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Vulnerability of hydropower generation to climate change in China: Results based on Grey Forecasting Model

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Abstract: This paper analyzes the long-term relationships between hydropower generation and climate factors (precipitation), hydropower generation capacity (installed capacity of hydropower station) to quantify the vulnerability of renewable energy production in China for the case of hydropower generation. Furthermore, this study applies Grey Forecasting Model to forecast precipitation in different provinces, and then sets up different scenarios for precipitation based on the IPCC Special Report on Emission Scenarios and results from PRECIS (Providing Regional Climate projections for Impacts Studies) model. The most important result found in this research is the increasing hydropower vulnerability of the poorest regions and the main hydropower generation provinces of China to climate change. Other main empirical results reveal that the impacts of climate change on the supply of hydropower generation in China will be noteworthy for the society. Different scenarios have different effects on hydropower generation, of which A2 scenario (pessimistic, high emission) has the largest. Meanwhile, the impacts of climate change on hydropower generation of every province are distinctly different, of which the Southwest part has the higher vulnerability than the average level while the central part lower.

Keywords: Climate change; Hydropower generation; Vulnerability

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1 Introduction

Developing renewable energy is an effective response to cope with climate change and to satisfy the energy demand (Yüksel, 2008). It is shown in the Working Group III special report on renewable energy sources and climate change mitigation (hereinafter referred to as the "report") issued by the Intergovernmental Panel on Climate Change (IPCC) that 2.5% of the global available technical renewable energy potential will be able to meet about 80% of global primary energy supply in 2050 (IPCC, 2011), which provides a strong scientific basis for the development of renewable energy in China. However, the structure of energy production in China indicates that non-fossil fuels only accounted for 8.7% of the total energy production in 2009 (CNBS, 2011a). In the power sector, the proportion of non-fossil energy installed power was 26.53%, of which the share of hydraulic generating capacity was approximately 22.5%. As hydropower capacity has kept an increasing rate of 10% for three years (Zhang, 2010a), renewable energy (especially hydropower) development is likely to be largely improved in China.

Report also pointed out that renewable energy has been playing a vital role in mitigating climate change and popularizing energy use. Once the existing policy bottleneck is eliminated, contributions made by renewable energy to the world will be unveiled (IPCC, 2011). What has been mentioned above makes it clear that renewable energy will act actively in energy security, climate change mitigation, and energy utilization promotion.

Non-fossil energy not only experiences rapid growth in China, but also leads the world energy development. In particular, China's nuclear power capacity under construction ranked first in 2010 over the world, while both of the hydropower capacity and installed capacity are far higher than those in other main hydroelectric power nations, even the highest of the world (Wei et al., 2012). In addition, China has become the world's largest wind power installed countries in 2010, and the average annual growth rate has been over 100% since 2005. Furthermore, China is also the world largest producer of solar energy photovoltaic cells in 2010 (Wei et al., 2012). It is not an exaggeration to say that China has already had the overwhelming leadership in developing the non-fossil energy.

However, utilization of the new energy in the world, especially the use of renewable energy, has been increasingly affected by climate change (Harrison, 2005). The report "Climate Impacts on Energy Systems" released by the World Bank recently demonstrated the direct effects of climate change on energy systems including energy supply and demand, energy endowments, energy infrastructure and energy transportation as well as the indirect effects of climate change through other economic sectors to energy systems (Ebinger and Vergara, 2011). Torben and Steffen (2010) analyzed the influences of climate change on the electric power market in terms of electricity supply and power demand. The U.S. Climate Change Science Program (CCSP) issued in 2007 estimated the impacts of climate change on the electric power production and utilization in America and concluded that renewable energy would play a key role in climate change mitigation and low carbon emissions in the future, but its high dependence on the climate conditions would make it vulnerable to climate change (Wilbanks et al., 2007).

At present, there are relatively few researches on the vulnerability of hydropower to climate change. Lucena et al. (2009) applied the seasonal ARMA model to analyze the vulnerabilities of renewable energy production in Brazil for the cases of hydropower generation and liquid biofuels production, and pointed out the increasing energy vulnerability of the poorest regions of Brazil to global climate change (GCC). From the perspective of regulation of water conservation, Ruiz et al. (2011) analyzed the influence of climate change on water runoff which led to a dramatic change of hydropower power generation capacity in the central Andean mountains, and revealed the urgency for management measures on sustainable development. Maurer et al. (2009) presented the relationship between the runoff of Central American Rio Lempa river basin and hydroelectric power, and concluded that the region with the decline trend in hydropower potential was likely to be around where the flow in the rivers were decreasing. Dursun and Gokcol (2011) investigated hydroelectric power in Turkey, in particular, its potential and present status, and concluded that there was much room for hydropower development in meeting the energy demand in Turkey.

Poor availability of historical data on rainfall and the inaccurate information of precipitation in each hydropower station are the main reasons why researches on hydroelectric vulnerability of climate change are limited. For that, the Grey system theory, which has been widely used for prediction, was employed in this paper as a new method to solve the problem of information inaccessibility and inaccuracy. But researches on energy and environment issues with the Grey system theory are relatively few. Feng et al. (2011) studied the influence of residents' consumption of China on the energy use and carbon dioxide emissions by means of Grey relation analysis and consumer lifestyle theory, and not only found out that the indirect effects were greater but also revealed the effects on the income of the residents as well as the different impacts on the different income levels. Zhang et al. (2011) analyzed the relationship between energy consumption and industrial structure, and obtained the Grey correlation degree between different industry and energy consumption, thus qualitatively forecasted the trend of energy consumption in the future. Yin and Gu (2003) forecasted the short-term energy demand, notably for coal, crude oil, natural gas and water electricity, by applying the generation buffer operator theorem in Grey system theory, which was highlighted in the energy structure of China.

Different from the past work, this paper applies Grey forecasting model for short-term forecast on rainfall, and regards this as the benchmark scenario. With PRECIS model, we assess the influences of climate change on rainfall in different situations. Although global climate change may affect the supply of other renewable energy, such as wind power (Breslowm and Sailor, 2002; Sailor et al., 2008), and non-renewable resources, namely gas-fired thermal generation that was also mentioned in Shaeffer et al. (2008) as well as those were not involved in our work. This paper only focuses on the influence of climate change on hydroelectric power, for it is one of the most important renewable energy sources in China. Furthermore, based on the definition of 'vulnerability' from IPCC (2007), we define the vulnerability of hydropower generation to climate change as "the relative degree of the hydropower system to cope with the adverse effects of climate change, especially the changes of rainfall pattern.

The next part will introduce the framework, methods and the GCC scenarios in this research. Section 3 revolves from results and analysis of relevant scenarios. Section 4 unveils the main conclusions of this study and some policy implications. Finally, concluding remarks and recommendations for model improvement are given in section 5.

2 Methodology

2.1 Conceptual framework

In this article, the classic regression method is introduced to analyze the long-term relationships between hydropower generation and climate change factors, hydraulic power generation capacity in China as well. With the extension of Grey prediction model, the rainfall forecast in the BAU (Business as Usual) scenario can be obtained. Based on the premises of installed capacity of hydropower station and with the help of the Special Report on Emissions Scenarios issued by the IPCC and PRECIS model, rainfall patterns of our country under A2 and B2 scenarios in 2020 and 2030 are obtained to evaluate the vulnerability of climate change on hydroelectric power in different situations of China. By analyzing the results, we put forward some recommendations for China's energy development. Fig. 1 illustrates the framework of this paper.

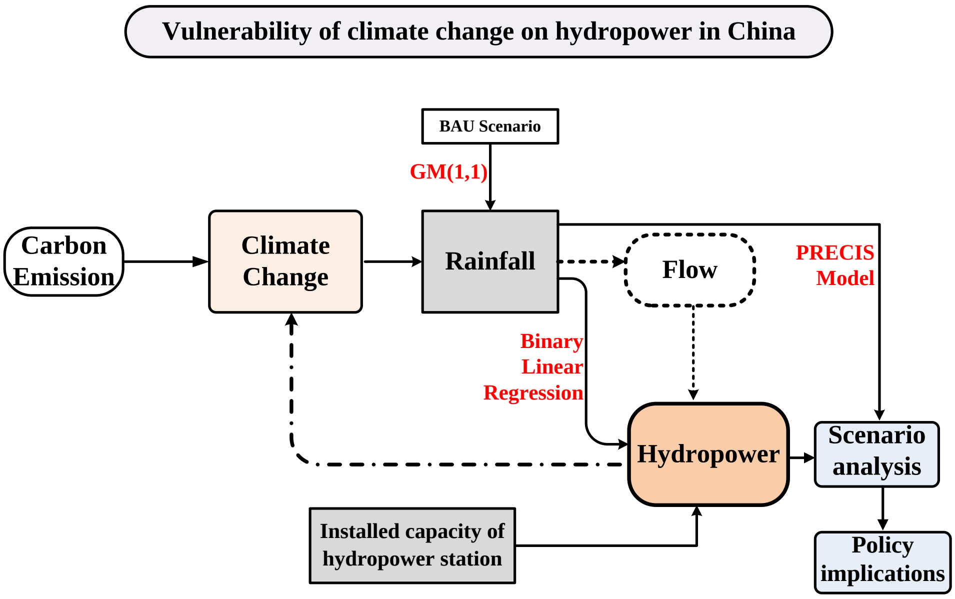

Fig. 1. Framework of this paper

2.2 Vulnerability assessment method based on Grey Model

Hydroelectric power is the most efficient way to meet energy demand (Dursun and Gokcol, 2011) and one of the largest renewable sources for electricity generation in China. Hydropower stations located in the Yangtze River basin dominate this sector. However, due to the influences of climate change and other factors, rainfall pattern in this basin changes easily, which is likely to result in drought and flood. As a result, the influence of climate change on the runoff of hydropower stations can be assessed through changes in the rainfall pattern. What's more, hydraulic power generation capacity should also be taken into account as the indicator of power generation capacity. As explained in Fig. 2, hydroelectric installed capacity has experienced rapid growth with an average annual growth rate of 9.71% since 1993 (CNBS, 2011). Also, hydroelectric power's capability being obviously enhanced strongly promotes China's economy

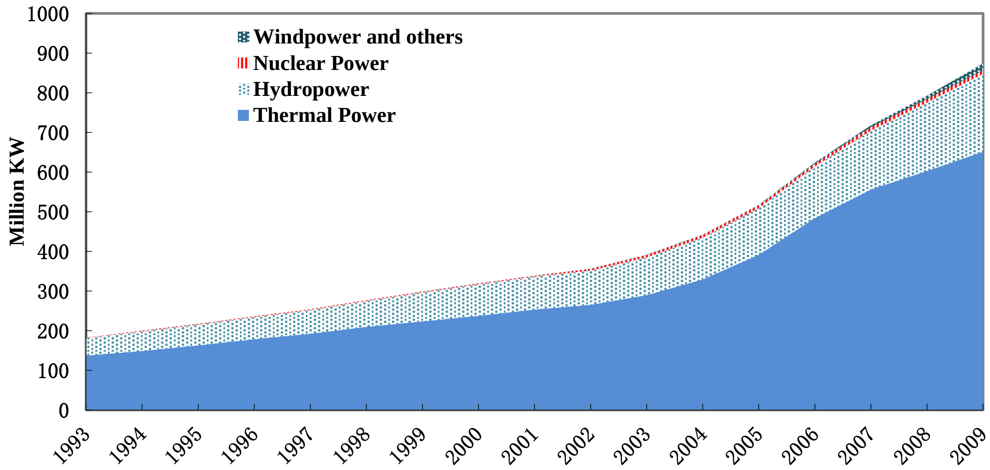

Fig. 2. Trend of hydroelectric installed capacity in China (1993-2009)

Considering the status quo in China, this article selects the top nine hydroelectric power provinces (Hubei, Sichuan, Yunnan, Guangxi, Hunan, Fujian, Guizhou, Guangdong and Gansu), shown in Fig. 3. To apply each province as the basic unit for regression analysis, this research presents the relationships between hydropower and the rainfall, installed capacity of hydropower during the period from 2000 to 2009. Regression parameters can be estimated by the least square method, and we set up two GCC scenarios resembling the two emission scenarios A2 (high emission) and B2 (low emission) proposed by the IPCC special report on emission scenarios (IPCC, 2000).

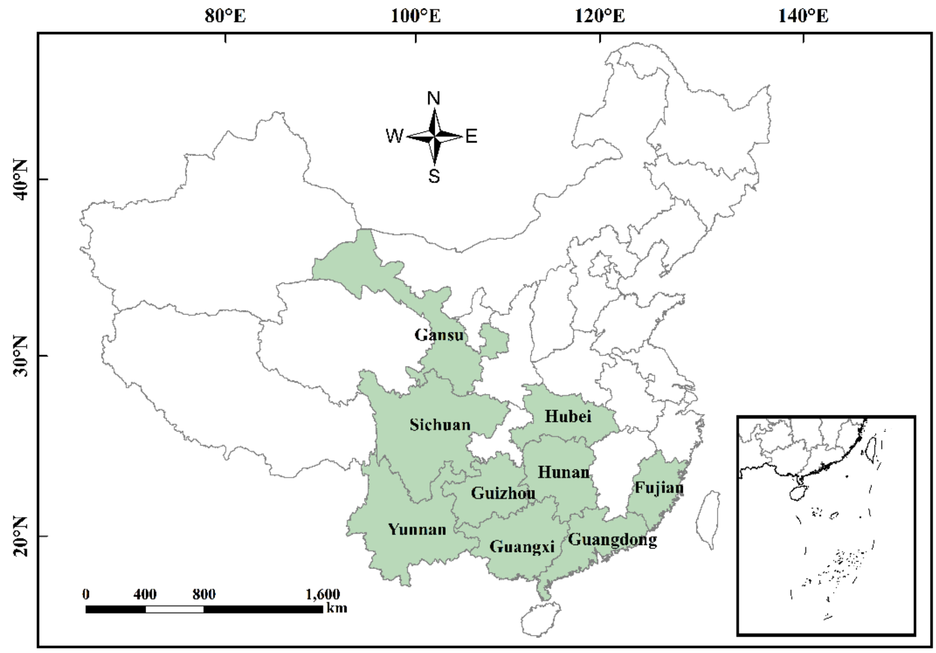

Fig. 3. Geographical location of those top nine hydroelectric power provinces

Note: It is a schematic map and does not implicate the definite boundaries.

The procedures of Grey Forecasting Model (Liu et al., 2010) on prediction of the rainfall in each province are as follows.

Suppose the original rainfall sequences of province *j* are $\boldsymbol{X}_j^{(0)}, j=1,2,\cdots,9$, which is a nonnegative sequence with the expression of $\boldsymbol{X}_j^{(0)}=\left\{x_j^{(0)}(1), x_j^{(0)}(2), \cdots, x_j^{(0)}(n)\right\}$, hereinto. $x_j^{(0)}(k) \geq 0, k=1,2,\cdots,n$. *k* is the target year and *j* is the specific regions or provinces.

The transformational rainfall sequences of *j* province ($\boldsymbol{X}_j^{(1)}, j=1,2,\cdots,9$) are the first-order accumulating generation operator sequence, which can be expressed as $\boldsymbol{X}_j^{(1)}=\left\{x_j^{(1)}(1), x_j^{(1)}(2), \cdots, x_j^{(1)}(n)\right\}$, where $x_j^{(1)}(k)$ is presented as Eq.(1).

$$x_j^{(1)}(k)=\sum_{\mathrm{i}=1}^{k} x_j^{(0)}(1), k=1,2,\cdots,n$$

(1)

The following transpositional precipitation sequences of provinces *j* are $\boldsymbol{Z}_j^{(1)}, j=1,2,\cdots,9$ with an expression of $\left\{z_j^{(1)}(1), z_j^{(1)}(2), \cdots, z_j^{(1)}(n)\right\}$, where $z_j^{(1)}(k)$ can be described as Eq. (2).

$$z_j^{(1)}(k)=\frac{1}{2}\left[x_j^{(1)}(k-1)+x_j^{(1)}(k)\right] \tag{2}$$

The following two theories are the key parts of **GM** (1, 1) (Liu et al., 2010).

Theory 1: If $\hat{\alpha}_j=\left[\mathrm{a}_j,\mathrm{b}_j\right]^{\mathrm{T}}$ is the parameter series of *j* province and $\boldsymbol{Y}_j=[x_j^{(0)}(2),x_j^{(0)}(3),\cdots,x_j^{(0)}(n)]^T$, $\boldsymbol{B}_j=\begin{bmatrix}-z_j^{(1)}(1) & -z_j^{(1)}(1)\cdots & -z_j^{(1)}(1)\\ 1 & 1\quad\cdots & 1\end{bmatrix}^T$, the parameter series estimated by the least square method in the $\mathrm{GM}(1,1)$ model (shown in Eq. (3)) can be presented as $\hat{\alpha}_j$ in Eq.(4)**.**

$$\boldsymbol{X}^{(0)}{}_j(\mathrm{k})+\mathrm{a}_j\boldsymbol{Z}^{(0)}{}_j(\mathrm{k})=\mathrm{b}_j$$

(3)

$$\hat{\alpha}_j=\left[\mathrm{a}_j,\mathrm{b}_j\right]^{\mathrm{T}}=\left(\boldsymbol{B}_j{}^{\mathrm{T}}\boldsymbol{B}_j\right)^{-1}\boldsymbol{B}_j{}^{\mathrm{T}}\boldsymbol{Y}_j \tag{4}$$

The results of theory 1 could be the data support for theory 2.

With other conditions in theory 1 fixed, we call Eq. (5) the shadow equation of $\mathrm{GM}(1,1)$ model.

$$\frac{dx^{(1)}}{dt}+ax^{(1)}=b$$

(5)

Theory 2: Supposed series $\boldsymbol{B}_j,\boldsymbol{Y}_j,\boldsymbol{\alpha}_j$ are the same as ***theory 1***, time response function 'Eq. (6)' which is in accordance with shadow Eq. (5) of $\mathrm{GM}(1,1)$ model will be obtained from this model, especially if we suppose the t in the Eq. (6) above is equal to *k*, we will demonstrate the time response series of this model. With the Eq. (1), the rainfall series of the j province in *k+1* time period will be presented as in Eq. (7)**.**

$$x^{(1)}(t)=\left(x^{(1)}(1)-\frac{b}{a}\right)e^{-at}+\frac{b}{a}$$

(6)

$$\hat{x}_j^{(0)}(k+1)=\hat{x}_j^{(1)}(k+1)-\hat{x}_j^{(1)}(k)=\left(1-e^{a}\right)\left(x_j^{(0)}(1)-\frac{b}{a}\right)e^{-ak} \tag{7}$$

In summary, we set the historical time data of precipitation (2000-2009) as the original data series $\boldsymbol{X}^{(0)}$ with the valuation of *n*. Further, *n* is equal to 10. Combined with the Eq. (1) and Eq. (2), this article can obtain the series $\boldsymbol{X}^{(1)}$ and $\boldsymbol{Z}^{(1)}$. Based on theory 1, the estimation of parameters will be employed in the forecast Eq. (7) as well as the forecast of rainfall. The current research applies the software GTMS 3.0 for calculation.

2.3 GCC scenarios and databases

The two IPCC emission scenarios on which the climate projections used in this study were based-A2 and B2-are two of four qualitative storylines (A1, A2, B1 and B2) characterized by different economic and energy development paths. They describe divergent futures in an attempt to cover significant portion of the underlying uncertainties in the key driving forces for greenhouse gases emissions (IPCC, 2000). The two scenarios have wide applications in the researches of vulnerability over the world, especially used in regional climate model of China (Chen et al., 2007; Liu 2011; Xu et al., 2005).

Scenario A2 (*pessimistic, high emission*) depicts a heterogeneous world, which places a considerable emphasis on the regional oriented economic development. Under this scenario, there is less focus on economic, social and cultural communications among regions, which becomes more self-reliant and tend to preserve the local identities. Furthermore, per capita economic growth and technological change are uneven and slow, which do not attempt to narrow the gap between newly-industrialized and developing parts of the world. Final energy intensities in the A2 scenario decline with a rate of 0.5%–0.7% per year (IPCC, 2000; Lucena et al., 2009).

In scenario B2 (*optimistic, low emission*), there is an intensive concern for environmental and social sustainable development at both national and local levels. This scenario depicts a world with continuously increasing population at a rate slightly lower than that of A2, also with intermediate levels of economic development and more regionally sound technological innovations. Finally, the final energy intensity in scenario B2 declines at the rate of 1% per year, in accordance with the average historical level since 1800 (IPCC, 2000; Lucena et al., 2009).

In a baseline (*business as usual, BAU*) scenario, it assumes that the concentration of greenhouse gases stays at the current level, and climate change factors are constant in the next 20 years. What is imagined in this scenario is quite idealistic, just as a comparative analysis to the above scenarios.

We set A2, B2 from IPCC report at a global scale, and it is necessary for the transition from the global scenarios to local ones. PRECIS (providing regional climate projections for impacts studies) is developed in order to help generate high-resolution climate change information for as many regions in the world as possible. The intention is to make PRECIS available to groups of developing countries in order that they may develop climate change scenarios at local level, which can avoid the deviation by using GCM (global climate model) for the impact studies. Xu et al. (2005) used PRECIS model for the influence analysis about the temperature and rainfall under different scenarios and time periods. Chen et al. (2007) applied PRECIS model for the prediction analysis of future ground temperature and rainfall under B2 scenario relative to benchmark period (the year 1961-1990) in Ningxia province, and concluded that the future average rainfall will increase in Ningxia province. Liu (2011) bracketed 20 GCMs issued by the IPCC 2000 which was divided into high/medium/low resolution model, and compared the simulation results from PRECIS with the results from GCM. In this paper, based on the results from the PRECIS model, the impact assessment of climate change on rainfall in China is relevant with the scenarios setting. This is helpful for the prediction of rainfall change caused by climate change and easy to evaluate the influence of different rainfall regime on hydroelectric generation.

The data in this article mainly refers to the rainfall of provinces from the national statistics yearbook 2000-2010 and statistical yearbook 2011 of each province (CNBS, 2011a). Interprovincial data of hydroelectric power and hydropower installed capacity comes from China power yearbook 1993-2010 (ECCPY, 1993-2010), and part of energy data comes from China's energy statistics yearbook 2011 (CNBS, 2011). China water resources development planning data is mainly derived from the information of ‘China hydropower 100 memorial conference’ (Zhang, 2010b), which predicts that China's hydropower capacity will increase to 380 million kW in 2020. What’s more, we set China's hydropower capacity of 2030 based on economic 402 million kilowatts, and determine the provincial hydropower capacity in 2020 and 2030 according to the current proportion of the each province.

As explained in Fig.4., the proportion of hydropower capacity of nine provinces accounts for about 80% of the national hydropower, particularly 81.49% in 2009 (ECCPY, 2010) which could indicate that the selected nine provinces in the model represent the correct application of this vulnerability analysis of climate change on the overall hydroelectric power station in China.

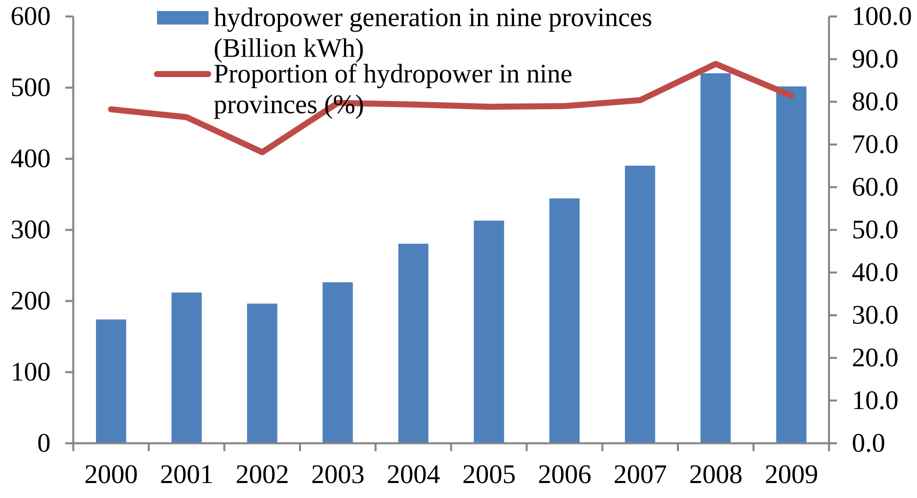

Fig. 4. Proportion of hydropower in nine provinces (2000-2009)

In addition to the uncertainties of the energy models, the estimated vulnerabilities of GCC on the energy sector in China presented in this study are intrinsically dependent on the climate projections adopted. Therefore, the trends and directions are the ones to be emphasized rather than the precise results provided.

3 Result analysis and discussions

3.1 Results on Grey regression model

Regarding each province as a regression unit, we establish the binary linear regression model for hydropower capacity. In light of criteria selection, we select the parameters under T statistic, F statistics and adjusted goodness-of-fit as the main standards. Table 1 lists the regression parameter for the selected nine provinces.

Table 1

Regression analysis for hydropower in the selected nine provinces

Variable		Partial Regression Parameters	Standard Deviation	T Statistic	F statistic	Adjusted R^2
Yunnan	Constant	-193.996	130.482	-1.487	64.356	0.948
	Rainfall	0.240	0.113	2.130*	(0.000)	

	I.C.	0.346	0.035	9.863**		
Guangdong	Constant	-376.932	163.090	-2.311*	6.606	0.809
	Rainfall	0.095	0.043	2.202*	(0.024)	
	I.C.	0.459	0.135	3.388**		
Hubei	Constant	-86.164	144.804	-1.595	130.551	0.974
	Rainfall	0.052	0.106	2.495*	(0.000)	
	I.C.	0.432	0.026	16.009**		
Sichuan	Constant	-256.763	161.836	-1.587	40.531	0.921
	Rainfall	0.255	0.174	2.464*	(0.000)	
	I.C.	0.434	0.049	8.911**		
Guangxi	Constant	-26.014	35.366	-0.736	119.114	0.971
	Rainfall	0.045	0.024	1.862*	(0.000)	
	I.C.	0.316	0.021	15.147**		
Hunan	Constant	49.599	101.952	0.486	12.172	0.777
	Rainfall	0.015	0.055	2.029*	(0.005)	
	I.C.	0.282	0.061	4.623*		
Fujian	Constant	-37.832	83.609	-0.452	7.240	0.674
	Rainfall	0.087	0.047	1.857*	(0.020)	
	I.C.	0.236	0.081	2.924*		
Guizhou	Constant	67.721	97.460	1.644	9.692	0.735
	Rainfall	0.076	0.079	1.961*	(0.010)	
	I.C.	0.190	0.043	4.371**		
Gansu	Constant	-53.225	33.346	-1.596	38.611	0.917
	Rainfall	0.049	0.066	2.742*	(0.000)	
	I.C.	0.474	0.055	8.644**		

Note: *** p<0.001; I.C. is the abbreviation of installed capacity of hydropower.

It can be seen from this table, the F value and goodness-of-fit on the return of the Guangdong province are in lower level condition of all selected provinces, but still pass the test. According to the results of regression in Table 1, the reference standards for the selection of regression results in this paper are presented as the following Formula 8.

$$R^2 \geq 0.800, F \geq 6.606, p \geq 1.812$$

(8)

In addition, the above table indicates that the factor rainfall plays a considerable role in the hydropower generation of Yunnan and Sichuan province, which are located in the

Southwest of China and the upper reaches of Yangtze River. Therefore, the changes of rainfall pattern in those provinces will result in the high vulnerability of hydropower in China.

3.2 High vulnerability of hydropower generation in national level

With the above regression equation and the forecast of rainfall and hydropower installed capacity, we can obtain total hydropower capacity of nine provinces under different scenarios in 2020 and 2030, which are listed in Table 2.

Table2

Hydropower generation of China in each scenario in 2020 and 2030 (Billion kWh)

Year	BAU	A2 scene	B2 scene
2020	1009.614	978.507	989.229
2030	1066.580	1008.943	1019.628

It can be seen from Table 2 that climate change on hydropower generation of China under A2 scenario would cause the losses of power generation-that refer to the difference of hydropower generation between A2 or B2 and BAU scenario-in 3.09% (2020) and 5.40% (2030), which equals to 31.107 billion kWh (2020), 57.637 billion kWh (2030). Meanwhile, under B2 scenario, the losses would be 2.02% (2020) and 4.41% (2030), which equals to 20.386 billion kWh (2020), 46.952 billion kWh (2030).

The effect of climate change on hydropower generation of China is significant. According to present per capita electric amount (2758 kWh per capita in 2010, see CNBS, 2011), it is estimated that under scenario A2 and B2 about 11.28 million and 7.39 million people have no access to electricity due to the decreases of hydropower generation in China potentially induced by climate change in 2020. Such facts may indicate the personal consumption would reduce 23.31 kWh per year (A2 scenario), 15.27 kWh per year (B2 scenario) in 2020. If it goes along this way, the situation would deteriorate, which should lead about 20.90 million people to electricity scarcity.

Under different scenarios of climate change, the effects on hydropower generation would be significantly different. Under A2, B2 and BAU scenario, the losses of hydropower considered in the paper can be explained as the losses caused by climate change. There is a difference of losses, accounting for 1% of total electricity generation under scenario A2 (high emission) and scenario B2 (low emission) for hydropower in next twenty years, which equals to 10.721 billion kWh (2020), 10.685 billion kWh (2030).

3.3 Significant difference of hydropower vulnerability in regional level

The impacts of climate change on hydropower vary significantly between regions, for example, the Southwest districts with high vulnerability are rich in hydropower but are less developed. As shown in Fig. 5, the loss value means the difference between the loss values of each province under scenario A2 or B2 and the average loss of all provinces. From Fig. 5, the losses of hydropower among the Southwest district of China (Sichuan, Yunnan, Guizhou) and Fujian, Guangdong are beyond the average level, while the amount of hydropower generated by the Southwest districts (Sichuan, Yunnan, Guizhou) is 33.93% of the total amount of hydropower of China.

In recent years, the hydropower generation in those districts which suffer from frequent droughts decreases obviously and the power proportion of the four provinces (Sichuan, Yunnan, Guangxi, Guizhou) decreased from 43.49% in 2008 to 42.33% in 2009. Furthermore, the hydropower generation of the two major hydropower provinces-Yunnan and Guangxi- are down by 3.78% and 1.19% respectively year-on-year along with the slower growth rate of hydropower generation of Sichuan and Guizhou provinces. Furthermore, though the resident consumption level of Sichuan was 8182 RMB in 2010, it was also relatively low in China, do not even mention that resident consumption of Yunnan and Guizhou provinces are only 6724 RMB and 5879 RMB, which were at the bottom level of China in 2010, and those of Yunnan, Guizhou and Sichuan province were below the average resident consumption level-9968 RMB (CNBS, 2011a)-of the whole country in 2010.

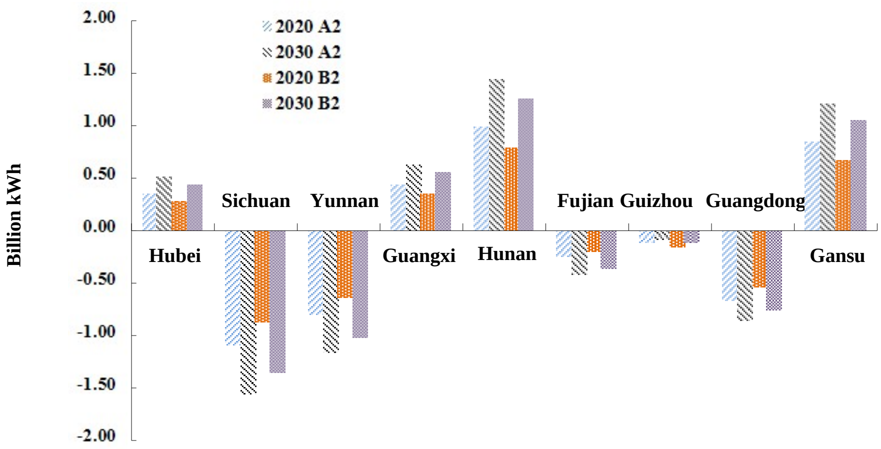

Fig. 5. Relative losses of each province under different scenarios

By contrast, the losses of hydropower in Fujian and Guangdong province exceed the average level, and those eastern coastal districts are susceptible to the extreme climate events due to the geographic position of these two provinces. In addition, the rainfall in those provinces is closely related to the monsoon and tropical storms. Consequently, the reason for the larger losses of these two eastern coastal provinces may lie in the extreme climate events, the change of monsoon and the frequency of tropical storms.

4 Conclusions and policy implications

4.1 Conclusions

From the analysis above, we can draw the following conclusions.

(1) Hydropower generation and its installed capacity in China have undergone rapid

growth, which provides a strong support for the economic development. The energy structure, however, with high dependence on thermal power generation has not changed yet. To deal with the serious environmental problems caused by this fact, the clean degree of electricity mix should be improved as soon. Though hydropower has been gradually increasing, its proportion still slightly decreases due to an unshakable high proportion of thermal power. Fortunately, other renewable sources, notably wind power, increase rapidly in recent years, which have exceeded nuclear power to take the third rank in the power generation.

(2) The effects of climate change on hydropower are fairly significant, and the vulnerabilities of hydropower generation to climate change vary greatly under different scenarios. In the future two decades, as for the climate change caused by CO_2 emission, the direct losses of hydropower could exceed 2%. Meanwhile, the reference scenarios of this paper are set as high emission and low emission. Our scenario analysis suggests that the vulnerability of hydropower under high emission scenario (A2) is significantly higher than low emission scenario (B2). If no relevant measures will be taken in the future, the effect of climate change on hydropower would be enlarged, which would influence the development of the economy and society of China.

(3) The effects of climate change on hydropower differ obviously among regions, and the Southwest and Eastern coastal districts of China are more vulnerable than other districts. Most importantly, those results indicate the fact of the increasing hydropower vulnerability of the poorest regions and the main hydropower generation provinces of China to climate change. In addition, compare to the lower loss in Middle district, the loss of hydropower caused by climate change in Southwest district is higher, which corresponds with the status quo in China. Along with the vulnerable situation to drought in the Southwest China, its growth rate of

hydropower generation has decreased obviously, leading to a negative growth for the first time in some Southwest provinces, like Yunnan. In view of the amount of rainfall in those vulnerable districts mentioned above, it could be seen that the rainfall have decreased drastically.

4.2 Policy implications

According to the results of the regression model and the analysis of the scenarios, some important implications for hydropower generation of China in the future are presented as below.

(1) Improving the structure of power generation, promoting the production of clean electricity, and developing renewable energy like hydropower and wind power are the most efficient and effective solutions for clean and sustainable energy development. Because of the high proportion of thermal power in the electric power structure and the major sources of thermal power from coal, the widespread power cuts will occur with tight supply of coal and the high demand of electricity in China. Since coal is the nonrenewable resource, the thermal power by coal is unsustainable and clean energy sources should be used for electricity generation. Even though nuclear power, as one kind of nonrenewable resource, has a plentiful reserves, it does not offer much help as what it is supposed to (Wang et al., 2013). Concerning the lower proportion of nuclear power in our country, nuclear power should be further developed on condition that the nuclear plants could be guaranteed safely. Hydropower and wind power are complementary in view of seasonal distribution, which benefit the steady supply of electricity. Nevertheless, the development of wind power is slightly slower than that of hydropower, which should be emphasized in further energy planning.

(2) It is wise to take measures in coping with climate change actively, reinforcing the

complementary management between hydropower and other powers, and keeping the balance between demand and supply of electricity for the purpose of enhancing the ability for climate change mitigation or adaptation. Due to its sustainability, the exploitation of hydropower would make less carbon emission and fewer environmental problems than the use of fossil fuels do, which indicates that hydropower is fairly environmental friendly, thus, works effectively to deal with climate change. Nevertheless, the utilization of hydropower depends greatly on the water flow, which relies heavily on climate conditions. As a result, climate change could inevitably increase the risks of the operation of hydropower as well as its output and long-term energy planning without consideration of the possible impact caused by the future GCC. In this case, it is far from enough to cope with climate change only, but should place more emphasis on avoiding losses of hydropower under climate change, since hydropower is closely related to rainfall and depends on its variability in seasons. Consequently, other powers, such as the hydro-wind power, need to be complementary on the dry season in order to make the electricity supply steady and sound. In brief, maintaining the balance of the demand and supply of electricity is not only what we need to do with climate change but also a requirement of strengthening the management of electricity.

Even though this work is the first attempt to research the vulnerability of hydropower generation to climate change in China, there are some limitations in this paper. Given the uncertainties of global climate change models and scenarios, conclusions of this research could reveal the tendencies and directions rather than a projection. In this way, there is no need to be intertwined with the number itself. In addition, the scenarios adopted by the models also have considerable effects on the results. Two scenarios from IPCC 2000 selected by this paper are calibrated by regional climate model-PRECIS to evaluate the influence of climate change on rainfall， which have indirect impacts on hydropower generation.

The ongoing vulnerability of hydropower generation from climate change, is the additional demand toward water resources from other social economic departments because of GCC, and may jeopardize the availability and reliability of hydropower. So its influence should be considered in future study. Furthermore, vulnerability of hydropower generation from extreme climate events (Tramblay et al., 2012), such as tropical storm, extreme weather and so on, and the relationships between climate change and energy security are also recent research fronts.

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