

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; Forecast; Panel Data; China

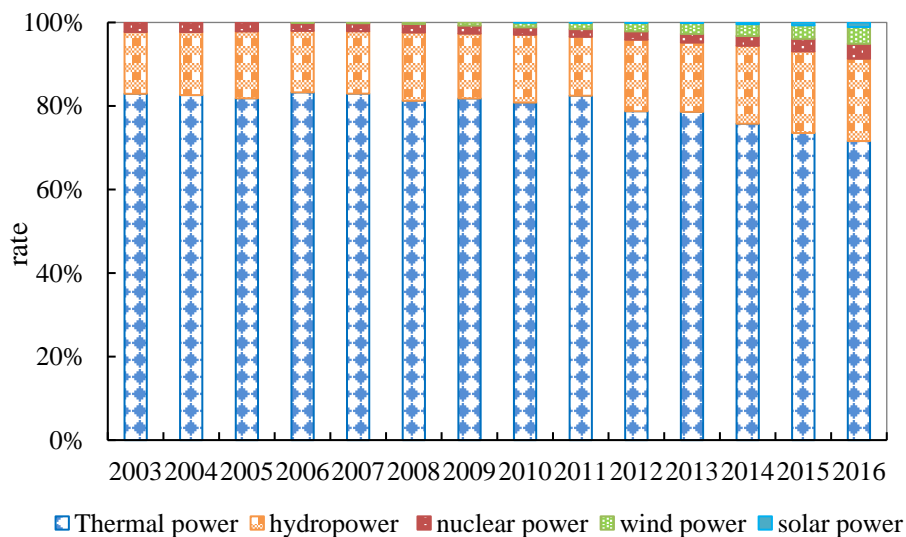
1. Introduction

Climate change is an indisputable fact, mainly caused by human activities, especially the

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

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



57
 58 **Figure 1 the electricity supply structure in China from 2003 to 2016**

59 Data source: China Electricity Council [6]
 60

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

72 To date, the research on the relationship between climate change and hydropower has focused
73 on two aspects, one being the role of hydropower in carbon emission reduction [2, 5, 13] and the
74 other is on the impact of climate change on hydropower. Most researches on the latter aspect focus
75 on hydropower resources endowment changes in a certain region under global warming from the
76 hydrological point of view [16, 19, 35, 37]. For instance, Freitas et al. [16] analyzed the relationship
77 between climate change and hydropower management in Brazil, and pointed out that further global
78 warming could change the hydrological cycle, thus affecting the hydropower resources of Brazil.
79 Hamududu and Killingtveit [19] simulated the change of regional runoff and estimated the
80 hydropower generation under climate change, using twelve different Global Climate models (GCM).
81 Spalding-Fecher et al. [35] assessed the vulnerability of hydropower in the Zambezi river basin in
82 southern Africa and noted that climate change would increase the regional water-use competition
83 between hydropower and irrigated agriculture. Vliet et al. [37] used the GCM model to assess the
84 change of global hydropower generation caused by climate change.

85 There are also some studies focusing on the impact of climate change on hydropower systems
86 from the perspective of social development and the electricity market [18, 34]. For instance, Gaudard
87 and Romerio [18] analyzed the influence of energy policy, climate policy, and the electric market on
88 hydropower generation, and pointed out that climate change was one of the main driving forces of
89 the power market, because climate warming would lead to a rising demand for electricity in summer.
90 Ruggiero and Lehkonen [34] studied the relationship between renewable energy growth (including

91 hydropower) and performance gains for electricity companies, using panel data regression analysis,
92 applying the fixed effects estimator, the random effects estimator and the Granger causality test. Other
93 studies have predicted the changes in hydropower output in different climate change scenarios in the
94 future [3, 27, 38]. Boehlert et al. [3] explored the physical and economic impacts on hydropower in
95 U.S. under a global greenhouse gas emissions scenario, and pointed out that under the high emissions
96 scenario, climate change will increase the hydropower generation of the Northwest Pacific Ocean.
97 Lucena et al. [27] used the Autoregressive Moving Average (ARMA) model to evaluate the climate
98 vulnerability of renewable energy (mainly hydropower and liquid biofuels) in Brazil, and gave a long-
99 term climate forecast with a set of the IPCC emissions scenarios. The results showed that biofuel
100 production (especially biodiesel) and power generation (especially hydropower) may suffer negative
101 effects from climate change. Wang et al. [38] analyzed the long-term relationships between
102 hydropower generation in China, climatic factors (rainfall) and hydropower installed capacity, and
103 predicted hydropower generation of nine hydropower provinces in China with different carbon
104 emission scenarios, applying a grey prediction model.

105 While previous works confirm that climate change do have an impact on hydropower, from the
106 perspective of the research region, there are few studies focusing on China. However, since China is
107 the largest single hydropower producer [4], investigating climate vulnerability of the hydropower
108 system of China seems to be typical and can also bring insights for other countries. In addition, from
109 the perspective of research scope, most studies have analyzed the climate vulnerability of hydropower
110 from the global or national level, and less research has been carried out on regional hydropower
111 systems. China is a vast country, with great differences in the extent of climate change among
112 different regions. For example, the drought has intensified and the precipitation has continued to
113 decrease in northern China in recent 50 years, while the precipitation in the south of China has
114 increased, and China may gradually present a trend of “southern flood, northern drought” in the future
115 [36].

116 Is there any difference in the impact of climate conditions on hydropower generation in different
117 regions within China? What is the extent of this impact? The answers to these questions are of great
118 importance for the optimized planning of hydropower development in various regions in China.
119 Therefore, another contribution of this paper is the concentration on the heterogeneity of impacts

120 caused by climate factors on hydropower generation in southern¹ and northern China.

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

133 Compared with previous studies, the main innovations of this work are as follows: 1) an
134 econometric model for regional hydropower generation is constructed to explore the impact of climate
135 factors on hydropower generation in different regions of China by using the monthly panel data from
136 January 2007 to December 2015², which can reflect the monthly temperature fluctuation
137 characteristics. 2) Heating degree day (HDD) and cooling degree day (CDD) are used as temperature
138 variables to access the effect of climate change on hydropower generation from the perspective of
139 demand. 3) Non-climatic variables, including fixed assets investment, installed capacity and on-grid
140 price, are used as control variables to construct a feedback model that reflects the influence of climate
141 change on hydropower generation. As a result, the results are more credible than those that only
142 consider climate factors. 4) Pooled Estimated Generalized Least Squares (Pooled EGLS) is used in
143 regression analysis to reduce the heteroscedasticity caused by cross-sectional data [40], which can
144 make the results more reliable. 5) We not only consider the climate vulnerability of hydropower at

¹According 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.

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.

145 the national level, but also analyze the influence of climate factors on hydropower generation in
146 different regions. 6) Further, we also predict the change of hydropower generation in China caused
147 by climatic factors under the three climate scenarios (RCP2.6, RCP4.5 and RCP8.5) from the IPCC's
148 fifth assessment report and some policy implications are put forward for the development of
149 hydropower in China.

150 **2. Econometric model and data source**

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

158 **2.1 Explanatory variables**

159 **2.1.1 Climate factors**

160 (1) Rainfall and sunshine duration

161 Rainfall is one of the most critical factors affecting hydropower [15,20]. Wang et al. [38] found
162 that rainfall had a significant impact on various regions of China, especially Yunnan and Sichuan.
163 Therefore, rainfall is selected in the econometric model in this paper. It is expected that with other
164 factors remaining unchanged, hydropower generation will increase if rainfall increases.

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

169 (2) Temperature

170 Temperature is one of the important factors influencing hydropower generation [16]. However,
171 the relationship between temperature and economic variables tends to be non-linear, so it is difficult
172 to obtain the electricity consumption changes caused by heating and cooling demand if the

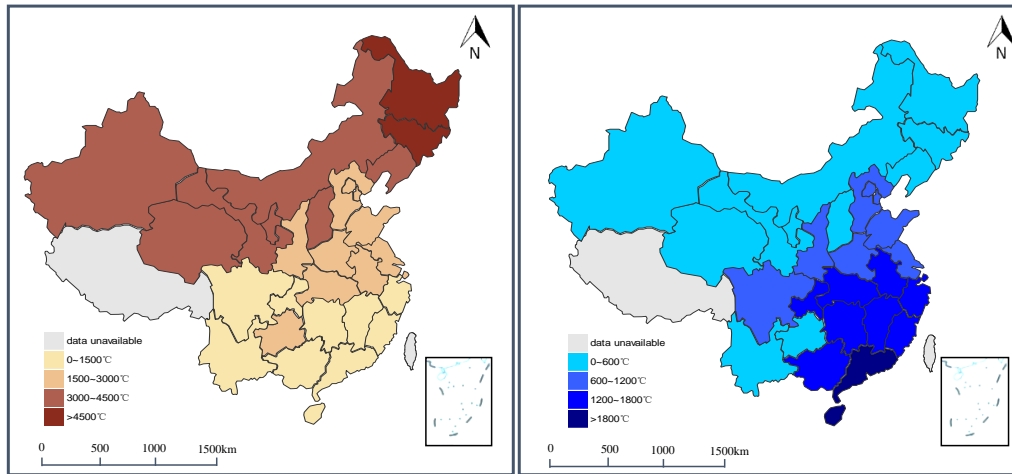
173 temperature is used as independent variable [14]. To avoid this problem, degree days are used as the
 174 proxy variable of temperature in this work. The degree days are divided into two types: heating degree
 175 day (HDD), measuring the severity and duration of cold pressure and cooling degree day (CDD),
 176 measuring the severity and duration of hot pressure. The temperature data are from the meteorological
 177 data center of the China Meteorological Administration [7]. There are many meteorological
 178 observation stations at each provincial level, so following [1, 14], the monthly HDD and CDD is
 179 defined as Eq.(1) and Eq.(2).

$$180 \quad HDD = \frac{1}{n} \sum_{k=1}^n \sum_{i=1}^{I_t} \alpha (T_b - T_{kit}) \quad (1)$$

$$181 \quad CDD = \frac{1}{n} \sum_{k=1}^n \sum_{i=1}^{I_t} (1 - \alpha) (T_{kit} - T_b) \quad (2)$$

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

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



a. heating degree day (HDD)

b. cooling degree day (CDD)

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

2.1.2 Non-Climate factors

(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) 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

221 as a non-climate factor in the model. Since data on the fixed assets investment in hydropower sector
222 are not available, the sum of the fixed assets investment in the power generation and water
223 management department and compensation for land expropriation³ is used as fixed assets investment
224 in the hydropower sector, which is adjusted into that at 2007 constant price by using fixed asset
225 investment index. The related data are from the Wind database.

226 (3) Price (at 2007 constant prices)

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

235 The descriptive statistics and correlation test of all variables used in this paper are shown in
236 Table 1 and Table 2. From Table 2, the correlation coefficient for the variables is less than 0.2, which
237 indicates that the correlation among variables is not obvious. Thus, the severe multicollinearity⁴
238 problem is avoided in the model.

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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 spurious regression.

Table 1 Definitions of variables

Variable name	Definition	Unit	Source
<i>HY</i>	Hydropower generation	10 ⁴ kWh	National Bureau of Statistics PRC, 2016
<i>IC</i>	Installed capacity	10 ⁴ kW	Wind database: the monthly value from January 2007 to December 2015;
<i>Price</i>	Price (at 2007 constant prices)	yuan/MW	Electricity Regulatory Commission : annual value from 2007 to 2015; Consumer Price Index (CPI) from 2007 to 2015
<i>FAI</i>	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
<i>hdd18</i>	Heating degree day (the reference temperature is 18 °C)	°C*d	China Meteorological Administration, 2017 and author s' calculation
<i>cdd18</i>	Cooling degree day (the reference temperature is 18°C)	°C*d	China Meteorological Administration, 2017 and author s' calculation
<i>rain</i>	Rainfall	mm	China Meteorological Administration, 2017
<i>sun</i>	Sunshine duration	H	China Meteorological Administration, 2017
<i>hdd17</i>	Heating degree day (the reference temperature is 17°C)	°C*d	China Meteorological Administration, 2017 and author s' calculation
<i>cdd17</i>	Cooling degree day (the reference temperature is 17°C)	°C*d	China Meteorological Administration, 2017 and author s' calculation

Table 2 Results of descriptive statistics and correlation test

Variables	Obs.	Mean	Std.Dev.	<i>IC</i>	<i>Price</i>	<i>FAI</i>	<i>hdd18</i>	<i>cdd18</i>	<i>rain</i>	<i>Sun</i>	<i>hdd17</i>	<i>cdd17</i>
<i>HY</i>	3019	204804.60	361180.60									
<i>IC</i>	2772	693.86	964.03	1.000								
<i>Price</i>	3024	369.84	72.08	-0.118	1.000							
<i>FAI</i>	2772	972.56	866.19	0.097	0.435	1.000						
<i>hdd18</i>	3024	193.64	260.64	-0.104	-0.188	-0.174	1.000					
<i>cdd18</i>	3024	80.97	114.43	-0.023	0.288	0.112	-0.515	1.000				
<i>Rain</i>	2908	79.34	94.89	0.074	0.286	0.089	-0.392	0.506	1.000			
<i>Sun</i>	3023	164.72	68.27	-0.265	-0.234	-0.083	-0.100	0.164	-0.197	1.000		
<i>hdd17</i>	3024	193.64	260.64	-0.104	-0.188	-0.174	1.000	-0.515	-0.392	-0.100	1.000	
<i>cdd17</i>	3024	176.01	249.66	-0.105	-0.185	-0.173	0.998	-0.485	-0.377	-0.099	0.998	1.000

2.2 Regression models

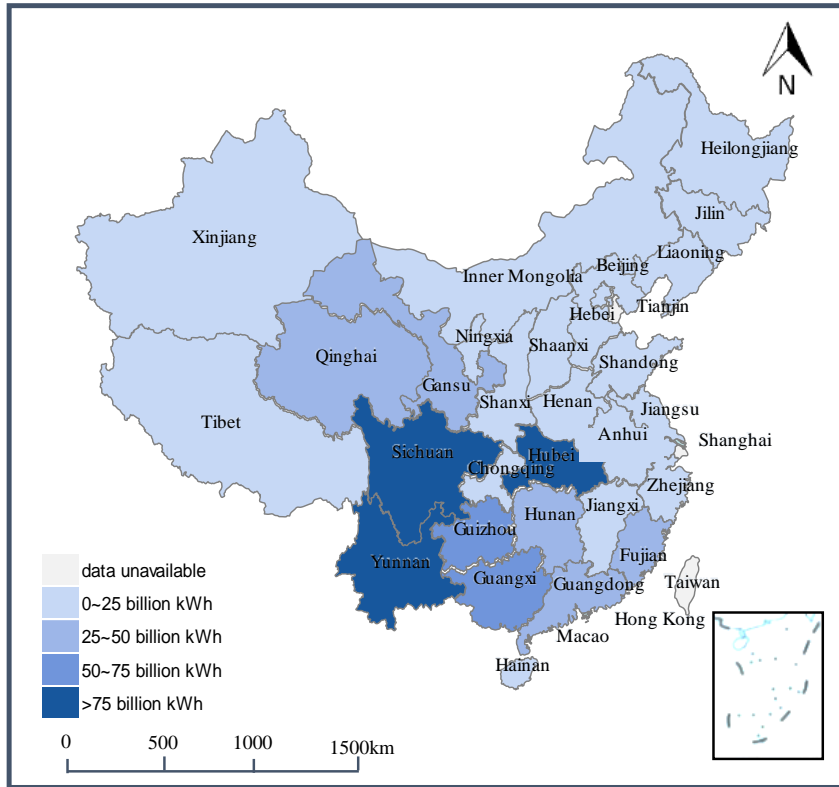
According to the above analysis, referring to [34], and combining the actual situation of China, the model of hydropower generation is defined as Eq.(3):

$$255 \quad \ln(HY)_{it} = c + \sum_{k=1}^K \beta_k \ln X_{kit} + \sum_{m=1}^M \gamma_m \ln Z_{mit} + a_i + \eta_t + \varepsilon_{it} \quad (3)$$

256 Where $\ln HY_{it}$ is the logarithmic variable of hydropower generation, c is the intercept term,
 257 $\ln X_{kit}$ is the logarithmic combination of the non-climatic factors (part or all of the installed capacity,
 258 fixed assets investment and price on hydropower generation). $\ln Z_{mit}$ is the logarithmic combination
 259 of the climatic factors (part or all of the HDD, CDD, rainfall and sunshine duration). K and M
 260 represent the number of variables of climatic variables and non-climatic variables respectively. β_k ,
 261 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
 262 random error term in the model. Regarding variables of other types of power generation such as wind
 263 power, they are not involved in our model although they may have a substituted effect on hydropower
 264 generation. It is due to that our work mainly focuses on the power generation perspective, rather than
 265 the power consumption perspective. The substituted effects among various types of renewable energy
 266 source play a major role in consumption side. In addition, the error term of the model also, to some
 267 extent, examines the effect of variables that not introduced into the model. Pooled EGLS is used in
 268 regression analysis to reduce the heteroscedasticity caused by cross-sectional data [40], thus making
 269 the results more robust.

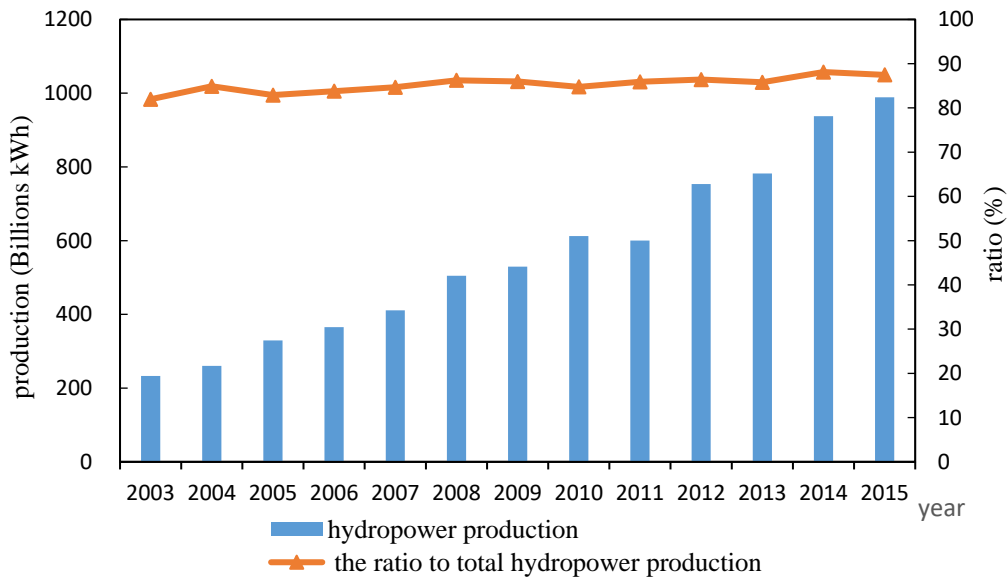
270 According to the actual situation in China, the hydropower generation in 10 provinces, including
 271 Sichuan, Yunnan, Hubei, Guizhou, Guangxi, Hunan, Fujian, Guangdong, Qinghai and Gansu is much
 272 higher than other regions in China (Figure 3). The total hydropower generation in these 10 provinces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

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278 **Figure 3 The distribution of hydropower generation in 2015 in China**

279 Data source: National Bureau of Statistics [33]



280
281 **Figure 4 The hydropower generation of 10 provinces and ratio to total hydropower generation in China**

282 Data source: National Bureau of Statistics [33]

283
284 2.3 Scenario

285 Since climate change is a long-time scale process, in order to better reflect the impact of climate
 286 change on China's hydropower output, following [24], we further make a prediction for the change
 287 of hydropower generation caused by temperature and precipitation changes under three climate
 288 change scenarios (compared with the 2011 benchmark) after the empirical research above based on
 289 the monthly panel data from 2007 to 2015. The three climate scenarios are the “typical concentration
 290 target” RCPs (Representative Concentration Pathways) scenario, comprising RCP 8.5, RCP4.5 and
 291 RCP2.6, proposed by the fifth assessment report [21].

292 The three climate change scenarios are as follows:

293 (1) RCP 8.5 is a high emission scenario with no climate policy. The greenhouse gases continue
 294 to grow and the radiation force caused by greenhouse gases will be 8.5 W/m² in RCP 8.5 in 2100 [36].

295 (2) RCP 2.6 is a low emission scenario. The most stringent climate policies, bioenergy and
 296 carbon capture technologies will be used to reduce carbon emission in RCP 2.6. The radiation force
 297 caused by greenhouse gases will be 2.6 W/m² in RCP 2.6 in 2100 [36].

298 (3) RCP4.5 is similar to RCP2.6 with a medium level. The radiation force caused by greenhouse
 299 gases will be 4.5 W/m² in RCP 4.5 in 2100 [36].

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

302

303 **Table 3 Change in temperature and precipitation in China from 2011 to 2100**

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

304 Note: The change in temperature and precipitation in 2100 is relative to 2011 while the latest year of the data
 305 is 2015 in this work. But considering that climate change is a long-time-scale, it argues that the scenario with 2011-
 306 2100 or 2015-2100 will not affect the final forecast.

307 Source: The Editorial Committee for the third national climate change assessment report [36].

308 3 Empirical results and discussion

309 3.1 Results at national level

310 The regression results of the Pooled EGLS at national level are show in Table 4 (model (1) -
 311 (4)). The Pooled EGLS regression results based on the panel data of the 10 hydropower provinces are
 312 shown in model (5) of table 4. All explanatory variables are included in models (1) and (5) while only
 313 HDD and CDD are in model (2). And the model (3) includes all climate variables. The reference
 314 temperature of HDD and CDD in model (4) is 17°C. Following [40], the values of AIC and SC can
 315 be used to compare the suitability of different regression models. Generally speaking, the smaller the
 316 AIC and SC, the better the model. Therefore, the results of model (1) are emphasized with the lowest
 317 AIC and SC values. In addition, compared the results of model (1) with (4), the coefficients of each
 318 variable have not changed significantly, which means that it is appropriate to choose 18 °C as
 319 reference temperature of HDD and CDD.

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Table 4 Results of Pooled EGLS for hydropower generation in China

Explanatory variables	National				Key provinces
	(1)	(2)	(3)	(4)	(5)
<i>Ln(HDD18)</i>	-0.016*** (0.005)	-0.066*** (0.003)	-0.057 *** (0.004)		-0.070*** (0.007)
<i>Ln(CDD18)</i>	0.089*** (0.006)	0.109*** (0.006)	0.092*** (0.006)		0.161*** (0.013)
<i>Ln(HDD17)</i>				-0.011* (0.006)	
<i>Ln(CDD17)</i>				0.082*** (0.005)	
<i>LnRain</i>	0.081*** (0.005)		0.076*** (0.005)	0.082*** (0.005)	0.154*** (0.010)
<i>LnSun</i>	-0.043* (0.011)		-0.059 (0.010)	-0.037* (0.011)	-0.087*** (0.021)
<i>LnIC</i>	0.047** (0.019)			0.045*** (0.019)	0.498*** (0.035)
<i>LnPrice</i>	-0.043* (0.042)			-0.039 (0.042)	0.043** (0.071)
<i>LnFAI</i>	0.268*** (0.012)			0.269** (0.012)	0.295*** (0.020)
<i>_cons</i>	9.099*** (0.267)	10.894*** (0.012)	10.961*** (0.023)	9.043*** (0.267)	8.777*** (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

322 Note: Figures in parentheses is the Standard error. * indicates significance at 10% level, * * indicates
323 significance at 5% level, *** indicates significance at 1% level.

324

325 From national level, the impact of climate factors on hydropower generation is significant. To
326 be specific, rainfall is positively related to hydropower generation at 1% level of significance. With
327 other factors remaining unchanged, hydropower generation will increase by about 0.081% as rainfall
328 increases by 1%. The result is consistent with our expectation because the increase in rainfall will
329 increase runoff and water storage of reservoirs, promoting hydropower generation. As the future
330 rainfall increases [36], the potential of hydropower in China will increase. For the temperature, the
331 coefficient of HDD is significantly negative. If the HDD increases by 1%, hydropower generation
332 will be reduced by 0.016%, which indicates that hydropower generation decreases with the stimulus
333 of cold pressure. The main reason is that heating demands are mainly met through coal or gas
334 combustion in cold season in China, so the growth of electricity demand is not obvious. In addition,
335 the runoffs in the river are minimal during the cold season, as a result, most of the hydropower plants
336 shut down equipment for inspection and maintenance in winter, resulting in a fall in hydropower
337 generation directly. Wang et al [38] also pointed out that the decline in water level in the dry season
338 had a negative effect on hydropower generation. Furthermore, there is a decline in hydropower
339 generation during the cold season, which will cause a break in the electricity supply and affect
340 people's production activity and daily life. The coefficient of CDD is positive at 1% significant level,
341 which means that if CDD increases by 1%, hydropower generation will increase by about 0.089%.
342 That is because the increase in cooling demand in the summer can increase demand for electricity,
343 further boosting hydropower output. This result is consistent with the conclusion in Gaudard and
344 Romerio [18], indicating the significant effect of temperature on hydropower generation. Moreover,
345 the CDD elasticity is relatively higher (0.089) than the elasticity of HDD (-0.016), indicating that
346 hydropower production will increase dramatically in the future due to increase of electricity demand
347 in China caused by climate change. Regarding the sunshine duration, it is used as the proxy variable
348 of evaporation to reflect the impact of evaporation on hydropower in this paper. The result in model
349 (1) is only significant at the 10% significance level. However, overall, the increase in sunshine
350 duration causes a decrease in hydropower generation, and the coefficient of sunshine duration is about
351 -0.043%. Further, compared to other models, the coefficients of the climate factors (precipitation,
352 CDD and sunshine duration) in model (5) are higher than others, meaning that climate factors have

353 had a more profound impact on areas with higher hydropower generation. This also demonstrates that
354 areas with rich hydropower resources may be more sensitive and vulnerable to climate fluctuation.

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

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

371 3.2 Results at regional level

372 In order to analyze the vulnerability of climate variation in different regions of China, we further
373 make a comparison of the impact of climate variabilities on hydropower generation in the southern
374 and northern regions in China, the results of which are shown in table 5. According to models (6) to
375 (11), the differences in the effect of climate variabilities on hydropower in different regions are
376 significant. To be specific, the impact of rainfall and sunshine for the northern region of hydropower
377 generation is not significant. This is because coal and oil resources are relatively rich in the northern
378 region, where thermal power generation dominates the power industry, resulting in the limited
379 influence of rainfall and evaporation on hydropower development. In contrast, it can be seen that
380 precipitation and sunshine duration are significantly correlated with hydropower output in southern
381 China, with abundant hydropower resources. In addition, the elasticity coefficients of CDD in

382 southern China are ranked in 0.117% ~ 0.136%, while the elasticity coefficients of CDD the northern
 383 China are only 0.04%~0.05% (models (6)-(11)). This shows that the effect of the heat pressure on the
 384 hydropower development is more significant in southern China, because most of the southern regions
 385 are in the high-temperature zone, thus causing more utilization of air conditioners in the southern
 386 region than northern region in the summer. The results show that hydropower in the south of China
 387 has stronger sensitivity to climate fluctuation than that in the north of China.

388

389

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)
<i>Ln(HDD18)</i>	-0.020** (0.009)	-0.036*** (0.005)		-0.009 (0.008)		
<i>Ln(CDD18)</i>	0.049*** (0.011)	0.040*** (0.012)		0.117*** (0.013)	0.136*** (0.009)	
<i>Ln(HDD17)</i>			-0.037*** (0.005)			
<i>Ln(CDD17)</i>			0.036*** (0.011)			0.128*** (0.009)
<i>Lnrain</i>	0.033 (0.024)			0.071*** (0.007)	0.115*** (0.012)	0.072*** (0.007)
<i>Lnsun</i>	-0.036 (0.025)			-0.077* (0.016)	-0.037 (0.029)	-0.063 (0.017)
<i>LnIC</i>	0.064*** (0.050)	0.164*** (0.044)	0.165*** (0.045)	0.218*** (0.026)	0.275*** (0.037)	0.205*** (0.027)
<i>LnPrice</i>	-0.257 (0.092)			0.270 ** (0.060)	0.181* (0.090)	0.272** (0.061)
<i>LnFAI</i>	0.298*** (0.019)	0.223*** (0.014)	0.222*** (0.015)	0.225*** (0.018)	0.213*** (0.025)	0.215 (0.020)
<i>_cons</i>	9.351*** (0.572)	7.790*** (0.210)	7.786*** (0.211)	7.190*** (0.354)	7.254*** (0.548)	7.219*** (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

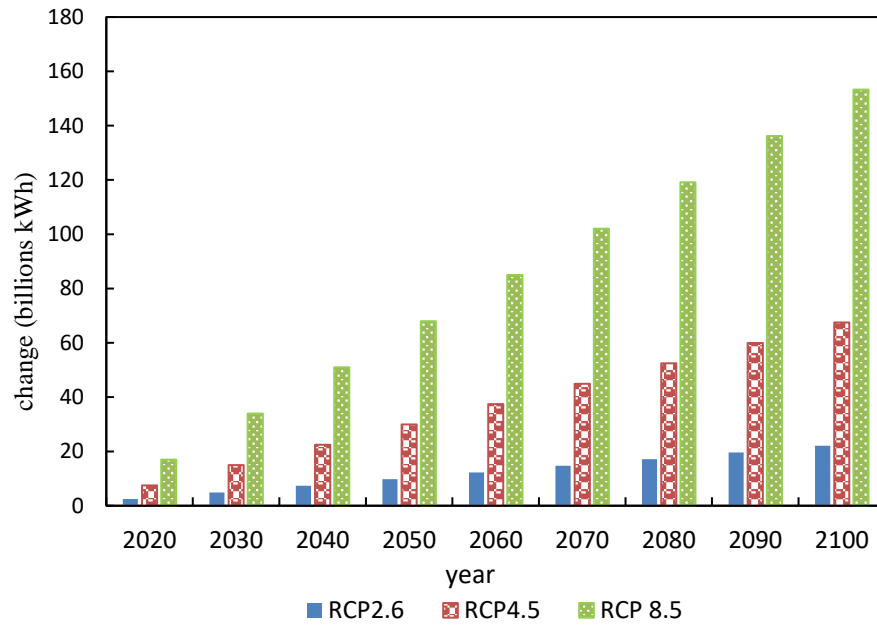
390 Note: Figures in parentheses is the Standard error. * indicates significance at 10% level, * *indicates
391 significance at 5% level, *** indicates significance at 1% level.

392
393 To sum up, the impact of installed capacity and fixed assets investment on hydropower
394 generation are greater in the southern region, which has rich hydropower resources. The average price
395 is negatively correlated with the hydropower output in the northern region, while it is positively
396 correlated with the hydropower output in the southern region. The results show that the substitution
397 of thermal power for hydropower is strong in northern China, confirming that the electricity price is
398 negatively related to hydropower generation at national level.

399 3.3 Forecast results

400 The changes in the national hydropower generation caused by temperature and precipitation in
401 the three climate scenarios (RCP8.5, RCP4.5 and RCP2.6) with setting 2011 as benchmark, are shown
402 in Figure 5. It can be seen that hydropower generation will keep growing under the three climatic
403 scenarios. Compared with 2011, the growth of hydropower generation by 2100 in RCP2.6, RCP4.5
404 and RCP8.5 caused by climatic factors (precipitation and temperature) will be 3.161% (22 billion
405 kWh), 9.656% (67.4 billion kWh), 21.932% (153.3 billion kWh) respectively, which reflects the
406 strong impact of climate on hydropower development and the great potential of hydropower
407 development in China in the future.

408



409

410 **Figure 5 The changes in the national hydropower generation caused by temperature and rainfall under**
 411 **three climate scenarios (based on 2011)**

412

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

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

429

430 **Table 6 Changes in percentage of hydropower output in China caused by HDD, CDD and rainfall**431 **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

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

433

4 Conclusions and policy implications

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

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

450 Overall, hydropower in China is sensitive and vulnerable to climate fluctuation, where the
451 temperature and rainfall are observed to be the most important factors in hydropower output.
452 Therefore, in the context of global warming, on the one hand, hydropower development in China will

453 experience more favorable conditions. On the other hand, extreme climatic events caused by global
454 warming, including rainfall, heat waves, floods, and drought, will impose more challenges for the
455 development of hydropower in China. Therefore, it is important for China to adhere to the strategy of
456 prioritizing to the development of hydropower. In addition, in order to gradually improve the
457 development and utilization of hydropower in various regions, we should constantly improve the
458 construction of the hydropower infrastructure to enable it to adapt to climate change.

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

466 (3) The differences in hydropower potential is significant under different climate scenarios.
467 Compared with 2011, the growth rate of hydropower generation by 2100 in RCP2.6, RCP4.5 and
468 RCP8.5 caused by climatic factors (precipitation and temperature) will be 3.161% (22 billion kWh),
469 9.656% (67.4 billion kWh), and 21.932% (153.3 billion kWh). This indicates that while hydropower
470 development in China shows great potential in the future, there still exist many uncertainties
471 surrounding it. Therefore, it may require the government to promote other types of renewable energies
472 expansion simultaneously when developing hydropower, to meet the electricity gap probably caused
473 by the decline in hydropower generation when it is in dry winter.

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

483 **5. Further perspectives**

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

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