plant moves further away from the city center. On the other hand, the further away from the city center the power plant is located, the longer the transmission distance becomes and thus the higher the transmission cost becomes. Therefore, there is an optimal distance from the city center at which the total cost is minimized. However, if the power generation and transmission businesses are different, the power producer only considers the cost of power generation and does not need to consider the cost of transmission. In other words, power producers will build power plants far from the city center where land prices are low, regardless of the total cost of supplying electricity in the area in which it is consumed.

In China, the power generation and transmission businesses were separated in 2002, and a feed-in tariff for wind power was introduced in 2009 (NDRC(2009)). This requires transmission companies to purchase wind-generated electricity, with the transmission companies bearing the cost of transmission and able to recover the cost out of the profits gained from the sale of electricity. While power producers are building large numbers of power plants in remote areas where wind conditions are favorable, China's electricity prices are regulated by the government, so changes in transmission cost are not fully reflected in electricity prices. Therefore, the transmission operators could not operate their businesses if they purchased power generated by renewable energy. In this way, the fact that wind farms were built in remote areas due to differences in cost-sharing entities is one of the reasons for the curtailment of wind power output.

In the past, China's power grid was operated at the regional grid level as shown in Table 1. Power supply and demand was regulated within the regional grid network. Therefore, there was little inter-regional power grid flexibility, and the high-voltage transmission lines were mainly short, at less than 300 km in length. However, as mentioned above, wind power plants were concentrated in the western and northern regions, where wind resources are abundant, making it difficult to coordinate the supply and demand for power within the region. As a result, wind power generation in the western and northern regions had to be suppressed.

The most effective way to solve the power curtailment problem is to transmit wind-generated power from the western and northern regions to the eastern coastal region, where demand for electricity is high. However, since the transmission distance in this case exceeds 500 km, the cost of conventional transmission methods will be high, and the transmission business will only be profitable if the power is transmitted at higher voltages. Therefore, the Chinese government has implemented a plan to build ultra-high-voltage (UHV), long-distance transmission lines to transmit wind-generated power from the western and northern regions to the eastern region.

Based on the above, this study considered how the optimal location of wind power generation could be changed by using transmission lines with different voltages. We conclude that the construction of a transmission network at higher voltage would considerably lower the urban supply price of wind-generated electricity in the western and northern regions. In other words, the profitability of wind-generated electricity in the western and northern regions has improved.

2. China's Electric Power Supply System

In 2002, the Chinese government reformed its power supply system by separating the generation and transmission of power. This separation of power generation and transmission is one of the reasons for the suppression of wind power output in the northern part of the western region, as already mentioned.

Table 2 Regional grid of China

Regional grid	Provinces
Northeast	Heilongjiang, Liaoning, Jilin, Inner Mongolia(East)
North China	Beijing, Tianjing, Shandong, Hebei, Shanxi
Northwest	Shaanxi, Ningxia, Gansu, Qinghai, Xinjiang, Tibet
Inner Mongolia	Inner Mongolia (West)
East China	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian
Central China	Chongqing, Jiangxi, Henan, Hubei, Hunan, Sichuan
South China	Guangdong, Guangxi, Hainan, Guizhou, Yunnan

Source: Created by the author based on State Grid Corporation of China (SGCC) HP

As shown in Table 2, China's power grid is roughly divided into six regions: Northeast, North China, Northwest, Inner Mongolia, East China, Central China, and South China, and the supply and demand of electricity was adjusted between these regions. As mentioned above, the concentration of wind power development in the northwest and north regions has made it difficult to adjust the supply-demand balance within the regions.

In order to solve the problem of power curtailment in these regions, the Chinese government has plans to transmit wind power from the Inner Mongolia Grid, the Northwest Grid, and the Northeast Grid to the eastern coastal regions where demand for electricity is high. However, because the transmission distance to the eastern region exceeds 500 km, UHV transmission lines are required. The UHV transmission system can compress the current and control power loss even when transmitting power over long distances. Conversely, transmitting power over long distances exceeding 500 km using normal high-voltage 220 kV transmission lines would result in large power losses and very high transmission cost.

This study compared the use of two transmission lines, one 220 kV and the other 750 kV, to examine how the optimal location for transmitting wind-generated power varies between existing high-voltage transmission lines and new UHV transmission lines.

3. A Model for Minimizing the Location Cost for Power Plants

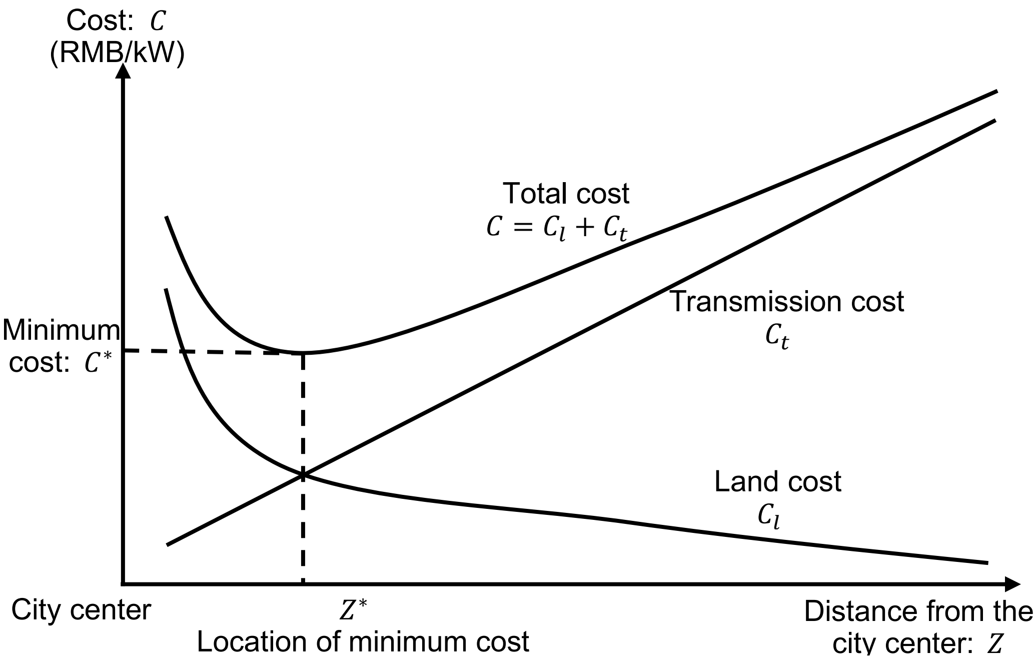
3-1 Kainou model

This study uses a model for minimizing the location cost for renewable energy power plants (Kainou (2009)). Figure 2 illustrates the Kainou model.

Wind power generation requires an overwhelmingly large land area compared to thermal power plants of the same capacity. This is due to technical restrictions such as the need for large spacing between wind turbines, in addition to the extremely low energy density of wind power. Therefore, in addition to the wind conditions, the land value of the site itself is critically important in determining the location of wind power generation.

In this study, it is assumed that the Beijing metropolitan area (Jing-jin region) is a demand center for electric power. The metropolitan area, along with the Yangtze River Delta and the Pearl River Delta, is the most densely populated and industrially developed region in China.

Figure 2 Illustration of Kainou model



Source: Created by the author based on Kainou (2009)

The total cost of a power plant consists of the cost of expropriating the land on which the plant is to be built (land cost), the cost of the generator itself and its installation, and the cost of the transmission facilities (transmission cost). However, the generator and installation cost are excluded from the cost considered in the power plant location model in this section because they are considered to be independent of the location of the power plant.

In general, as the distance (Z) from the city center (the location of electricity demand) increases, the land cost (C_l) decreases because competition for land use decreases and land prices become cheaper. The incline of the decline is initially steep, but this is expected to gradually slow down as the distance increases. Next, transmission cost (C_t) are expected to increase proportionally with the increase in the distance of the transmission line extension. Therefore, the transmission cost (C_t) are assumed to be a straight line with a constant term. Therefore, the total cost of constructing a power plant ($C = C_t + C_l$) is U-shaped as shown in Figure 3, and this exists at a distance (Z^*) from the city center that achieves the minimum cost (C^*).

3.2 Estimation of Land Cost

Land cost is expressed as the product of land area and land price, and land price is considered to depend on the distance from the city center, as described above. Although the data is somewhat old, for land prices, we used 210 items of industrial land data around the metropolitan area from the China Land Market Network (2010). However, this data does include industrial parks. Land prices in industrial parks are higher than those in surrounding areas because of the infrastructure for roads and electricity. This makes them unsuitable for power plant construction. Therefore, in this study, the industrial parks were excluded from the sample, and the remaining 154 data items were used to estimate the relationship between land price and distance. The estimation results are shown in equation (1), where P is the land price (RMB per square meter) and Z is the distance of the land from the city center.

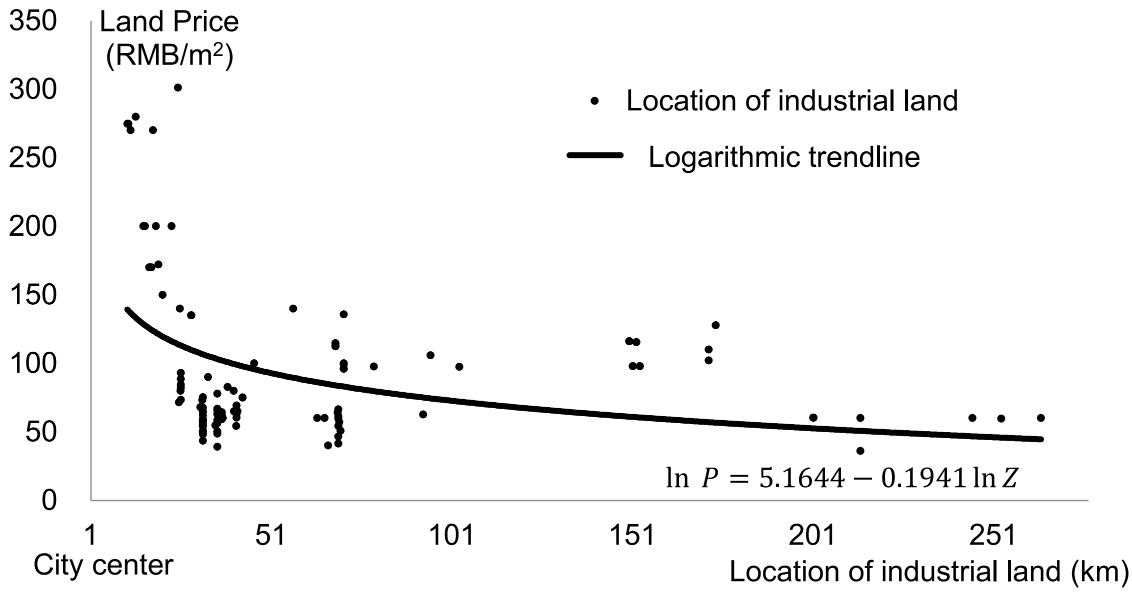
$$\ln P = \underset{(26.23)}{5.1644} - \underset{(-3.91)}{0.1941} \ln Z \tag{1}$$

The coefficient of distance ($\ln Z$) was significant at a 95% degree of significance. The adjusted R-square with degrees of freedom was 0.801. According to this estimation, land price decreases by about 0.19% when the distance of land from the city center increases by one percent. The land cost can be expressed as follows.

$$\begin{aligned} C_l = A \cdot P &= 49.6 \cdot \exp(5.1644 - 0.1941 \cdot \ln Z) \\ &= 49.6 \cdot e^{5.1644} \cdot Z^{-0.1941} \end{aligned} \tag{2}$$

A is a constant value for the area of land required for the power plant which was set to 49.6 m^2/kW in this study with reference to Kainou (2009).

Figure 3 The industrial land price and distance from the city center



Source: Created by the authors based on the data from landChina.com(2011)

3.3 Estimation of Power Cost

Transmission cost (C_t) consist of transmission facility construction and maintenance cost (C_{tn}) and substation facility construction and maintenance cost (C_{ts}). The former are assumed to increase in proportion to the increase in transmission distance (Z: distance from city center), while the latter are assumed to be fixed. The parameters used in the model are shown in Table 3.

Table 3 The parameters used in the transmission cost

Cost \ Transmission voltage	220kV	750kV
C_{tn} (RMB/kW/km)	5.7	1.1
C_{ts} (RMB /kW)	135.3	149.7

Source: Created by the authors based on the data from SPC(2001) and SGCC(2008)

The cost of transmission is expressed in the following equation for a 220 kV transmission line

$$C_t = 135.3 + 5.7\,Z \tag{3}$$

If the transmission line is 750 kV, this can be obtained as follows:

$$C_t = 149.7 + 1.1\,Z \tag{4}$$

Therefore, we can solve the following minimization problem to find the location (distance from the city center) where the cost of the power plant will be lowest.

$$\underset{0\le Z}{\text{Min}}\, C(Z) = \underset{0\le Z}{\text{Min}}(C_l(Z) + C_t(Z)) \tag{5}$$

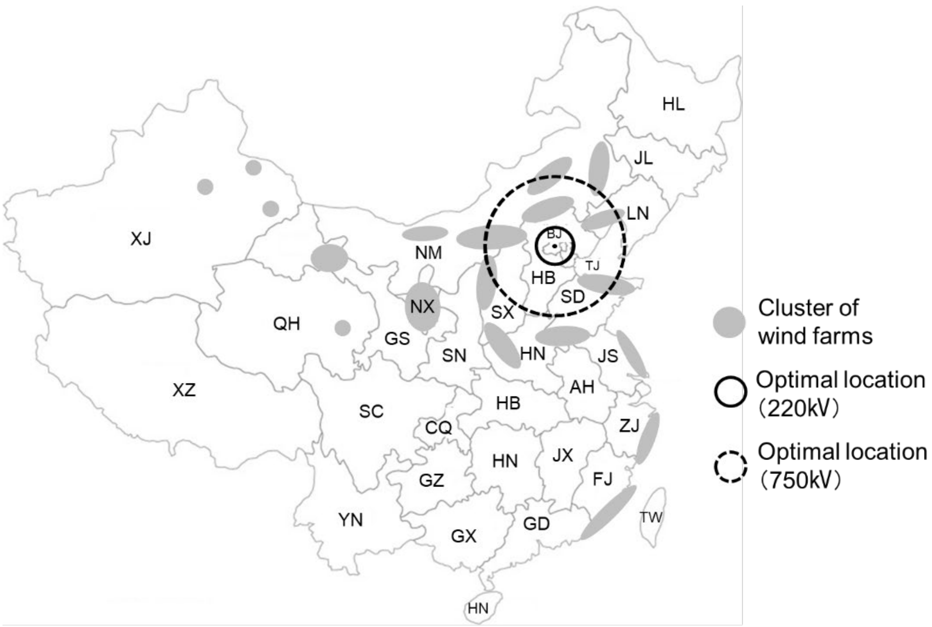
4. Estimation Results

When the transmission line is 220 kV, the least expensive location for a large-scale wind farm is 118 km from the city center. Figure 4 shows the locations of wind farms and the optimal location areas as of 2010. As shown in the figure, most of the wind farms in this region are located farther away from the optimal location area. Under the Chinese system, wind farm operators do not bear transmission cost, so their only concerns are wind conditions and land prices. This has led to wind farms being built far apart from urban centers.

Next, we estimated the minimum cost location for a case involving a 750 kV transmission line: the cost of 750 kV transmission is about 20% of that of 220 kV transmission, so the incline of the straight line in Figure 2 representing the cost of transmission is quite moderate. However, since land prices are taken from 2010, the land cost curve in Figure 2 is invariant. Therefore, the minimum cost point for 750 kV transmission is farther away from the metropolitan area than for 220 kV transmission.

The distance with the lowest total cost of power generation using 750 kV transmission lines is 471 km (Figure 4). 750 kV transmission lines eliminate the cost bottleneck for wind power development in the Inner Mongolia grid, the Northeast grid, and the Northwest grid, and ensure the economic viability of transmission projects to the metropolitan area.

Figure 4 Optimal location and current status of wind power in China



Source: The cluster of wind farms based on the data from people.cn(2021). The optimal location based on the author's simulation.

5. Situation and issues surrounding long-distance transmission lines

China is building UHV transmission lines for long-distance transmission at a rapid pace to solve the shortage of transmission capacity. According to the China Electricity Council [1], the total distance of transmission lines above 750 kV in China in 2010 was about 10,657 km. However, by 2020, this will be 66,682 km, a six-fold increase. On the other hand, the total distance of transmission lines below 750 kV has only increased by a factor of 1.5, and they have been replaced by transmission lines with a relatively high voltage. Therefore, since 2016, there have been improvements in wind power suppression.

While UHV transmission lines tend to ensure the economic efficiency of long-distance transmission, there are some challenges in operating UHV transmission lines. First, the large transmission capacity of UHV transmission lines requires a large amount of electricity for stable transmission. On the other hand, the output of renewable energy power is not stable because the output of a single power plant is not large and is weather-dependent. Therefore, when operating a high-voltage transmission line, it is necessary to take power from several renewable energy power plants and combine them into a large capacity, and then add these to a regulating power source such as a thermal power or hydroelectric power source[2]to ensure stability.

In 2014, operation of the "Hami South-Zhengzhou" transmission line, which integrates wind and thermal power generation, began. The 14th Five-Year Plan for 2020-25 includes a plan to develop renewable energy power generation in combination with hydroelectric and thermal power generation. This is a necessary measure to ensure the stable operation of the UHV power grid.

6. Conclusion

This study introduces a cost minimization model for the locating of large-scale wind power plants. Using this model, the optimal location of wind power plants in the metropolitan area of China (Jing-jin region) was examined by referencing, as an example, the change in the optimal location of wind power plants due to the increase in transmission voltage (which can be interpreted as a technological advancement in the electric power industry).

In China, where the power generation and transmission businesses are separate, the wind power promotion policy allows power producers to build power plants but not to bear the cost of transmission, so power plants are located in remote areas where the cost of land expropriation is low. However, for the utilities that transmit power to urban areas with high electricity demand, longer transmission lines increase cost. On the other

1 China Electricity Council, "2011 Basic Electricity Statistical Data List" and "2020 Basic Electricity Statistical Data List"

2 Power sources necessary to maintain the supply-demand balance by adjusting the imbalance between supply and demand of electricity caused by load fluctuations and unexpected problems at power plants, and other factors.

hand, while transmission and distribution companies are obliged to purchase electricity generated from renewable energy sources, because the supply price of electricity is regulated, the increase in transmission cost cannot be directly reflected in the supply price. This has led to transmission and distribution companies refusing to allow renewable energy-generated electricity to be connected to the grid. If left unchecked, this could have put the brakes on the spread of renewable energy generation.

Transmission of wind-generated power built in western and northern China to the eastern coastal areas, where demand for electricity is high, is an effective solution, but transmission over existing 220 kV transmission lines is too costly. This study examined the economic feasibility of transmitting wind-generated power at 750 kV, which is the highest voltage available. As a result, it was found that the point where the cost is minimized is far from the metropolitan area (expanded from about 120 km to about 500 km), and that transmission from Inner Mongolia and the northeastern region to the metropolitan area is also economically feasible.

As of 2020, the total distance of China's UHV transmission lines above 750 kV is about six times greater than in 2010. The development of the UHV grid is alleviating the problem of wind-generated electricity power curtailment in the northwest region. However, it should not be forgotten that the use of wind-generated power poses other problems. Wind power is an unstable power source as it is affected by weather and other factors. Therefore, it is necessary to develop a regulating power supply with thermal and hydroelectric power generation to transmit wind power at very high voltages. The Chinese government must build a power supply system capable of stably transmitting renewable energy power at very high voltage in order to further promote the spread of renewable energy.

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