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Impacts of climate change on hydropower generation in China

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Abstract

Analyzing the impact of climate change on China's hydropower system can make great contribution to understanding the feedback mechanism of the climate change on energy system. In this work, an econometric model for regional hydropower generation is constructed to explore the impact of climate factors on hydropower generation in different regions of China by using the monthly panel data of 28 provinces in China. Further, we also make a prediction for the changes of hydropower generation in China caused by the changes of climatic factors under the three climate change scenarios (RCP2.6, RCP4.5 and RCP8.5) proposed in the Intergovernmental Panel on Climate Change's (IPCC) fifth assessment report. The results show that: (1) At the national level, the influences of climatic factors on hydropower generation are significant, the elasticity coefficients of rainfall, heating degree day (HDD), cooling degree day (CDD) and sunshine duration are 0.081, −0.016, 0.089 and −0.043 respectively. (2) The impacts of climatic factors on the hydropower generation in the northern and southern regions of China are different. The effect of rainfall on the hydropower generation is significant in the southern regions, but not in the northern region. The CDD has a significant effect on both the northern and southern regions, and the latter is greater (0.136%). The impact of HDD on the northern area is significant, while its influence on the southern area is not significant. The influence of sunshine duration is not significant in any region in China. (3) Compared with the year of 2011, the total changes of hydropower output caused by climate factors by 2100 under the RCP8.5, RCP4.5 and RCP2.6 scenarios are 153.29 billion kWh, 67.49 billion kWh and 22.10 billion kWh, respectively. The results imply that the hydropower is sensitive and vulnerable to climate fluctuation, leading to many uncertainties for its development in the future. Finally, some policy implications are proposed for the planning of hydropower in China.

Keywords: Climate change; Hydropower; Degree day; Panel data; China

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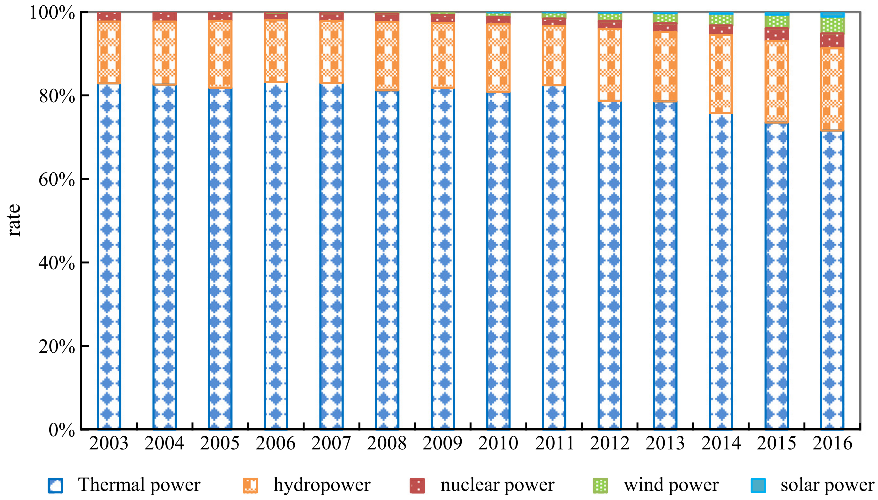


Fig. 1. The electricity supply structure in China from 2003 to 2016.
Source: China Electricity Council [6].

1. Introduction

Climate change is an indisputable fact, mainly caused by human activities, especially the combustion of fossil fuels that directly result in greenhouse gas emissions. As the issues surrounding climate change have become more and more serious, most countries in the world have been gradually reducing their dependence on fossil fuels and have been seeking other cleaner energies and technologies [1]. Therefore, renewable energy has been considered having a key role in mitigating climate change and has been actively promoted by many countries globally [27,29]. Particularly in China, with the largest carbon emissions in the world, great efforts have been made to promote renewable energy [8,9,28]. The share of renewable energy power generation in total electricity generation in China increased from 17.08% in 2003 to 28.4% in 2016 [6], making great contribution in alleviating the contradiction between reducing carbon emissions and meeting the growing energy demand in China [39].

Hydropower dominates China's renewable energy generation. Since 2003, hydropower generation has accounted for more than 15% of total power generation in China (Fig. 1), which is much greater than other renewable energy sources such as wind power and nuclear power, and is still in steady growth. Compared to other renewable energy sources, hydropower enjoys advantages such as more mature technology, stable operation, and lower operating and maintenance costs. However, although China is rich in hydropower resources, the utilization rate of hydropower resource is relatively low in comparison with developed countries, which is 37% (according to the amount of electricity generated) by the end of 2015 [31]. Therefore, there is still great potential for the development of hydropower in China in the future.

However, hydropower has strong sensitivity to climate fluctuation, because the daily operation of hydropower depends largely on weather and climate conditions [25,41]. On the one hand, a rise in temperature will increase the use of cooling equipment such as air conditioners in summer. Thus the increased power demand may stimulate hydropower generation as well. On the other hand, the frequency of extreme weather and climate events such as heavy rainfall, floods, hurricanes and freezing are likely to increase due to global warming, which may cause great damage to the electrical infrastructure. For example, Hurricane Sandy broke the power grid in the New York State, causing widespread blackouts in 2012. In addition, global warming can also change the water cycle and affect the hydropower resource endowment redistribution across regions [2]. Therefore, investigating the impact of climate change on the hydropower system is important for stabilizing the power supply and ensuring the production and life.

To date, the research on the relationship between climate change and hydropower has focused on two aspects, one being the role of hydropower in carbon emission reduction [2,5,13] and the other is on the impact of climate change on hydropower. Most researches on the latter aspect focus on hydropower resources endowment changes in a certain region under global warming from the hydrological point of view [16,19,35,37]. For instance, Freitas et al. [16]

analyzed the relationship between climate change and hydropower management in Brazil, and pointed out that further global warming could change the hydrological cycle, thus affecting the hydropower resources of Brazil. Hamududu and Killingtveit [19] simulated the change of regional runoff and estimated the hydropower generation under climate change, using twelve different Global Climate models (GCM). Spalding-Fecher et al. [35] assessed the vulnerability of hydropower in the Zambezi river basin in southern Africa and noted that climate change would increase the regional water-use competition between hydropower and irrigated agriculture. Vliet et al. [37] used the GCM model to assess the change of global hydropower generation caused by climate change.

There are also some studies focusing on the impact of climate change on hydropower systems from the perspective of social development and the electricity market [18,34]. For instance, Gaudard and Romerio [18] analyzed the influence of energy policy, climate policy, and the electric market on hydropower generation, and pointed out that climate change was one of the main driving forces of the power market, because climate warming would lead to a rising demand for electricity in summer. Ruggiero and Lehkonen [34] studied the relationship between renewable energy growth (including hydropower) and performance gains for electricity companies, using panel data regression analysis, applying the fixed effects estimator, the random effects estimator and the Granger causality test. Other studies have predicted the changes in hydropower output in different climate change scenarios in the future [3,27,38]. Boehlert et al. [3] explored the physical and economic impacts on hydropower in U.S. under a global greenhouse gas emissions scenario, and pointed out that under the high emissions scenario, climate change will increase the hydropower generation of the Northwest Pacific Ocean. Lucena et al. [27] used the Autoregressive Moving Average (ARMA) model to evaluate the climate vulnerability of renewable energy (mainly hydropower and liquid biofuels) in Brazil, and gave a long-term climate forecast with a set of the IPCC emissions scenarios. The results showed that biofuel production (especially biodiesel) and power generation (especially hydropower) may suffer negative effects from climate change. Wang et al. [38] analyzed the long-term relationship between hydropower generation in China, climatic factors (rainfall) and hydropower installed capacity, and predicted hydropower generation of nine hydropower provinces in China with different carbon emission scenarios, applying a grey prediction model.

While previous works confirm that climate change do have an impact on hydropower, from the perspective of the research region, there are few studies focusing on China. However, since China is the largest single hydropower producer [4], investigating climate vulnerability of the hydropower system of China seems to be typical and can also bring insights for other countries. In addition, from the perspective of research scope, most studies have analyzed the climate vulnerability of hydropower from the global or national level, and less research has been carried out on regional hydropower systems. China is a vast country, with great differences in the extent of climate change among different regions. For example, the drought has intensified and the precipitation has continued to decrease in northern China in recent 50 years, while the precipitation in the south of China has increased, and China may gradually present a trend of "southern flood, northern drought" in the future [36].

Is there any difference in the impact of climate conditions on hydropower generation in different regions within China? What is the extent of this impact? The answers to these questions are of great importance for the optimized planning of hydropower development in various regions in China. Therefore, another contribution of this paper is the concentration on the heterogeneity of impacts caused by climate factors on hydropower generation in southern[1] and northern China.

In terms of the quantitative research methods, the existing research methods on the impact of climate change on hydropower include the GCM model [19,25,37], time series analysis [27] and the grey prediction model [38], setting different climate change scenarios to forecast future hydropower output. These studies may reflect future trends in hydropower generation but there remain some issues to be investigated. For instance the GCM models do not detail the impact of climate factors on hydropower generation, while some other models will ignore the individual effects on different regions if only time series is used for regression analysis. Further, due to the availability of data, most studies analyze the relationship between climate change and the hydropower system by establishing a regression model concerning only climate factors, with no or less economic elements in regression, which may reduce the degree of robustness and credibility of results. What is more, there are more accurate climate change scenarios in the IPCC's fifth report. Will the new data and scenarios negate previous research results? The answer to this question is worth seeking.

[1] According to the National Bureau of Statistics (NBS), the southern region comprises Jiangsu, Zhejiang, Fujian, Sichuan, Chongqing, Guizhou, Yunnan, Guangdong, Guangxi, Hainan, Hubei, Hunan, Anhui and Jiangxi, while the northern region includes Jilin, Liaoning, Heilongjiang, Gansu, Inner Mongolia, Xinjiang, Shaanxi, Shanxi, Henan, Shandong, Hebei, Beijing, Qinghai and Ningxia.

Compared with previous studies, the main innovations of this work are as follows: (1) an econometric model for regional hydropower generation is constructed to explore the impact of climate factors on hydropower generation in different regions of China by using the monthly panel data from January 2007 to December 2015,[2] which can reflect the monthly temperature fluctuation characteristics. (2) Heating degree day (HDD) and cooling degree day (CDD) are used as temperature variables to access the effect of climate change on hydropower generation from the perspective of demand. (3) Non-climatic variables, including fixed assets investment, installed capacity and on-grid price, are used as control variables to construct a feedback model that reflects the influence of climate change on hydropower generation. As a result, the results are more credible than those that only consider climate factors. (4) Pooled Estimated Generalized Least Squares (Pooled EGLS) is used in regression analysis to reduce the heteroscedasticity caused by cross-sectional data [40], which can make the results more reliable. (5) We not only consider the climate vulnerability of hydropower at the national level, but also analyze the influence of climate factors on hydropower generation in different regions. (6) Further, we also predict the change of hydropower generation in China caused by climatic factors under the three climate scenarios (RCP2.6, RCP4.5 and RCP8.5) from the IPCC's fifth assessment report and some policy implications are put forward for the development of hydropower in China.

2. Econometric model and data source

There are many factors influencing hydropower generation. In addition to climate factors such as temperature, rainfall and sunshine duration, some non-climate factors such as installed capacity, working hours, fixed assets investment, price, operating costs, thermal power and other types of energy production, policy adjustment and so on can also affect hydropower generation. Therefore, after considering the data availability, we chose installed capacity, fixed assets investment and price to assess the impacts of non-climate factors on hydropower generation. The data used in this paper covers 28 provinces in China from January 2007 to December 2015.

2.1. Explanatory variables

2.1.1. Climate factors

2.1.1.1. Rainfall and sunshine duration. Rainfall is one of the most critical factors affecting hydropower [14,20]. Wang et al. [38] found that rainfall had a significant impact on various regions of China, especially Yunnan and Sichuan. Therefore, rainfall is selected in the econometric model in this paper. It is expected that with other factors remaining unchanged, hydropower generation will increase if rainfall increases.

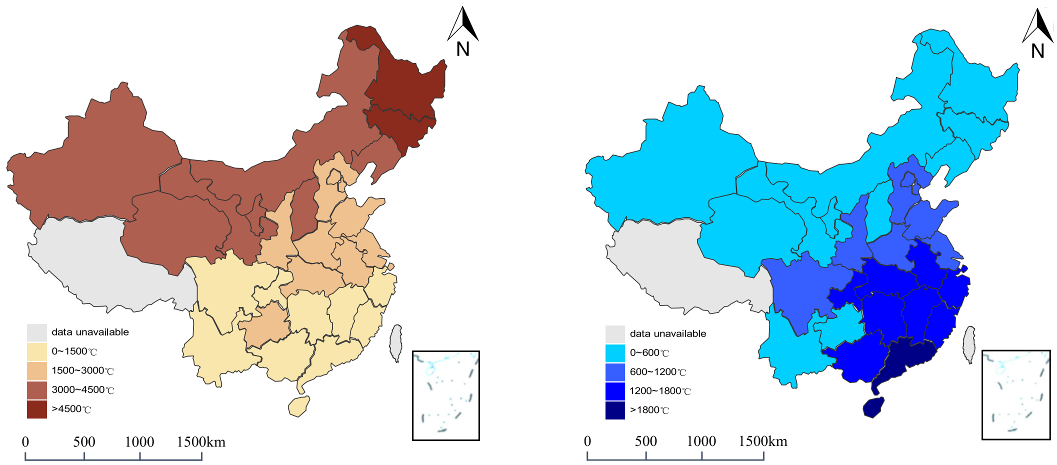
Besides, evaporation also has a direct impact on the generation of hydropower because it can reduce the storage capacity of reservoirs. Thus sunshine duration is used as the proxy variable of evaporation in this paper. The rainfall and sunshine duration data are from the monthly average data of the meteorological data center of the China Meteorological Administration [7].

2.1.1.2. Temperature. Temperature is one of the important factors influencing hydropower generation [16]. However, the relationship between temperature and economic variables tends to be non-linear, so it is difficult to obtain the electricity consumption changes caused by heating and cooling demand if the temperature is used as independent variable [15]. To avoid this problem, degree days are used as the proxy variable of temperature in this work. The degree days are divided into two types: heating degree day (HDD), measuring the severity and duration of cold pressure and cooling degree day (CDD), measuring the severity and duration of hot pressure. The temperature data are from the meteorological data center of the China Meteorological Administration [7]. There are many meteorological observation stations at each provincial level, so following [1,15], the monthly HDD and CDD are defined as Eqs. (1) and (2)

$$HDD = \frac{1}{n}\sum_{k=1}^{n}\sum_{i=1}^{I_t}\alpha(T_b - T_{kit}) \tag{1}$$

$$CDD = \frac{1}{n}\sum_{k=1}^{n}\sum_{i=1}^{I_t}(1-\alpha)(T_{kit} - T_b) \tag{2}$$

[2] The data limitation is one of the reasons for us to adopt the monthly panel data of 2007–2015. Therefore, greater effort will be made to collect relative data to get deeper knowledge of these issues.



(a) Heating degree day (HDD). (b) Cooling degree day (CDD).

Fig. 2. The distribution of average HDD and CDD from 2007 to 2015 in China.

where n is the number of meteorological observation stations; I_t is the number of days in the t months; T_{kit} is the daily average temperature in the k meteorological observation station on day i of month t. T_b is the reference temperature α varies with daily temperature and reference temperature. When daily temperature is more than the reference temperature, α is 1, otherwise it is 0.

There may be differences in the reference temperature and the extent of climate change in different regions in China because of China's vast territory. In order to ensure the accuracy and reliability of the results, we compare the results with alternative reference temperatures in this study. In addition, the distribution of HDD and CDD in different provinces in China in 2015 is given in this work (Fig. 2) to show the geographical distribution characteristics of HDD and CDD in different regions. The general trend is that HDD gradually increases and CDD gradually decreases from south to north. Higher HDD appears mainly in the cold northeastern region (Fig. 2(a)), while higher CDD mainly appeared in the southeastern region (Fig. 2(b)). There are significant differences in climatic conditions in different regions of China, which can lead to the difference of hydropower's sensitivity to climate. As a result, the impacts of climate change on hydropower generation of different regions will be heterogeneous, which is one of the reasons that we analyze the vulnerability of hydropower in the north and south regions of China separately.

2.1.2. Non-Climate factors

2.1.2.1. Installed capacity. Installed capacity plays an important role in the electric power generation. Electric power generation is determined by installed capacity, equipment working hours and power generation efficiency [30]. Therefore, the installed capacity is included in the econometric model in this paper, with the data taken from the Wind database. Regarding the working hours of the equipment, it turns out to be seasonal fluctuations for it can be significantly affected by the weather condition as well as the market supply and demand. Therefore, if we simultaneously add climate variables, electricity prices and the working hours of the equipment into the model, it will probably increase the risk of multicollinearity. In addition, considering the correlation between the working hours and the installed capacity of the equipment, we choose the installed capacity of the equipment in the regression model rather than the working hours of the equipment in this paper.

2.1.2.2. Fixed assets investment (at 2007 constant price). Compared with other types of energy such as thermal power, hydropower has a higher initial investment, which is one of the main economic factors restricting its development [23,42]. An increase in investment in hydropower can improve its competitiveness, which will promote hydropower development. Hamududu and Killingtveit [19] also pointed out that investment in the hydropower industry (building a new factory) would help reduce the impact of climate change on hydropower and promote hydropower development. Therefore, fixed assets investment is regarded as a non-climate factor in the model. Since data on the fixed assets investment in hydropower sector are not available, the sum of the fixed assets investment in

Table 1
Definitions of variables.

Variable name	Definition	Unit	Source
HY	Hydropower generation	10^4 kWh	National Bureau of Statistics PRC, 2016
IC	Installed capacity	10^4 kW	Wind database: the monthly value from January 2007 to December 2015;
Price	Price (at 2007 constant prices)	yuan/MW	Electricity Regulatory Commission: annual value from 2007 to 2015; Consumer Price Index (CPI) from 2007 to 2015
FAI	Fixed assets investment (at 2007 constant prices)	10^9 yaun	Wind database: the monthly value from January 2007 to December 2015; fixed asset investment index from 2007 to 2015
hdd18	Heating degree day (the reference temperature is 18 °C)	°C ∗ d	China Meteorological Administration, 2017 and authors' own calculation
cdd18	Cooling degree day (the reference temperature is 18 °C)	°C ∗ d	China Meteorological Administration, 2017 and authors' own calculation
Rain	Rainfall	mm	China Meteorological Administration, 2017
Sun	Sunshine duration	H	China Meteorological Administration, 2017
hdd17	Heating degree day (the reference temperature is 17 °C)	°C ∗ d	China Meteorological Administration, 2017 and authors' own calculation
cdd17	Cooling degree day (the reference temperature is 17 °C)	°C ∗ d	China Meteorological Administration, 2017 and authors' own calculation

Table 2
Results of descriptive statistics and correlation test.

Variables	Obs.	Mean	Std. Dev.	*IC*	*Price*	*FAI*	*hdd18*	*cdd18*	*Rain*	*Sun*	*hdd17*	*cdd17*
HY	3019	204 804.60	361 180.60									
IC	2772	693.86	964.03	1.000								
Price	3024	369.84	72.08	−0.118	1.000							
FAI	2772	972.56	866.19	0.097	0.435	1.000						
hdd18	3024	193.64	260.64	−0.104	−0.188	−0.174	1.000					
cdd18	3024	80.97	114.43	−0.023	0.288	0.112	−0.515	1.000				
Rain	2908	79.34	94.89	0.074	0.286	0.089	−0.392	0.506	1.000			
Sun	3023	164.72	68.27	−0.265	−0.234	−0.083	−0.100	0.164	−0.197	1.000		
hdd17	3024	193.64	260.64	−0.104	−0.188	−0.174	1.000	−0.515	−0.392	−0.100	1.000	
cdd17	3024	176.01	249.66	−0.105	−0.185	−0.173	0.998	−0.485	−0.377	−0.099	0.998	1.000

the power generation and water management department and compensation for land expropriation[3] is used as fixed assets investment in the hydropower sector, which is adjusted into that at 2007 constant price by using fixed asset investment index. The related data are from the Wind database.

2.1.2.3. Price (at 2007 constant prices). Electricity price is also an important economic factor for power generation. Increasing the price of electricity generated by hydropower is conducive to expanding hydropower development. Gaudard et al. [17] noted that climate change and market liberalization may alter runoff and market prices and hinder hydropower development. From the point of view of producer profit (= revenue − cost), we believe that the market price will affect the output of hydropower. Normally, the higher the price of electricity, the greater the power output [22]. Because of the availability of data, the average on-grid electricity price is used as the proxy variable of the hydropower price in this work. And they are adjusted by consumer price index.

The descriptive statistics and correlation test of all variables used in this paper are shown in Tables 1 and 2. From Table 2, the correlation coefficient for the variables is less than 0.2, which indicates that the correlation among variables is not obvious. Thus, the severe multicollinearity[4] problem is avoided in the model.

[3] The 13th Five-Year Plan for hydropower development points out that compensation for land expropriation has become a challenge to hydropower development. Therefore, compensation for land expropriation is considered to be one of the hydropower investments in this work.

[4] Multicollinearity is a linear relationship between explanatory variables, resulting in spurious regression.

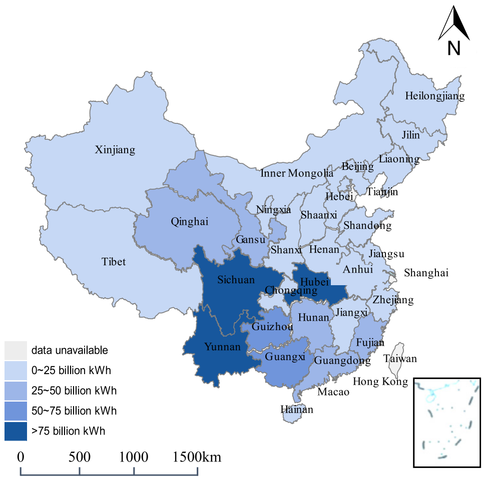


Fig. 3. The distribution of hydropower generation in 2015 in China.
Source: National Bureau of Statistics [33].

2.2. Regression models

According to the above analysis, referring to [34], and combining the actual situation of China, the model of hydropower generation is defined as Eq. (3):

$$ln(HY)_{it} = c + \sum_{k=1}^{K} \beta_k lnX_{kit} + \sum_{m=1}^{M} \gamma_{\mathrm{m}} lnZ_{mit} + a_i + \eta_t + \varepsilon_{it} \tag{3}$$

where $lnHY_{it}$ is the logarithmic variable of hydropower generation, c is the intercept term, lnX_{kit} is the logarithmic combination of the non-climatic factors (part or all of the installed capacity, fixed assets investment and price on hydropower generation). lnZ_{mit} is the logarithmic combination of the climatic factors (part or all of the HDD, CDD, rainfall and sunshine duration). K and M represent the number of variables of climatic variables and non-climatic variables respectively. β_k, γ_m is the regression coefficient. a_i is the regional fixed effect. η_t is the time point fixed effect. ε_{it} is the random error term in the model. Regarding variables of other types of power generation such as wind power, they are not involved in our model although they may have a substituted effect on hydropower generation. It is due to that our work mainly focuses on the power generation perspective, rather than the power consumption perspective. The substituted effects among various types of renewable energy source play a major role on consumption side. In addition, the error term of the model also, to some extent, examines the effect of variables which are not introduced into the model. Pooled EGLS is used in regression analysis to reduce the heteroscedasticity caused by cross-sectional data [4], thus making the results more robust.

According to the actual situation in China, the hydropower generation in 10 provinces, including Sichuan, Yunnan, Hubei, Guizhou, Guangxi, Hunan, Fujian, Guangdong, Qinghai and Gansu is much higher than other regions in China (Fig. 3). The total hydropower generation in these 10 provinces accounts for more than 80% of total national hydropower output (Fig. 4). In order to ensure the reliability and robustness of the results, the Pooled EGLS regression results based on the panel data of the 10 hydropower provinces are used as a reference for the results at national level.

2.3. Scenario

Since climate change is a longtime scale process [10], in order to better reflect the impact of climate change on China's hydropower output, following [24], we further make a prediction for the change of hydropower generation caused by temperature and precipitation changes under three climate change scenarios (compared with the 2011 benchmark) after the empirical research above based on the monthly panel data from 2007 to 2015. The three climate

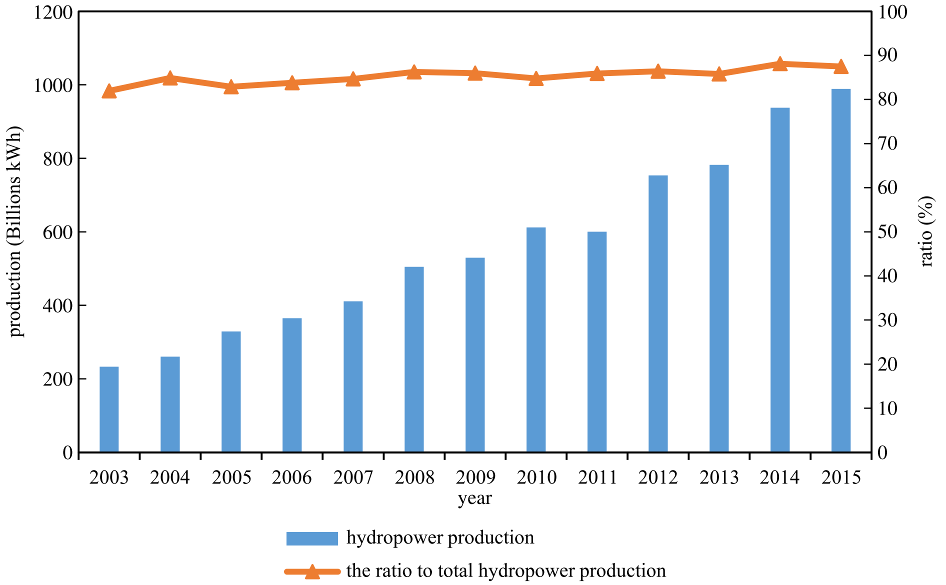


Fig. 4. The hydropower generation of 10 provinces and ratio to total hydropower generation in China.
Source: National Bureau of Statistics [32].

Table 3
Change in temperature and precipitation in China from 2011 to 2100.
Source: The Editorial Committee for the third national climate change assessment report [36].

Climate scenarios	Temperature		Precipitation	
	Change (°C/10a)	Change in 2100 (°C)	Change (%/10a)	Change in 2100 (%)
RCP 8.5	+0.61	+5.0	+1.6	+14
RCP4.5	+0.26	+2.6	+1.1	+10
RCP2.6	+0.08	+1.3	+0.6	+5

Note: The change in temperature and precipitation in 2100 is relative to 2011 while the latest year of the data is 2015 in this work. But considering that climate change is a long-time-scale, it argues that the scenario with 2011–2100 or 2015–2100 will not affect the final forecast.

scenarios are the "typical concentration target" RCPs (Representative Concentration Pathways) scenario, comprising RCP 8.5, RCP4.5 and RCP2.6, proposed by the fifth assessment report [21].

The three climate change scenarios are as follows:

(1) RCP 8.5 is a high emission scenario with no climate policy. The greenhouse gases continue to grow and the radiation force caused by greenhouse gases will be 8.5 W/m^2 in RCP 8.5 in 2100 [36].

(2) RCP 2.6 is a low emission scenario. The most stringent climate policies bioenergy and carbon capture technologies will be used to reduce carbon emission in RCP 2.6. The radiation force caused by greenhouse gases will be 2.6 W/m^2 in RCP 2.6 in 2100 [36].

(3) RCP4.5 is similar to RCP2.6 with a medium level. The radiation force caused by greenhouse gases will be 4.5 W/m^2 in RCP 4.5 in 2100 [36].

Table 3 shows the change in temperature and precipitation in China under the three climate change scenarios.

3. Empirical results and discussion

3.1. Results at national level

The regression results of the Pooled EGLS at national level are shown in Table 4 (models (1)–(4)). The Pooled EGLS regression results based on the panel data of the 10 hydropower provinces are shown in model (5) of Table 4. All explanatory variables are included in models (1) and (5) while only HDD and CDD are in model (2). And the model

Table 4
Results of Pooled EGLS for hydropower generation in China.

Explanatory variables	National				Key provinces
	(1)	(2)	(3)	(4)	(5)
Ln(HDD18)	−0.016***	−0.066***	−0.057 ***		−0.070***
	(0.005)	(0.003)	(0.004)		(0.007)
Ln(CDD18)	0.089***	0.109***	0.092***		0.161***
	(0.006)	(0.006)	(0.006)		(0.013)
Ln(HDD17)				−0.011*	
				(0.006)	
Ln(CDD17)				0.082***	
				(0.005)	
LnRain	0.081***		0.076***	0.082***	0.154***
	(0.005)		(0.005)	(0.005)	(0.010)
LnSun	−0.043*		−0.059	−0.037*	−0.087***
	(0.011)		(0.010)	(0.011)	(0.021)
LnIC	0.047**			0.045***	0.498***
	(0.019)			(0.019)	(0.035)
LnPrice	−0.043*			−0.039	0.043**
	(0.042)			(0.042)	(0.071)
LnFAI	0.268***			0.269**	0.295***
	(0.012)			(0.012)	(0.020)
_cons	9.099***	10.894***	10.961***	9.043***	8.777***
	(0.267)	(0.012)	(0.023)	(0.267)	(0.407)
R^2	0.930	0.902	0.920	0.922	0.940
AIC	1.599	1.900	1.713	1.601	0.798
SC	1.721	1.969	1.821	1.723	0.893
VIF	2.37	1.28	1.44	2.40	2.33
Obs.	1540	1540	1540	1540	920

Note: Figures in parentheses are the standard errors.
* Indicates significance at 10% level.
** Indicates significance at 5% level.
*** Indicates significance at 1% level.

(3) includes all climate variables. The reference temperature of HDD and CDD in model (4) is 17 °C. Following [40], the values of AIC and SC can be used to compare the suitability of different regression models. Generally speaking, the smaller the AIC and SC, the better the model. Therefore, the results of model (1) are emphasized with the lowest AIC and SC values. In addition, comparing the results of model (1) with (4), the coefficients of each variable have not changed significantly, which means that it is appropriate to choose 18 °C as reference temperature of HDD and CDD.

From national level, the impact of climate factors on hydropower generation is significant. To be specific, rainfall is positively related to hydropower generation at 1% level of significance. With other factors remaining unchanged, hydropower generation will increase by about 0.081% as rainfall increases by 1%. The result is consistent with our expectation because the increase in rainfall will increase runoff and water storage of reservoirs, promoting hydropower generation. As the future rainfall increases [36], the potential of hydropower in China will increase. For the temperature, the coefficient of HDD is significantly negative. If the HDD increases by 1%, hydropower generation will be reduced by 0.016%, which indicates that hydropower generation decreases with the stimulus of cold pressure. The main reason is that heating demands are mainly met through coal or gas combustion in cold season in China, so the growth of electricity demand is not obvious. In addition, the runoffs in the river are minimal during the cold season, as a result, most of the hydropower plants shut down equipment for inspection and maintenance in winter, resulting in a fall in hydropower generation directly. Wang et al. [38] also pointed out that the decline in water level in the dry season had a negative effect on hydropower generation. Furthermore, there is a decline in hydropower generation during the cold season, which will cause a break in the electricity supply and affect people's production activity and daily life. The coefficient of CDD is positive at 1% significant level, which means that if CDD increases by 1%, hydropower generation will increase by about 0.089%. That is because the increase in cooling demand in the summer can increase demand for electricity, further boosting hydropower output. This result is consistent with the conclusion in Gaudard and Romerio [18], indicating the significant effect of temperature on hydropower generation. Moreover, the CDD elasticity is relatively higher (0.089) than the elasticity of HDD (−0.016), indicating that hydropower production will increase dramatically in the future due to increase of electricity demand in China caused by climate change. Regarding the sunshine duration it is used as the proxy variable of evaporation to reflect the impact of evaporation on hydropower in this paper. The result in model (1) is only significant at the 10% significance level. However, overall, the increase in sunshine duration causes a decrease in hydropower generation, and the coefficient of sunshine duration is about −0.043%. Further, compared to other models, the coefficients of the climate factors (precipitation, CDD and sunshine duration) in model (5) are higher than others, meaning that climate factors have had a more profound impact on areas with higher hydropower generation. This also demonstrates that areas with rich hydropower resources may be more sensitive and vulnerable to climate fluctuation.

For other non-climate factors affecting hydropower generation, the impacts of installed capacity and fixed asset investment on the hydropower generation are consistent with expectation because their coefficients are positive and significant. They play a more important role in the region with abundant hydropower resources. In addition, considering the coefficient of fixed asset investment is relatively higher (0.268) than the coefficients of installed capacity (0.047) and price (−0.043), increasing hydropower fixed asset investment can be priority for hydropower development in China.

The average electricity price is negatively correlated with the hydropower generation in the country. Hydropower generation will reduce 0.043% with a 1% increase in price of electricity. This is mainly due to the fact that the national average electricity price rather than the electricity price of hydropower is applied in the model. On the one hand, thermal power generation still dominates in China. On the other hand, since the initial investment cost for thermal power is lower than for hydropower [11,12], an increase in the average electricity price will lead to an increase in thermal power generation in priority, which is substitute to hydropower. As a result, hydropower output will decrease with fixed total electricity demand. Compared with model (5), it can also be seen that the higher power price also benefits the hydropower development in the region, with rich hydropower resources.

3.2. Results at regional level

In order to analyze the vulnerability of climate variation in different regions of China, we further make a comparison of the impact of climate variabilities on hydropower generation in the southern and northern regions in China, the results of which are shown in Table 5. According to models (6) to (11), the differences in the effect of climate variabilities on hydropower in different regions are significant. To be specific, the impact of rainfall and sunshine for the northern region of hydropower generation is not significant. This is because coal and oil resources are relatively rich in the northern region, where thermal power generation dominates the power industry, resulting in the limited influence of rainfall and evaporation on hydropower development. In contrast, it can be seen that precipitation and sunshine duration are significantly correlated with hydropower output in southern China, with abundant hydropower resources. In addition, the elasticity coefficients of CDD in southern China are ranked in 0.117%–0.136%, while the elasticity coefficients of CDD the northern China are only 0.04%–0.05% (models (6)–(11)). This shows that the effect of the heat pressure on the hydropower development is more significant in southern China, because most of the southern regions are in the high-temperature zone, thus causing more utilization of air conditioners in the southern region than northern region in the summer. The results show that hydropower in the south of China has stronger sensitivity to climate fluctuation than that in the north of China.

To sum up, the impact of installed capacity and fixed assets investment on hydropower generation is greater in the southern region, which has rich hydropower resources. The average price is negatively correlated with the hydropower output in the northern region, while it is positively correlated with the hydropower output in the southern region. The results show that the substitution of thermal power for hydropower is strong in northern China, confirming that the electricity price is negatively related to hydropower generation at national level.

3.3. Forecast results

The changes in the national hydropower generation caused by temperature and precipitation in the three climate scenarios (RCP8.5, RCP4.5 and RCP2.6) with setting 2011 as benchmark, are shown in Fig. 5. It can be seen

Table 5
Results of Pooled EGLS for hydropower generation in northern and southern regions.

Explanatory variables	Northern region			Southern region		
	(6)	(7)	(8)	(9)	(10)	(11)
Ln(HDD18)	−0.020**	−0.036***		−0.009		
	(0.009)	(0.005)		(0.008)		
Ln(CDD18)	0.049***	0.040***		0.117***	0.136***	
	(0.011)	(0.012)		(0.013)	(0.009)	
Ln(HDD17)			−0.037***			
			(0.005)			
Ln(CDD17)			0.036***			0.128***
			(0.011)			(0.009)
Lnrain	0.033			0.071***	0.115***	0.072***
	(0.024)			(0.007)	(0.012)	(0.007)
Lnsun	−0.036			−0.077*	−0.037	−0.063
	(0.025)			(0.016)	(0.029)	(0.017)
LnIC	0.064***	0.164***	0.165***	0.218***	0.275***	0.205***
	(0.050)	(0.044)	(0.045)	(0.026)	(0.037)	(0.027)
LnPrice	−0.257			0.270 **	0.181*	0.272**
	(0.092)			(0.060)	(0.090)	(0.061)
LnFAI	0.298***	0.223***	0.222***	0.225***	0.213***	0.215
	(0.019)	(0.014)	(0.015)	(0.018)	(0.025)	(0.020)
_cons	9.351***	7.790***	7.786***	7.190***	7.254***	7.219***
	(0.572)	(0.210)	(0.211)	(0.354)	(0.548)	(0.366)
R^2	0.868	0.849	0.849	0.849	0.860	0.848
AIC	2.093	2.005	2.09	1.089	1.066	1.083
SC	2.173	2.127	2.243	1.172	1.152	1.165
VIF	2.42	2.12	2.14	3.37	3.24	3.25
Obs.	812	812	812	1246	1246	1246

Note: Figures in parentheses are the standard errors.
* Indicates significance at 10% level.
** Indicates significance at 5% level.
*** Indicates significance at 1% level.

that hydropower generation will keep growing under the three climatic scenarios. Compared with 2011, the growth of hydropower generation by 2100 in RCP2.6, RCP4.5 and RCP8.5 caused by climatic factors (precipitation and temperature) will be 3.161% (22 billion kWh), 9.656% (67.4 billion kWh), 21.932% (153.3 billion kWh) respectively, which reflects the strong impact of climate on hydropower development and the great potential of hydropower development in China in the future.

At the same time, there are obvious differences in hydropower generation under different climate scenarios. The change in hydropower output in RCP 8.5 is significantly higher than that in RCP4.5 and RCP2.6, confirming that there is a strong vulnerability to climate in hydropower under the high emission scenario with no climate policy. Therefore, climate change will bring great uncertainty for hydropower development in the future.

Table 6 shows the changes in percentage in China's hydropower output caused by HDD, CDD and rainfall in 2100 (based on 2011) under the three climate scenarios. From Table 4, the impact of CDD on hydropower generation in China is far greater than that of HDD and precipitation in all of the climate scenarios, implying the impact of heat pressure on the hydropower development is greater in southern China. The result also shows that, as the climate warms up in the future, the increase in electricity demand can promote the increase of hydropower generation. This differs from the conclusions in Freitas et al. [16] and de Lucena [27] because we consider the effect of temperature on hydropower generation from the provision of the supply and demand of electricity market, rather than hydrological perspectives considering the change of runoff. This is a very interesting discovery. Although it does not take into account the effects of other variables in this work, it is still a strong complement to similar studies that do not take climate change into account.

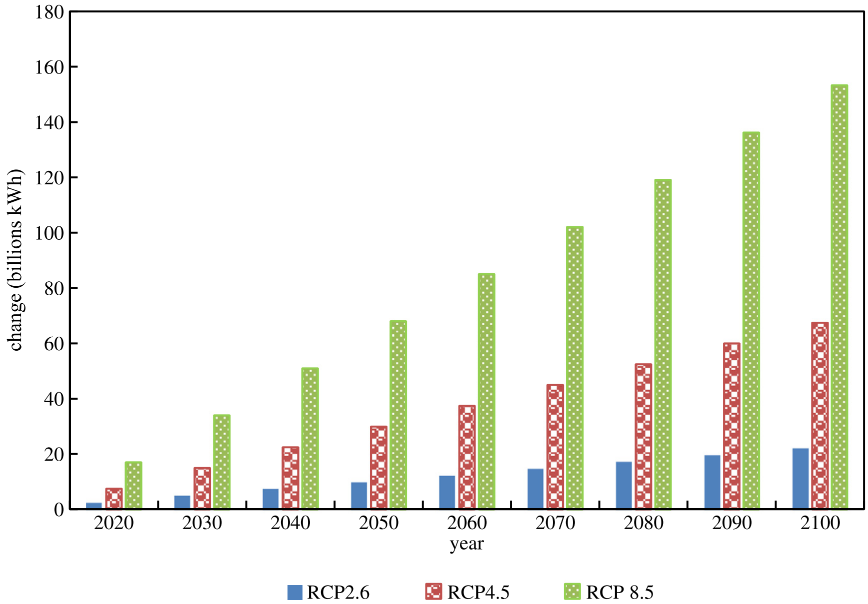


Fig. 5. The changes in the national hydropower generation caused by temperature and rainfall under three climate scenarios (based on 2011).

Table 6
Changes in percentage of hydropower output in China caused by HDD, CDD and rainfall in 2100 (billion kWh).

Climate scenarios	Temperature		Rainfall	All
	HDD	CDD		
RCP 8.5	+9.122	+135.477	+8.694	+153.294
RCP4.5	+3.888	+57.744	+5.858	+67.490
RCP2.6	+1.196	+17.768	+3.132	+22.095

Note: The changes in temperature and rainfall in 2100 are relative to 2011.

4. Conclusions and policy implications

In this work, an econometric model is constructed to estimate the feedback of climate change on hydropower generation in China by using the monthly panel data of 28 provinces in China from January 2007 to December 2015. Further, according to the three climate scenarios (RCP2.6, RCP4.5 and RCP8.5) proposed in the IPCC report, we make a prediction for the changes of hydropower generation in China caused by changes of climatic factors in a large time scale (2011–2100). Thus we are able to make a comprehensive and accurate assessment for the impacts of climate change on hydropower production. According to the results, conclusions and policy implications are drawn as follows:

(1) Climate factors have a significant impact on the generation of hydropower in China, especially for those provinces with abundant hydropower resources. At the national level, the elasticity coefficients of HDD and CDD are −0.016% and 0.089%, showing that a rise in temperature can increase electricity demand and boost hydropower output, which is consistent with the conclusion in Gaudard and Romerio [18]. In addition, rainfall is also an important factor affecting hydropower generation. If rainfall increases by 1%, the hydropower output will increase by 0.081%. The impact of sunshine duration (evaporation) on the generation of hydropower is not significant, but it can reduce the storage capacity of reservoirs and cause a decline in hydropower output to some extent.

Overall, hydropower in China is sensitive and vulnerable to climate fluctuation, where the temperature and rainfall are observed to be the most important factors in hydropower output. Therefore, in the context of global warming, on the one hand, hydropower development in China will experience more favorable conditions. On the other hand, extreme climatic events caused by global warming, including rainfall, heat waves, floods, and drought, will impose more challenges for the development of hydropower in China. Therefore, it is important for China to adhere to the strategy of prioritizing to the development of hydropower. In addition, in order to gradually improve the development and utilization of hydropower in various regions, we should constantly improve the construction of the hydropower infrastructure to enable it to adapt to climate change.

(2) The impact of climate factors on hydropower in different regions is heterogeneous. The southern region, abundant in hydropower resources, is the most strongly influenced area in China, implying that hydropower in southern China is highly vulnerable to climate. The government should make a specific inventory for the factors affecting the generation of hydropower in different regions, and make scientific planning for the development of hydropower in appropriate areas. In addition, the southern region should pay more attention to the issues related to climate change and take action to adapt to climate change [26].

(3) The differences in hydropower potential are significant under different climate scenarios. Compared with 2011, the growth rate of hydropower generation by 2100 in RCP2.6, RCP4.5 and RCP8.5 caused by climatic factors (precipitation and temperature) will be 3.161% (22 billion kWh), 9.656% (67.4 billion kWh), and 21.932% (153.3 billion kWh). This indicates that while hydropower development in China shows great potential in the future, there still exist many uncertainties surrounding it. Therefore, it may require the government to promote other types of renewable energies expansion simultaneously when developing hydropower, to meet the electricity gap probably caused by the decline in hydropower generation when it is in dry winter.

(4) Economic factors also have a significant impact on hydropower generation in all regions. The empirical results indicate that economic factors such as installed capacity, fixed asset investment and average electricity price can also affect hydropower output, while the extent of which also shows great heterogeneity across regions. Specifically, there is a comparatively stronger influence in southern regions with rich hydropower resources. When considering hydropower development of China in the future, expanding the scale of the installed hydropower systems, strengthening the investment for construction of infrastructure, and improving the hydropower price appropriately can promote the utilization rate of hydropower resources in various regions, especially in the underdeveloped western regions.

5. Further perspectives

Although this paper has explored the vulnerability to climate change of hydropower systems in China by applying an econometric model based on panel data, it does have some limitations. First, the changes in hydropower generation have been forecast at national level, but not at regional level. The regional level of climate change vulnerability will be our next step of work. In addition, regarding the data limitation, although we make an analysis for the changes of hydropower generation in China caused by changes of climatic factors in a large time scale (2011–2100) by constructing an econometric model, we can only utilize the monthly panel data from 2007 to 2015 in our regression analysis. And due to the availability of electricity price data, the average electricity price is used as the proxy variable of hydropower price in the empirical research. Although we have taken into account the effects of thermal power and other alternatives on empirical results when analyzing the impact of electricity price on hydropower generation this may be still not adequate for more accurate and comprehensive results. Therefore, greater effort will be made to collect relative data to have a deeper knowledge of these issues. Finally, since there is a great uncertainty in climate change prediction and impact assessment, it is also important for further research to consider the economic impact of climate change from a broader perspective.

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