The Future of Hydropower in Sichuan Province, China: High-voltage Transmission Line Extension and Hydropower Installed Capacity

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ABSTRACT

Currently, the increasing hydropower installed capacity in Sichuan exceeds the provincial demand for electricity, and many hydropower plants decrease their operating hours to prevent the grid system from being overloaded. Lower operating hours decreases profits and could lower investor interest in new hydropower plant construction in Sichuan. However, with the installation of high-voltage (500 Kv) power transmission lines, more hydroelectricity can be transmitted from Sichuan to other provinces, which promotes the development of the hydropower industry. In this research paper, I determine the numerical relationship between the length of high-voltage power transmission line and hydropower installed capacity in Sichuan. I collected four sets of data, including the hydropower installed capacity, the annual amount of hydroelectricity, exported hydroelectricity, and the length of high-voltage transmission line from 2009 to 2016 in Sichuan Statistical Yearbooks. I found the exported hydroelectricity and length of the high-voltage transmission line was positively correlated, and the slope of the best fit line was 0.0163. Additionally, the annual hydroelectricity and hydropower installed capacity were positively correlated, and the slope of the best fit line was 0.228. Through those two equations, I estimated the increasing of hydropower installed capacity in relation to the extension of the high-voltage transmission line in 2020. This research paper can serve as a model for analyzing the effects of extending the high-voltage transmission line on the development of hydropower in other regions.

KEYWORDS

Sichuan, oversupplied electricity, exported hydroelectricity, length of high-voltage transmission line, linearity

INTRODUCTION

As China has experienced rapid development since economic reform in the 1980s, energy demand has steadily grown in recent decades (Liu et al. 2015). Presently, China's primary energy resource is coal. However, increasing energy demand cannot be met solely by coalburning plants, supplies of which are limited by mining and transportation infrastructure (Chang et al. 2010). More importantly, since nearly seventy percent of carbon dioxide released to the atmosphere is from the combustion of coal, higher coal consumption has driven severe environmental issues in China (Fang and Zeng 2007). Thus, to achieve the Chinese government's stated goal of decreasing Chinese carbon dioxide emissions by 40-45% in 2020 relative to 2005, China urgently needs to develop renewable energy supplies to supplement and ultimately replace coal-burning plants (Liu et al. 2018). Hydropower, in particular, has been prioritized by the Chinese government in the 12th and 13th Five Year Plans.

Sichuan Province has the second most hydropower resources among China's provinces, and has been a center for development of new hydropower plants in recent years (Wang et al. 2018). The latest hydropower resources report, published in 2008 by Chinese government, proves that hydropower installed capacity in Sichuan can reach a maximum of 131 million kilowatts (Liu 2010). From 2008 to 2016, the hydropower installed capacity increased from 22 million kilowatts to 72 million kilowatts (Sichuan Provincial Bureau of Statistics 2017). Even though the hydropower installed capacity continuously increased during this period, the decreasing average operating hours of hydropower plants and growth of abandoned hydropower resources underscores uncertainty regarding future development of hydropower in Sichuan province (Wang et al. 2018).

Since the electricity generated by hydropower projects cannot be stored, it must be immediately transmitted to consumers through transmission lines. However, if transmission line are overloaded, hydropower plants supplying the lines have to stop generating electricity. From 2012 to 2016, the average annual operating hours of each hydropower project in Sichuan decreased from 4208 to 3602 (Sichuan Statistical Yearbook). In other words, Sichuan hydropower plants in 2016 operated 14.4% less than they did in 2012. With lower operating hours, hydropower resources that could be used to generate electricity have been abandoned in recent years. As hydropower plants cannot maximize electrical output, their total revenues decrease, which can result in reduced investment in the hydropower industry in Sichuan

(Phoenix News 2017). One means of maximizing the electrical output of hydropower is to export more electricity to nearby provinces by building high-voltage transmission lines which are necessary for long-distance electricity transmission. In 2008, 500 kilo-voltage transmission lines in Sichuan transmitted 9.535 billion kilowatt-hour electricity to other provinces (Sichuan Provincial Bureau of Statistics 2010). Since then, both the length of highvoltage transmission line and the quantity of exported hydroelectricity have increased.

In this research paper, I document historical patterns of and construct a model for predicting the relationship between the extension of the high-voltage transmission lines and installed hydropower capacity on Sichuan Province, generating an estimate of the rise of the hydropower installed capacity corresponding to the extension of the high-voltage transmission lines in Sichuan in 2020s. Thus, my central research question is to what extent does the hydropower installed capacity in Sichuan increase with the expansion of highvoltage transmission line. To determine this, I pose two sub-questions: what is the relationship between the quantity of exported hydroelectricity and the length of high-voltage transmission line? And, what is the relationship between the hydropower installed capacity and the actual amount of annual electricity generated by hydropower.

BACKGROUND

Since 2008, the hydropower industry has experienced rapid growth in Sichuan province. From 2009 to 2016, the hydropower installed capacity increased from 26.76 million kilowatts to 72.45 million kilowatts (Figure 1). Then at the end of 2016, the total amount of hydropower installed capacity was 72.45 million kilowatts exceed the hydropower installed capacity in Yunnan province and made Sichuan have the most abundant hydropower installed capacity compared with other provinces in China (Sichuan Provincial Bureau of Statistics 2017).

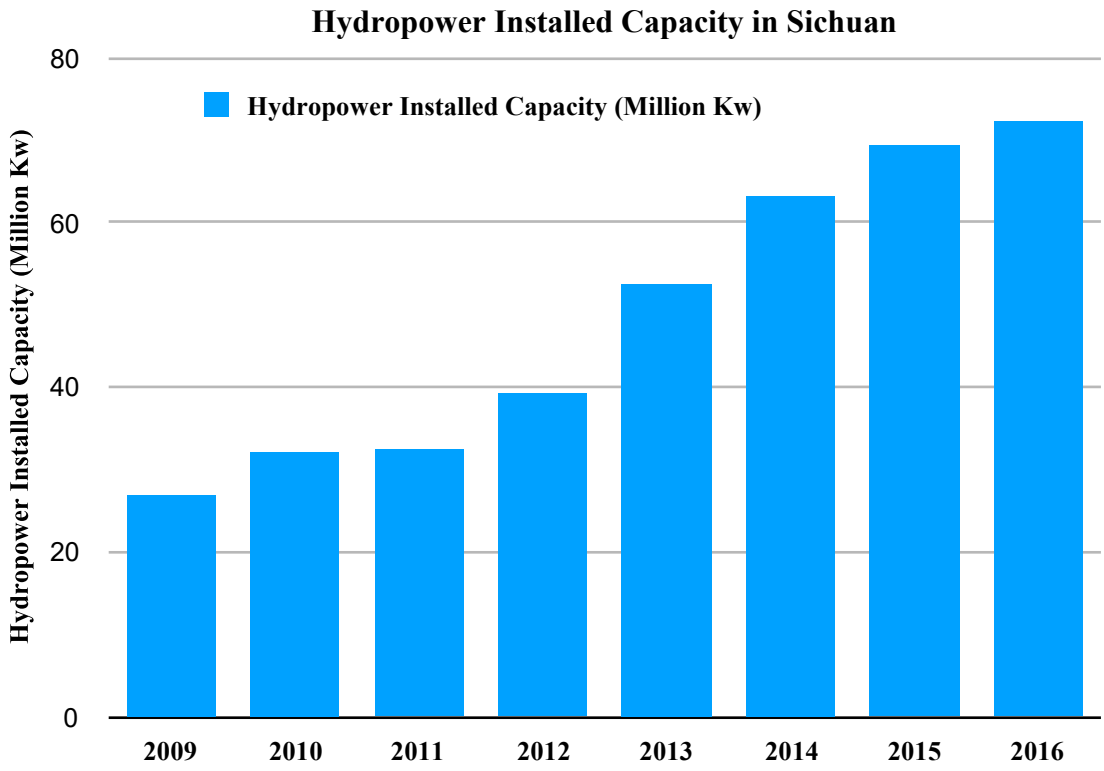

Figure 1. Hydropower Installed capacity changes from 2009 to 2016. Those data were collected from the Sichuan Statistical Yearbooks.

With the increasing number of hydropower plants and existing coal-burning plants in Sichuan, the total annual electricity generation capacity is more than the Sichuan provincial electricity consumption. From 2009 to 2016, Sichuan provincial electricity consumption has an average yearly increasing rate of 6.8%, and the average annual growth rate for hydropower installed capacity in Sichuan is 15.3% in the same period. The higher growth rate of hydropower plants resulted in the rising exported hydroelectricity. The graph shown below can vividly illustrate the change in the quantity of provincial electricity consumption and the exported hydroelectricity (Figure 2).

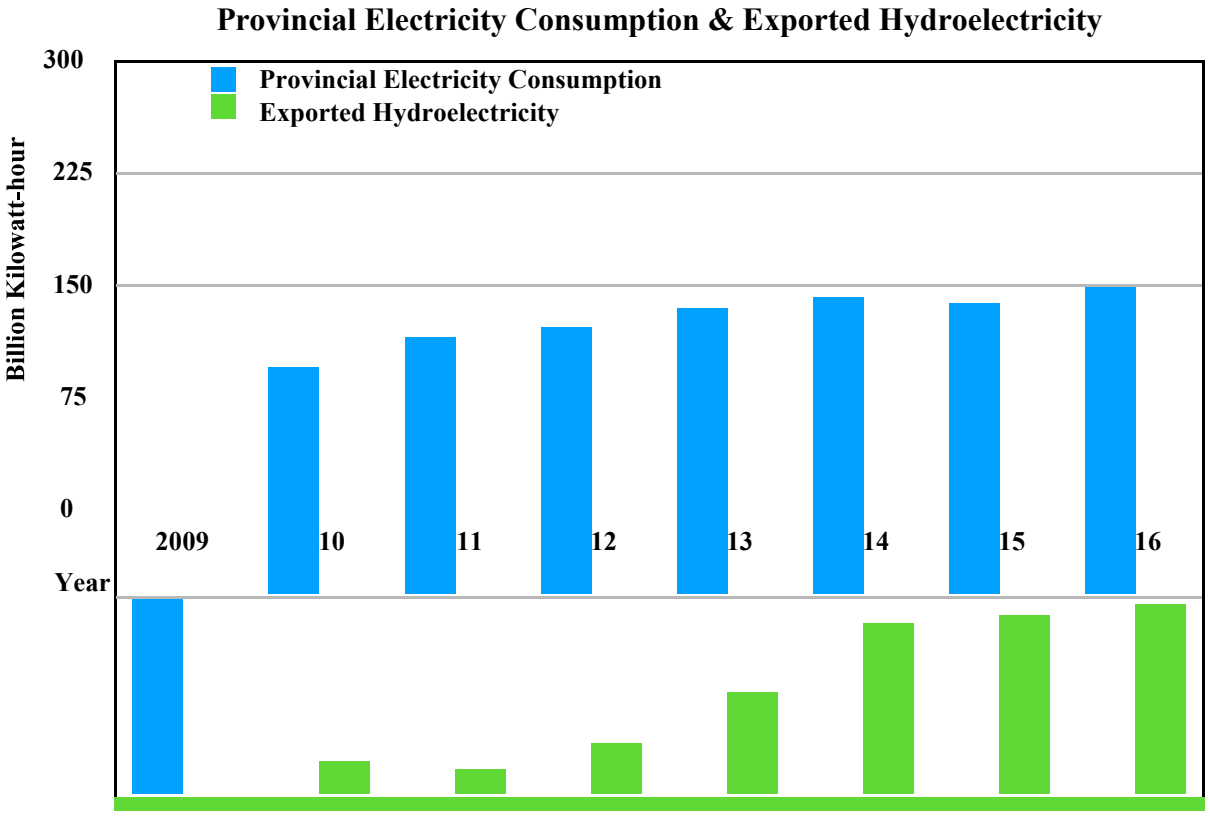

Figure 2. Changes in the quantity of provincial electricity consumption and exported hydroelectricity in Sichuan. Those data were collected from the Sichuan Statistical Yearbooks.

To transmit more hydroelectricity from Sichuan to other provinces, the Chinese government has extended the length of high-voltage (500 kilo-voltage) transmission lines. In 2009, the 500 kilo-voltage transmission line between Baoji city and Deyang city was operated, which made the hydroelectricity from Sichuan can be transmitted to Shanxi province (Sichuan Provincial Bureau of Statistics 2010). In 2013, the construction of highvoltage power transmission line had made it possible to transmit more hydroelectricity from Sichuan to Chongqing, Zhejiang, Hubei, Xian, Jiangsu, and Shanghai (Sichuan Provincial Bureau of Statistics 2014).

In this research paper, I used the past several years' data to figure out the relationship between the quantity of exported hydroelectricity in Sichuan and the construction of highvoltage transmission line. Then, I calculated the coefficient between the annual hydroelectricity production and the hydropower installed capacity. Eventually, given the assumption about the future construction of high-voltage transmission line, I predicted the increasing amount of hydropower installed capacity in corresponding to the development of the high-voltage transmission line in Sichuan.

Methodology

I used the past several years' data to determine the relationship between the quantity of exported hydroelectricity in Sichuan and the construction of high-voltage transmission line. Then, I calculated the coefficient between the annual hydroelectricity production and hydropower installed capacity. Given the assumption about the future construction of highvoltage transmission line, I then predicted the increasing amount of hydropower installed capacity in corresponding to the development of high-voltage transmission lines in Sichuan.

To analyze the effects of extending the high-voltage transmission line on hydropower installed capacity in Sichuan, I used historical data on the length of high-voltage transmission line in the Sichuan grid system to represent the development of the high-voltage transmission line. Then, I found the correlation between the length of high-voltage transmission line and the quantity of exported hydroelectricity from Sichuan to demonstrate that these two variables are correlated. Based on data from 2009 to 2016, I calculated the slope and intercept of the best-fit-line through applying Python. Also, I determined the relationship between the annual hydroelectricity production and the hydropower installed capacity by analyzing previous data from 2009 to 2016. I found that those variables are correlated as well, and I calculated the slope and intercept of the best-fit line.

I used these calculations to predict the increasing amount of exported hydroelectricity in 2020 by assuming the high-voltage transmission line in Sichuan extend at the steady rate. Then, I applied the rising amount of exported hydroelectricity in the best-fit line of annual hydroelectricity and the installed capacity to calculate the increased amount of hydropower installed capacity in corresponding to the higher hydroelectricity. Through those two-steps, I determined the effects of extending the high-voltage transmission line on hydropower installed capacity in Sichuan.

METHODS

I collected four sets of data from 2009 to 2016 in Sichuan Statistical Yearbooks: hydropower installed capacity, annual hydroelectricity production, exported hydroelectricity, and the length of the high-voltage power transmission line (Table 1). I chose 2009 as the initiated year in analyzing because the data in 2008 can cause bias as the huge earthquake happened in 2008 in Sichuan resulted in the damages to both hydropower plants and the transmission line.

Table 1. Summary of four sets of data from 2009 to 2016. Those data were collected from the Sichuan Statistical Yearbooks

Year	Hydropower Installed Capacity (Million Kw)	Annual Hydroelectricity Production (Billion Kwh)	Exported Hydroelectricity (Billion Kwh)	Length of High-Voltage Power Transmission Line (km)
2009	26.76	93.87	9.535	6400
2010	32.13	113.98	21.4	8016
2011	32.36	125.7	15.8	9123
2012	39.32	154.52	34.3	9702
2013	52.66	202.34	68.8	12193.9
2014	63.27	257.8	116.5	13078
2015	69.39	276.74	122.6	14808.3
2016	72.45	298.87	128.5	13560

Calculate the correlation and linearity between length of high-voltage power transmission line and the quantity of exported hydroelectricity

Firstly, I inputted those four sets of data in Python. To determine the degree of association between two variables, I created a function to return the standard unit of each number by subtracting individual numbers by the mean of the group and then dividing by the standard deviation of the group of data. After that, I created another function to calculate the degree of association between two variables by presenting the mean of the sum of those standardized variables. After calculating the level of correlation between two variables, I measured the slope of the best-fit line through the equation . The intercept of the best-fit line was estimated by subtracting the mean of y by the sum of the mean of x and slope. By inputting the data length of high-voltage power transmission line and quantity of exported hydroelectricity, I

```
def parameter_estimates(t):
    y_mean = np.mean(t.column(3))
    y_sd = np.std(t.column(3))
    x_mean = np.mean(t.column(4))
    x_sd = np.std(t.column(4))
    r = correlation(t.column(3), t.column(4))
    slope = r* (y_sd/x_sd)
    intercept = y_mean - slope*x_mean
    return make_array(r, slope, intercept)

parameters = parameter_estimates(Sichuan)
print('r:', parameters.item(0), '; slope:', parameters.item(1), '; intercept:', parameters.item(2))
```

```
r: 0.94790371702903 ; slope: 0.016321343764393318 ; intercept: -112.5728664828761
```

Figure 2. Correlation and linearity between length of high-voltage power transmission line and the quantity of exported hydroelectricity. The symbol r represents the correlation coefficient between those two variables, and the slope of the best-fit line is 0.0163 with a y-intercept -112.572.

calculated the correlation between the length of high-voltage power transmission line and quantity of exported hydroelectricity, the slope of the best-fit line, and the intercept of the best-fit line through the following steps shown below (Figure 2).

```
def parameter_estimates(t):
    y_mean = np.mean(t.column(1))
    y_sd = np.std(t.column(1))
    x_mean = np.mean(t.column(2))
    x_sd = np.std(t.column(2))
    r = correlation(t.column(1), t.column(2))
    slope = r* (y_sd/x_sd)
    intercept = y_mean - slope*x_mean
    return make_array(r, slope, intercept)

parameters = parameter_estimates(Sichuan)
print('r:', parameters.item(0), '; slope:', parameters.item(1), '; intercept:', parameters.item(2))
```

```
r: 0.9981570190331113 ; slope: 0.22834507508018526 ; intercept: 5.047900961414008
```

Figure 3. Correlation and linearity between quantity of annual hydroelectricity production and the amount of hydropower installed capacity. The symbol r represents the correlation coefficient between those two variables, and the slope of the best-fit line is 0.228 with a y-intercept 5.048.

Calculate the correlation and linearity between quantity of annual hydroelectricity production and the amount of hydropower installed capacity

Then, I inputted other two sets of data to calculate the correlation and linearity between the actual amount of hydroelectricity production and the hydropower installed capacity in Sichuan through the following steps that shown below (Figure 3).

Predict the length of high-voltage power transmission line in Sichuan in 2020

Based on the average increasing rate of length of high-voltage power transmission line in Sichuan from 2009 to 2016, I predicted the length of high-voltage power transmission line at the end of 2020. From 2009 to 2016, the total length of high-voltage power transmission increased by 7160 kilometers, and the average annual increasing rate is 11.3% (Table 1).
Thus, I estimated the total length of the high-voltage power transmission line would equal to 13560! $*(1.113)^4$ which is 20808 kilometer in 2020.

RESULT

I estimated the increasing amount of hydropower installed capacity in Sichuan in relation to the extension of high-voltage power transmission line in 2020 by calculating the degree of linearity between the length of high-voltage power transmission line and the quantity of exported hydroelectricity and the degree of linearity between quantity of annual hydroelectricity production and the amount of hydropower installed capacity.

Level of correlation and degree of linearity between length of high-voltage power transmission line and the quantity of exported hydroelectricity

By putting the data on length of high-voltage power transmission line and the quantity of exported hydroelectricity from 2009 to 2016 in those function, I calculated the correlation and linearity between those two variables (Figure 2). The correlation coefficient r between those two variables was 0.948, which represents a strong positive linear relationship. The slope of the best-fit line was 0.0163 and the y-intercept of the best- fit line was -112.57. I then plotted a graph to vividly illustrate this best-fit line (Figure 4).

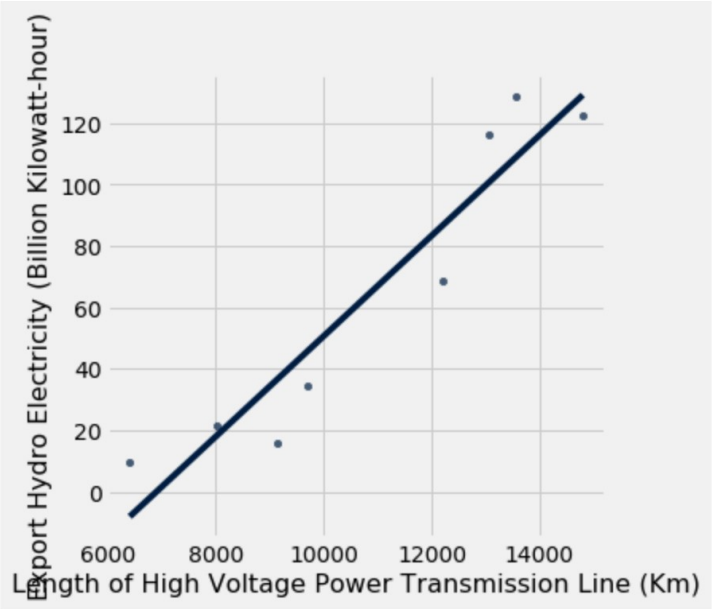

Figure 4. Linearity between length of high-voltage power transmission line and the quantity of exported hydroelectricity.

Level of correlation and degree of linearity between quantity of annual hydroelectricity production and the amount of hydropower installed capacity

Then, I inputted the data about the quantity of annual hydroelectricity production and the amount of hydropower installed capacity from 2009 to 2016 in those functions (Figure 3). I calculated the correlation coefficient between those two variables as 0.998, which reflects a strong positive linear relationship. The best-fit line of those variables had a slope of 0.228, and the y-intercept of the line was 5.048 (Figure 5).

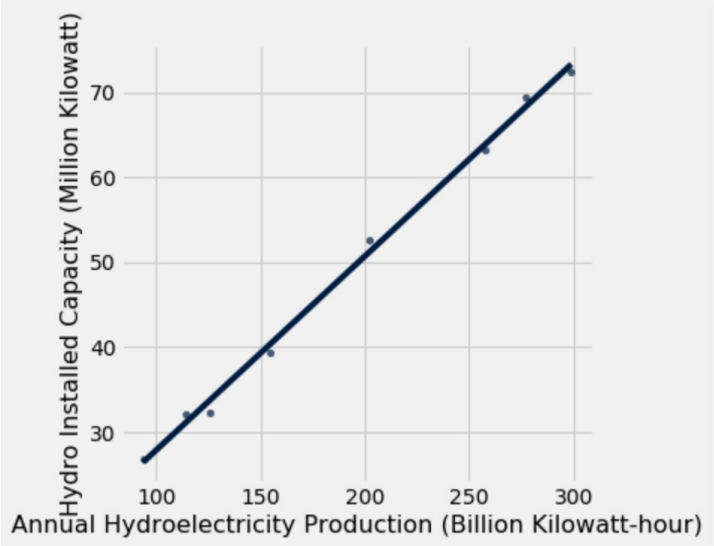

Figure 5. Linearity between quantity of annual hydroelectricity production and the amount of hydropower installed capacity.

The increasing amount of hydropower installed capacity in Sichuan in 2020 in corresponding to the extension of the high-voltage power transmission line

After estimating the length of high-voltage power transmission line in 2020, I predicted the amount of exported hydroelectricity by multiplying the length of the transmission line by the slope of the best-fit line in figure 4. I found the quantity of exported hydroelectricity could increase by 339.615 billion kilowatt-hours in Sichuan in 2020. Then, since the increasing amount of exported hydroelectricity represented more hydroelectricity would be produced in 2020, I calculated the growing amount of hydropower installed capacity in 2020 would be 77.548 million kilowatts through multiplying the growing amount of exported hydroelectricity by the slope of the best-fit line in the figure 5. Finally, I determined that hydropower installed capacity in Sichuan will increase by 77.548 million kilowatts, and reach 149.998 million kilowatts in 2020.

DISCUSSION

I determined the quantitative relationship between the length of high-voltage transmission line and exported hydroelectricity, and calculated the quantitative relationship between the actual hydroelectricity production and hydropower installed capacity in Sichuan. The positive correlation coefficients between those variables prove the length of high-voltage power

transmission line can affect the hydropower installed capacity in Sichuan. This suggests that, since hydropower resources are unevenly distributed in China, only a comprehensive grid system which connects easterners and western provinces can effectively promote the development of hydropower in China.

Effects of extending the high-voltage power transmission line on the hydropower installed capacity

The construction of high-voltage power transmission lines should be applied as an essential guideline in analyzing the future development of hydropower throughout China. As researchers and policy-makers predicted the growth of hydropower industry in China, some believed the hydropower industry would rapidly grow because China has abundant hydropower resources, huge market demand for the electricity, and enough funding to build hydropower projects (Chang et al. 2010). However, those factors can only guarantee that the hydroelectricity can be produced, but they cannot ensure all the hydroelectricity can be consumed by users. Thus, it is necessary to extend the high-voltage power transmission line which can transmit electricity to other provinces to increase the demand for the hydroelectricity.

Lacking high-voltage transmission can negatively affect the development of the hydropower industry. Adjacent to Sichuan province, Yunnan province also has an enormous amount of hydropower resources. However, the weak grid system that limits the transmission of hydroelectricity has resulted in hydropower curtailment since 2009. In 2009, 4.4 billion kilowatt-hours hydroelectricity was curtailed (Liu et al. 2018). In 2016, the curtailed hydroelectricity in Yunnan reached 31.2 billion kilowatt-hours which are equal to 22.1% of the total annual electricity consumption in Yunnan (Liu et al. 2018). Undoubtedly, the hydropower curtailment in Yunnan resulted in lower profit in the hydropower industry and negatively influenced investment in and growth of hydropower. Clearly, one of the most important reasons behind the massive hydropower curtailment is the insufficient high-voltage transmission line (Liu et al. 2018).

With the construction of a high-voltage power transmission line, the demand for hydroelectricity will increase, and the hydropower installed capacity can expand in the future. I predicted the increase of annual hydroelectricity production in Sichuan in 2020 by calculating the relationship between exported hydroelectricity and the extension of the length of high-

voltage transmission line in Sichuan. I assumed the length of high-voltage power transmission line in Sichuan would continuously extend in 2020. Eventually, higher levels of exported hydroelectricity can promote the growth of hydropower installed capacity in Sichuan.

Significance of comprehensive grid system in promoting the development of hydropower industry

To maximize nationwide hydropower installed capacity, the Chinese government has to build a comprehensive grid system connecting western and southern provinces, as the hydropower resources are unevenly distributed in China. The western provinces, including Yunnan and Sichuan, have 78% of the total national hydropower resources, but the electricity consumption in those provinces are relatively low (Liu et al. 2010). On the contrary, the 11 provinces located in the east and coastal areas only contain 6% of the total hydropower resources, but consume 51% of total electricity in China (Liu et al. 2010). Thus, only with a robust, effective and comprehensive grid system which connects eastern and western provinces, large quantities of hydroelectricity can be transmitted to eastern provinces, and the hydropower industry can expand in western regions, helping to meet China's renewable energy goals.

Limitations and future directions

One of the key limitations in this research paper is that I neglected other factors besides the length of the high-voltage power transmission line which can influence the hydropower installed capacity in Sichuan. Besides the length of the high-voltage power transmission line, the costs of the hydroelectricity can also significantly affect the growth of hydropower industry (Chang et al. 2010). Investors are more willing to build new hydropower projects if the average cost of hydroelectricity is low. Another limitation is that in reality the amount of exported hydroelectricity is not perfectly proportioned to the length of the high-voltage power transmission line. In the future, a more comprehensive analysis of the growth of hydropower installed capacity in China should consider effects from different factors.

This research paper offers a model for analyzing the effects of extending the high-voltage power transmission line on the hydropower installed capacity in other Chinese provinces. More

importantly, the methodology of the research paper can be applied in analyzing the effects of other factors on the development of hydropower industry. For example, I can find the level of linearity between the price of electricity and the installed hydropower in Sichuan to by analyzing data. Through considering more factors which can influence the development of hydropower industry, those researchers can create an accurate model to accurately estimate optimal hydropower installed capacity in relation to those factors.

Broder implications

After doing this research about the extension of high-voltage power transmission line and hydropower installed capacity in Sichuan province, I have the evidence to prove that extending the high-voltage power transmission line can promote the growth of hydropower in Sichuan because more hydroelectricity are needed by other regions. Also, I realize that Sichuan provincial government should build more high-voltage power transmission line to maintain the growth of hydropower installed capacity. In the report published by Jiangxi provincial government, a new high-voltage power transmission line connecting Sichuan and Jiangxi was initiated in 2018, and Jiangxi plans to largely import electricity from Sichuan (Lian 2018).

More importantly, the finding about the relationship between extension of high-voltage transmission line and annual hydroelectricity production in Sichuan proves the average operating hours of each hydropower project will increase with the development of highvoltage power transmission line given that the hydropower installed capacity is constant. As the demand for hydroelectricity increases and the increasing rate of hydropower installed capacity is lower than the total increasing rate of hydroelectricity consumption, the operating hours of each hydropower project will increase. Thus, those renewable energy companies can predict the operating hours and annual hydroelectricity production by the hydropower plant based on the assumptions about the total hydroelectricity consumption and hydropower installed capacity.

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