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Estimating the impacts of climate change on electricity supply infrastructure: A case study of China

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ABSTRACTS

Understanding the impacts of climate change on electricity supply infrastructure (ESI) is important to maintain a reliable power supply. Nonetheless, most existing studies focus on the physical impacts rather than the economic impacts, failing to provide references for the cost-benefit analysis of different abatement policies and measures. With this motivation, this study firstly employs a downscaled climate system model to project temperature paths in the future. Then, an integrated model is established to quantify both physical and economic impacts of long-term future temperature rise on the existing ESI components. Finally, the maximum climate-attributable impacts on China's ESI are assessed for the period from 2018 to 2099. Our major findings are that: (1) 10.2% of the generator ratings, 17.8% of the transmission and distribution line ratings and 10.0% of the transformer ratings are at risk of outage from expected climate change effects. (2) Around $258 billion of the existing ESI assets are at risk of outage due to the future surface temperature rise, representing 14.2% of the ESI assets in 2017. (3) The impacts of climate change on ESI vary substantially among different provinces and among different infrastructure components. These obtained results can provide important guidance for the mitigation and adaption strategies for the climate change impacts on the electricity sector.

1. Introduction

Electricity Supply Infrastructure (ESI) is regarded as the backbone of the modern economy, which is now facing great reliability risks due to the climate change and extreme weather events (Chen et al., 2020; Kufeoglu et al., 2014). Both the materials and operating efficiencies of ESI are temperature sensitive, so the temperature rise from climate change will affect the working performance of each ESI component, including the generators, Transmission and Distribution (T&D) lines and transformers (Burillo et al., 2016; Craig et al., 2018; van Vliet et al., 2012). To mitigate these impacts, additional infrastructure has to be built or abatement measures need to be taken to maintain safe planning reserve margins and to prevent electricity interruptions (Burillo et al., 2019). It is necessary to quantify the impacts of rising air temperatures on the ESI to support for the mitigation and adaptation actions (Martinich and Crimmins, 2019; Pryor and Barthelmie, 2010). With a better understanding of the magnitude and locations of ESI vulnerabilities, we can evaluate the effectiveness of investment and policy options to reduce the climate change risks more accurately.

It is important to understand how the performances of ESI will be affected by temperature rise before quantification, so we have summarized the impact mechanism of climate change on different ESI components from previous studies, see Fig. 1. We can see that the impact mechanism is complex and quantifying the impacts is not an easy task. On the one hand, there are multiple impact paths of temperature rise on the same type of ESI components. For example, temperature rise can not

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only reduce the density of input air in the coal generators, but also affect the availability of cooling water. On the other hand, there are mixed directions (positive and negative) of climate change impacts on the same ESI components, such as climate change can increase the wind speeds in some regions while decrease the wind speeds in other regions.

Several existing studies have quantified the physical impacts of climate change on the ESI, and most of them define the impacts as the potential de-ratings of infrastructure components that can safely supply or deliver, such as the reduced GW capacity of generators, GVA capacity of transformers and ampacity of transmission lines (Craig et al., 2018; Linnerud et al., 2011). Two main types of methodology have been used in the impact estimations. The first one is based on thermophysical models, which simulate the capacity reductions due to the temperature rise by physical experiments or simulations (Chuang and Sue, 2005; Rousseau, 2013; Rubbelke and Vogele, 2011). This method is highly suitable for modeling the impacts on a specific technology or infrastructure. The second one directly uses the de-rating factors of ESI caused by climate change from synthesizing the previous estimated results (Bartos et al., 2016; Burillo et al., 2019; Sathaye et al., 2013). Although this is a simplification approach, this method is still effective because the detailed parameters of ESI are sometimes difficult to be obtained (Chandramowli and Felder, 2014; Sathaye et al., 2013). Although several studies have estimated the effects of temperature rise on the ESI, there are still some points to be improved. First, most studies focus on the physical impacts rather than the economic impacts, failing to provide references for the cost-benefit analysis of different abatement measures. Moreover, many studies have neglected the line lengths when estimating the climate change impacts on the T&D infrastructure, thus resulting in a bias in the estimation of adaption costs. Second, most existing studies were conducted for the developed countries, whilst studies for the developing countries are still lacking. However, some developing countries (especially China) deserve to be studied due to its large scale and big potentials of vulnerabilities. China has the largest electricity supply system in the world, whose total electricity generation accounts for 26.72% (BP, 2019) and installed capacity represents 26.94% (IRENA, 2020) of the world in 2018. Third, most studies overlook the impact differences among the sub-types of grid lines and transformers, whereas the voltage levels of these two ESI components differ a lot (from 3 kV to 1000 kV). Therefore, this study attempts to bridge these gaps and quantify both physical and economic vulnerabilities of ESI assets due to the rising air temperatures in China. With this motivation, we aim to answer the following three questions.

(1) What are the characteristics of temperature rise due to the climate change in China?
(2) What is the magnitude of ESI assets at risk of outage due to climate change by the end of this century?
(3) How will the estimated impacts of climate change on ESI be influenced by different influencing factors?

To answer these questions, this study firstly employs a Climate System Model (CSM) to forecast the future temperatures under different Representative Concentration Pathways (RCPs) at the provincial level. Then, an impact estimation model is developed to quantify the long-term future climate-attributable impacts on the existing ESI components. Finally, the established methodology is applied to China to analyze both the magnitude and the locations of the climate change impacts, and suggestions are proposed to better inform the long-term capital investment and policy designs.

The remainder of this paper is structured as follows. The second section describes the methodology and data used to conduct the estimation of climate change impacts on ESI. The third section shows the spatial and temporal distributions of the estimated ESI vulnerabilities. The last section summarizes the conclusions and proposes suggestions to mitigate the climate change impacts.

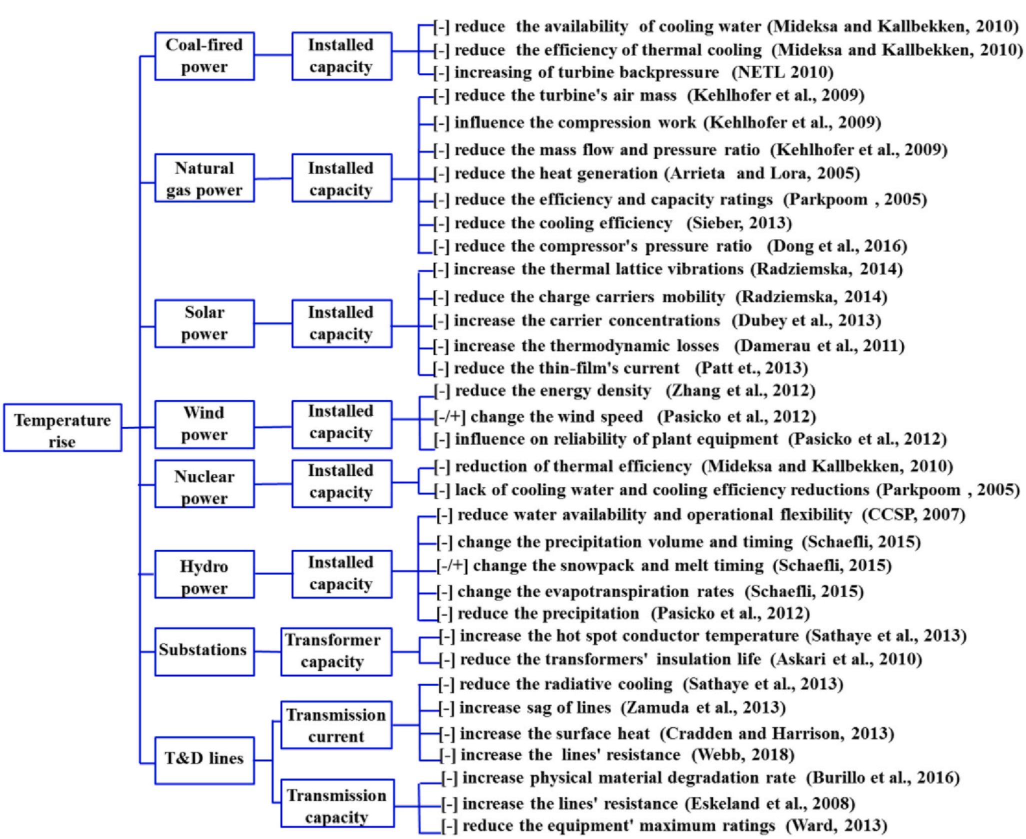

Fig. 1. The impact mechanism of temperature rise on ESI (Askari et al., 2010; Damerau et al., 2011; Dubey et al., 2013; Eskeland et al., 2008; Kehlhofer, 2009; Mideksa and Kallbekken, 2010; NETL, 2010; Schaefli, 2015; Ward, 2013; CCSP, 2007; Webb and Gundlach, 2018; Zamuda et al., 2013).
Notes: The second column shows the ESI components. The third column lists the impact indicators. The fourth column summarizes the major impact paths, and '+/-' in the square brackets indicates the impact directions.

2. Methodology

This section will describe the methodology used in this study. A research framework will firstly be proposed to estimate the impacts of temperature rise on the ESI. Then, a methodology will be established to quantify the temperature-induced vulnerabilities of different ESI components. At last, the data used in quantifying the ESI vulnerabilities in China will be explained.

2.1. Research framework

The research framework of estimating the climate change impacts on ESI is shown in Fig. 2. We firstly project the temperature paths for the period from 2018 to 2099 using a CSM under RCP 8.5. By comparing the projected annual peak temperatures with the highest temperature in the base year of 2017, the maximum temperature increase due to the climate changes can be obtained. Then, an impact estimation model is developed to quantify the de-rated capacity of different ESI components under 1 °C of temperature rise. Integrating the forecasted temperature rise and the impact estimation results, the magnitude of ESI at risk of outage is calculated based on an accounting of the existing assets.

2.2. Climate change impacts estimation model

This study quantifies both the physical and economic impacts of climate change on ESI assets. The physical impacts are defined as the ESI ratings at risk of outage due to the temperature rise, while the economic influences are the monetary values of the physical impacts. Considering the fact that the estimation of climate change impacts is complex and faces uncertainties, several assumptions have been made as follows.

(1) This study estimates the long-term future impacts of temperature rise on the existing quantity and locations of ESI. This assumption has limitations because it neglects the potential future changes of electricity supply structure. However, it allows us to focus on the climate change impacts rather than many other highly uncertain variables, such as technology progress, population growth and equipment deployment. Several studies have also used this static analysis approach on this topic, such as Craig et al. (2018) and Lucena et al. (2010).

(2) This study only quantifies the impacts of temperature rise on the overhead T&D lines, neglecting the impacts on the underground lines. There are two reasons for this assumption. On the one hand, the overhead T&D lines account for more than 97% of the total lengths of T&D lines in China (EPPEI, 2018). On the other hand, the impacts of temperature rise from climate change on the underground lines are not significant (ADB, 2012).

(3) The climate change induced temperature increases can not only influence the water availability for hydro generators, but also affect the cooling water usage of thermal generators and nuclear generators. However, the study does not account for water-resource/precipitation impacts on the ESI due to the data availability.

Based on these assumptions, a methodology is established to quantify the impacts of climate change on the ESI. Considering the fact that the impact mechanisms vary by different components, this study will describe the established impact estimation models for different ESI components separately. The descriptions and sources of parameters used in the model are listed in Table 1.

The physical impacts of climate change on the generators are defined as the capacity (GW) at risk of outage. Similar to Henry and Pratson (2016), this study only considers the temperature-induced impacts on the air-cooled generators, neglecting the impacts on the water-cooled generators. For every type of generation technology, the de-rated generation capacity is assumed to be the product of total installed generation capacity (IC_i), predicted temperature rise (ΔT), shares of air-cooled generators (φ_i) and temperature-induced de-rating factors (λ_i) beyond the threshold temperature (T_{max}). Therefore, the total capacity at risk of outage (C_g) within a specific region is calculated by equation (1).

$$C_g = \begin{cases} \sum_i \lambda_i \cdot \varphi_i \cdot IC_i \cdot \Delta T, & T \geq T_{max} \\ 0, & T < T_{max} \end{cases} \tag{1}$$

The physical vulnerabilities of transformers are modeled as the capacity (GVA) at risk of outage due to the rising air temperatures. The de-rated transformer capacity is calculated based on the transformer capacity (TF_j), the temperature rise (ΔT) and the temperature-induced de-rating factors (η_j) over the threshold temperatures (T_{max}). The total transformer capacity (C_s) at risk of outage caused by climate change in a specific region is shown in equation (2).

$$C_s = \begin{cases} \sum_j \eta_j \cdot TF_j \cdot \Delta T, & T \geq T_{max} \\ 0, & T < T_{max} \end{cases} \tag{2}$$

The physical impacts of climate change on the T&D lines (GW*km) are defined as the results of multiplying the line lengths by the carrying capacity at risk of outage due to the climate change. Since the carrying capacity data of T&D lines after the temperature rise is unavailable, we

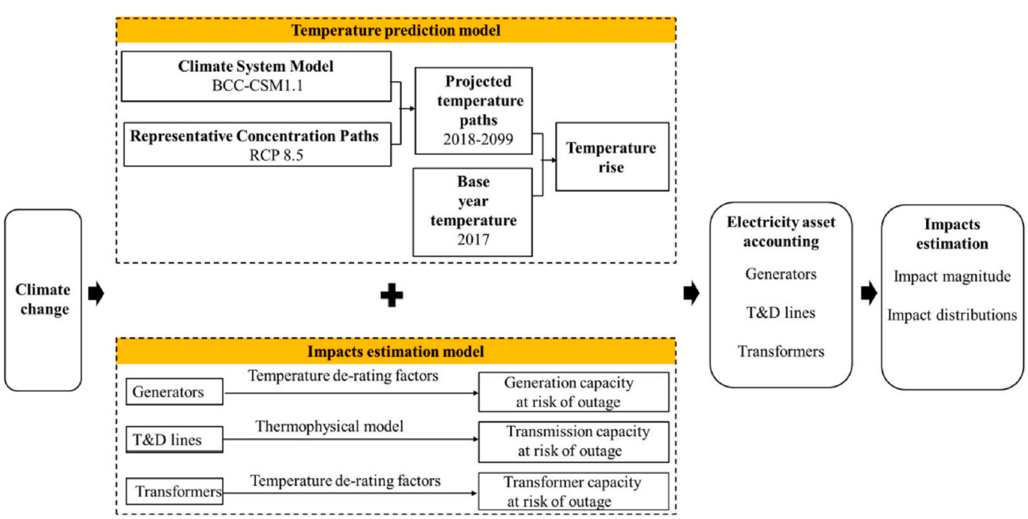

Fig. 2. Research framework.

Table 1
Data sources and explanations.

Parameters	Descriptions	Data sources
Indices		
i	Different types of generators	Defined in this study
j	Different voltage levels of transformers	Defined in this study
k	Different voltage levels of T&D lines	Defined in this study
Infrastructure		
IC_i	Generation capacity	NBS (2018)
L_t	T&D line lengths	NBS (2018)
TF_j	Transformer ratings	NBS (2018)
C_k	Rated transmission capacity	Calculated in this study
CC_k	Transmission capacity after considering temperature increase	Calculated in this study
CR_k	Transmission capacity changes	Calculated in this study
φ_i	The share of air-cooled generators	Platts database
Impact model		
λ_{coal}	De-rating factors of coal generators	Van Vliet et al. (2016)
λ_{gas}	De-rating factors of gas generators	(Dong et al., 2016; Zhou, 2018)
λ_{hydro}	De-rating factors of hydro generators	(Fan et al., 2018; Liu et al., 2016; Turner et al., 2017; Wang et al., 2014; Zhang et al., 2017)
$\lambda_{nuclear}$	De-rating factors of nuclear generators	(Yang et al., 2016; Zhang, 2018)
λ_{wind}	De-rating factors of wind generators	(Sherman et al., 2017; Zhang et al., 2012)
λ_{solar}	De-rating factors of solar generators	Crook et al. (2011)
η_j	De-rating factors of transformers	IEEE (2007)
T_{max}	Threshold temperature	(EPPEI, 2001; Ioanna et al., 2014; Linnerud et al., 2011; Sathaye et al., 2013; Swift et al., 2001)
h	Average heat transfer coefficient of T&D	EPPEI (2001)
D	Conductor diameter of T&D	EPPEI (2001)
T_c	Maximum temperature of conductors	Ren et al. (2006)
T_a	Ambient air temperature	BCC_AGCM 2.0
ε	Emissivity of conductor surface	0.9, (Lu, 2017)
σ	Stefan-Boltzmann constant	5.67E-08, (Bartos et al., 2016)
δ	Solar flux	1000 W/m^2, (Qin, 2015)
α	Solar absorptivity of conductor surface	0.9, (Ren, 2014)
R_c	AC resistance of conductor	EPPEI (2001)
I	Electric current	Calculated in this study
U	Conductor voltages	NBS (2018)
θ	Power factor	0.95, (Sathaye et al., 2013)
Economic values		
$V_{g,i}$	Capital cost of generators	EPPEI (2018)
$V_{t,k}$	Capital cost of T&D lines	EPPEI (2018)
$V_{s,j}$	Capital cost of transformers	EPPEI (2018)
Climate change		
ΔT	Temperature changes	BCC_AGCM 2.0

have to estimate them using a thermophysical model proposed by IEEE (2007). The current-carrying capacity of transmission lines is primarily limited by the conductor's maximum allowed operating temperature (T_c). Overhead electricity grid lines are located in a state of thermal balance, indicating that the convective and radiative heat losses of the line are equal to the heat gained from the sun plus the heat additions caused by the power flow. Therefore, the effects of air temperature (T_a) on the maximum safely allowable current (I) can be calculated for the overhead conductors by equation (3).

$$I = \sqrt{\frac{\pi \cdot h \cdot D \cdot [T_c - (T_a + \Delta T)] + \pi \cdot \varepsilon \cdot \sigma \cdot D \cdot [T_c^4 - (T_a + \Delta T)^4] - \delta \cdot D \cdot \alpha}{R_c}} \tag{3}$$

Once the transmitted electricity current is obtained, the maximum transmission capacity (CC_k) of grid lines can be calculated by equation (4).

$$CC_k = \sqrt{3} \cdot \theta \cdot I \cdot U \tag{4}$$

The transmission capacity (CR_k) at risk of outage is shown in equation (5).

$$CR_k = C_k - CC_k \tag{5}$$

The physical impacts of T&D lines depend on both the transmission capacity and the line length, so the total physical impacts of climate change on grid lines within a specific region are calculated by equation (6).

$$C_t = \sum_k CR_k \cdot L_k \tag{6}$$

Apart from the physical impact estimations, we have also quantified the economic values of physical impacts due to the temperature rise, which are calculated as a result of multiplying the estimated physical impacts by the embodied economic values, see equation (7).

$$EI = \sum_i \lambda_i \cdot \theta_i \cdot IC_i \cdot \Delta T \cdot V_{g,i} + \sum_k CR_k \cdot L_k \cdot V_{t,k} + \sum_j \eta_j \cdot TF_j \cdot \Delta T \cdot V_{s,j} \tag{7}$$

2.3. Data

This study estimates the impacts of climate change on the ESI assets in 31 Chinese provinces for the period from 2018 to 2099. The ESI components considered in this study include six types of generators (coal generators, gas generators, hydro generators, nuclear generators, wind generators and solar generators), ten voltage levels (from 35 kV to 1000 kV) of T&D lines and ten voltage levels (from 35 kV to 1000 kV) of transformers in the substations.[1] To obtain the physical de-rating factors of different ESI components within a specific region, the preferred approach is to simulate the temperature impacts on ESI ratings by thermophysical models. However, most of the thermophysical models are very complex and require a large number of input parameters. It is also difficult to obtain a full set of parameters to estimate the de-rating factors. Therefore, this study uses de-rating factors from two types of sources based on the data availability. The de-rating factors of transmission lines are calculated by thermophysical models using input parameters from China, while the de-rating factors of other ESI components are directly drawn from previous estimated results for China (see Table 1). In order to increase the representativeness of the de-rating factors used in this study, we have tried our best to collect as many de-rating factors as possible, and used their average values for the impact estimations. For example, the two de-rating factors collected for Chinese gas generators are -0.83% from Dong et al. (2016) and -0.52% from Zhou et al. (2018), so we use the average value of these two numbers -0.68%= (-0.83%–0.52%)/2 in the impact estimation (see Fig. 6). The threshold temperatures of different ESI components are shown in Table 2. Most of them are directly drawn from previous case studies from China. However, the threshold temperatures of some ESI components (solar generators, nuclear generators and transformers) cannot be found for China, so we use data from other countries as a substitution. We assume the threshold temperatures of ESI in other countries are still applicable to the same ESI in China considering the

[1] Due to the data constraints, only six types of generation technologies are considered in this study and they occupy over 98% of the total installed capacities in China.

Table 2
The threshold temperatures of different ESI components.

ESI	Coal generators	Gas generators	Hydro generators	Nuclear generators	Wind generators	Solar generators	Transformers
Tmax (°C)	30	15	20	20	30	25	30

Notes: For the T&D lines, the threshold temperatures are not considered because all temperature rise can result in carrying capacity losses according to the thermophysical models.

product globalization in the electricity industry. This can also be supported by the fact that the threshold temperatures of gas generators are found to be the same as 15 °C in different countries, such as in the United States (Sathaye et al., 2013), in Brazil (Arrieta and Lora, 2005) and in China (Dong et al., 2016).

The temperature trajectories during the study period are simulated by BCC-CSM1.1 under different RCPs. BCC-CSM1.1 is a CSM developed by Nation Climate Centre of China Meteorological Administration, and the model details can be referred to Wu et al. (2013). However, the original output from BCC-CSM1.1 has a rough spatial grid cell resolution of 2.8125°latitude * 2.8125°longitude, so an algorithm of Inverse Distance Weight (IDW) is used to conduct fine mesh interpolation to downscale these temperature data to a resolution of 0.1°latitude * 0.1°longitude. The average temperature of all grid points within a specific province is used to represent the provincial data. In addition, this study aims at estimating the largest potential impacts of climate change on ESI, so only the annual peak temperatures of different provinces are drawn from the simulation results and used for calculations.

A statistical analysis of major input parameters used in this study is shown in Table 3. All the monetary parameters have been converted to the year of 2017 using the Consumer Price Index (CPI). We can see that the parameters vary a lot among different provinces and among different ESI components, exhibiting the necessity to consider both the regional heterogeneity and infrastructure heterogeneity in the impact quantifications.

Table 3
Statistical analysis of major parameters.

Parameters	Units	Maximum	Minimum	Average	Std.dev
IC_{coal}	GW	96.76	0.00	31.65	24.57
IC_{gas}	GW	13.17	0.00	2.44	3.81
IC_{hydro}	GW	77.14	0.00	11.08	17.69
$IC_{nuclear}$	GW	10.46	0.00	1.16	2.70
IC_{wind}	GW	26.70	0.01	5.27	5.97
IC_{solar}	GW	10.52	0.12	4.17	3.43
L_{1000kV}	km	1839.00	0.00	402.88	547.70
$L_{\pm800kV}$	km	2599.00	0.00	556.14	637.23
L_{750kV}	km	5872.00	0.00	753.16	1708.19
$L_{\pm660kV}$	km	415.00	0.00	63.52	127.79
L_{500kV}	km	14420.00	0.00	5875.86	4478.26
$L_{\pm400kV}$	km	1217.00	0.00	82.00	283.36
L_{330kV}	km	11040.00	0.00	1207.28	3158.60
L_{220kV}	km	32998.00	0.00	13390.71	8789.11
$L_{110kV\ and\ 66kV}$	km	39875.00	993.00	20366.55	10176.98
L_{35kV}	km	34112.00	38.00	16407.48	10617.32
TF_{1000kV}	GVA	44.67	0.00	5.99	9.87
$TF_{\pm800kV}$	GVA	29.28	0.00	2.87	6.54
TF_{750kV}	GVA	45.20	0.00	5.59	12.43
$TF_{\pm660kV}$	GVA	4.84	0.00	0.20	0.99
TF_{500kV}	GVA	125.74	0.00	46.81	38.06
$TF_{\pm400kV}$	GVA	0.00	0.00	0.00	0.00
TF_{330kV}	GVA	42.85	0.00	5.21	12.43
TF_{220kV}	GVA	204.62	0.00	65.60	53.22
$TF_{110kV\ and\ 66kV}$	GVA	206.47	3.86	67.69	52.35
TF_{35kV}	GVA	66.66	0.01	16.34	15.56
ΔT	°C	11.92	-11.70	-0.55	3.39
$V_{g,i}$	Yuan/kW	12038.00	2823.00	7265.53	3360.04
$V_{td,k}$	Million yuan/km	5.56	0.21	2.32	1.63
$V_{tf,j}$	Yuan/kVA	496.00	70.40	247.16	115.13
θ	%	54.97	0.00	11.65	19.50

3. Results and discussions

3.1. The temporal and spatial characteristics of temperature changes

To assess the impacts of climate change on the ESI at the provincial level, we firstly forecast the temperature rise during the planning horizon using the BCC-CSM1.1. The temperature projections are simulated under RCP 8.5, which represents a future world where fossil fuels continue to power robust global economic growth and the world is absent of climate policy by the major emitting countries. All the annual peak temperatures in the projected period are compared with the base year 2017 to obtain the magnitude of temperature rise, see Fig. 3. We can see that the average temperature rise shows an increasing trend, peaking in 2096 as 7.0 °C. Moreover, although they fluctuate a lot during the study period, they do not show any obvious periodicity.

Based on the temperature projections of the study period, the maximum rise of annual peak temperatures in different provinces can be obtained and shown in Fig. 4. There are significant differences in the temperature increases among different provinces. The Central China region, such as Chongqing (12.3 °C), Henan (11.5 °C) and Sichuan (11.2 °C), has the highest temperature increase. However, Hainan (4.9 °C), Liaoning (5.9 °C) and Guangdong (5.9 °C) are the three provinces that have the smallest temperature increases. The average increase of maximum temperatures in different provinces is 8.5 °C during the period from 2018 to 2099, which is much higher than the forecasted average temperature increase in China by the end of this century (1.3~5.0 °C).[2] This also highlights the necessity to analyze the impacts of extremely high temperatures on the ESI in addition to the influences of average temperature.

Apart from the temperature rise, the impacts of climate change on ESI are also affected by the spatial overlaps between electricity assets and temperature rise. A higher overlap will result in bigger possible losses of ESI assets. Fig. 5 shows the correlations between ESI assets and maximum temperature increases in 31 Chinese provinces. The temperature changes have positive correlations with the generator assets (0.26) and transmission line assets (0.18), while having small negative correlations with the transformer assets (-0.05). Therefore, more attention needs to be paid to the ESI components that are more exposable to the climate changes.

3.2. The impacts of temperature rise on the ESI

Before we quantify the impacts of climate change on the ESI assets, we first show the physical de-rating factors of 1 °C increase on different ESI components in Fig. 6. We can see that the impacts of temperature rise on different ESI components differ a lot. 1 °C of temperature rise has the biggest impacts on the supply capacity of the wind generators, while

[2] The forecasted average temperature increases can be seen from http://www.cma.gov.cn/2011xwzx/2011xqxxw/2011xqxyw/201511/t20151121_297881.html.

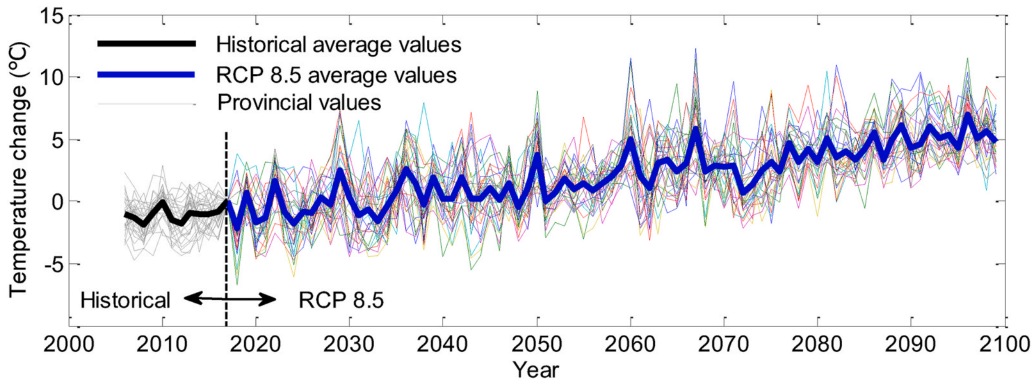

Fig. 3. The changes of annual peak temperature when compared with base year 2017.

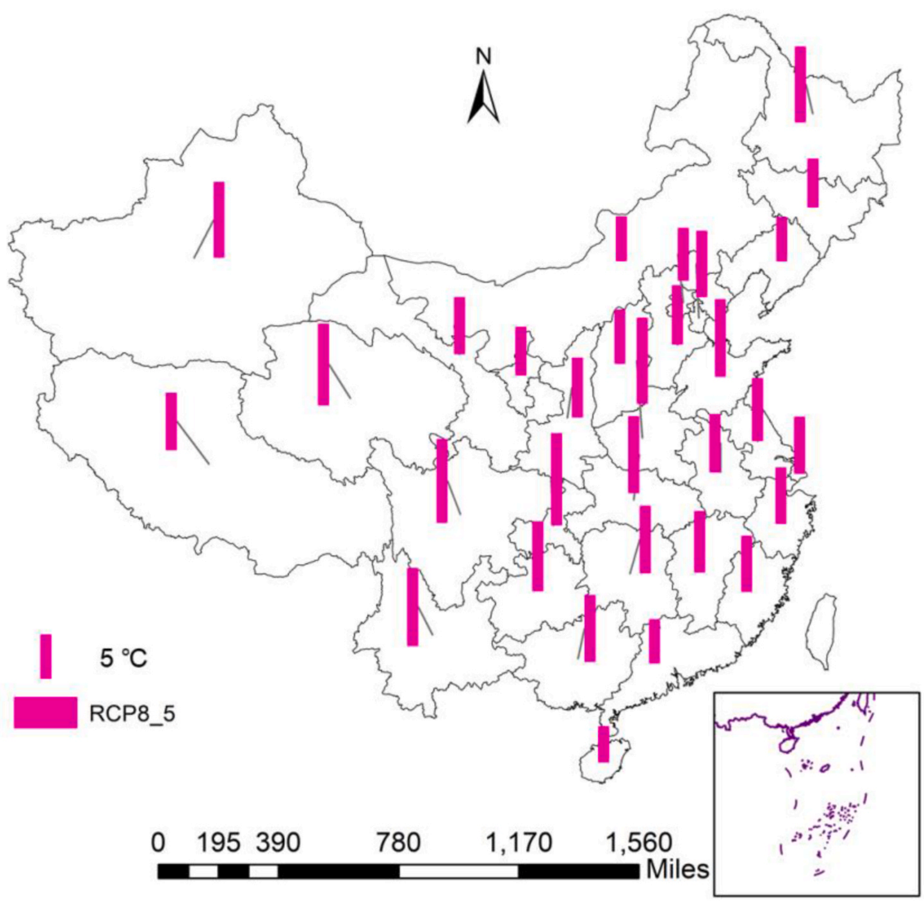

Fig. 4. The increases of maximum annual temperature in different provinces.
Notes: the values in the upper triangle region are the estimated correlation coefficients.

it has the smallest impacts on the supply capacity of the nuclear generators. Due to the different materials used in the cables and equipment, the impact differences also exist among different T&D lines and transformers, but they are smaller when compared with that of generators.

Based on the temperature rise projections and the estimated derating factors, the biggest potential impacts of climate change on ESI are estimated for the study period (see Fig. 7). 10.2% of the generator ratings, 17.8% of the transmission and distribution line ratings and 10.0% of the transformer ratings are at risk of outage from expected climate change effects in China. The most vulnerable regions can be identified by comparing these physical impacts. The largest generation capacity at risk of outage will occur in Xinjiang, while both the biggest vulnerabilities of grid lines and transformers will happen in Shandong. Therefore, greater efforts must be made in these provinces by strengthening the ESI supply capacity, such as investing into more resilient electricity equipment and accounting for local climatic impacts when siting new generation facilities. The most fragile ESI components can also be found from Fig. 7. Wind generators are affected most in the generation part, 220 kV grid lines are damaged most among different voltages of T&D lines and 110 kV transformers are the most vulnerable among all the transformers. To increase the robustness of these fragile ESI components, more Research and Development (R&D) should be devoted to developing new materials and equipment technologies to reduce the damages from climate change.

The estimated physical impacts are converted to the economic impacts using the monetary value embodied in the ESI. The spatial

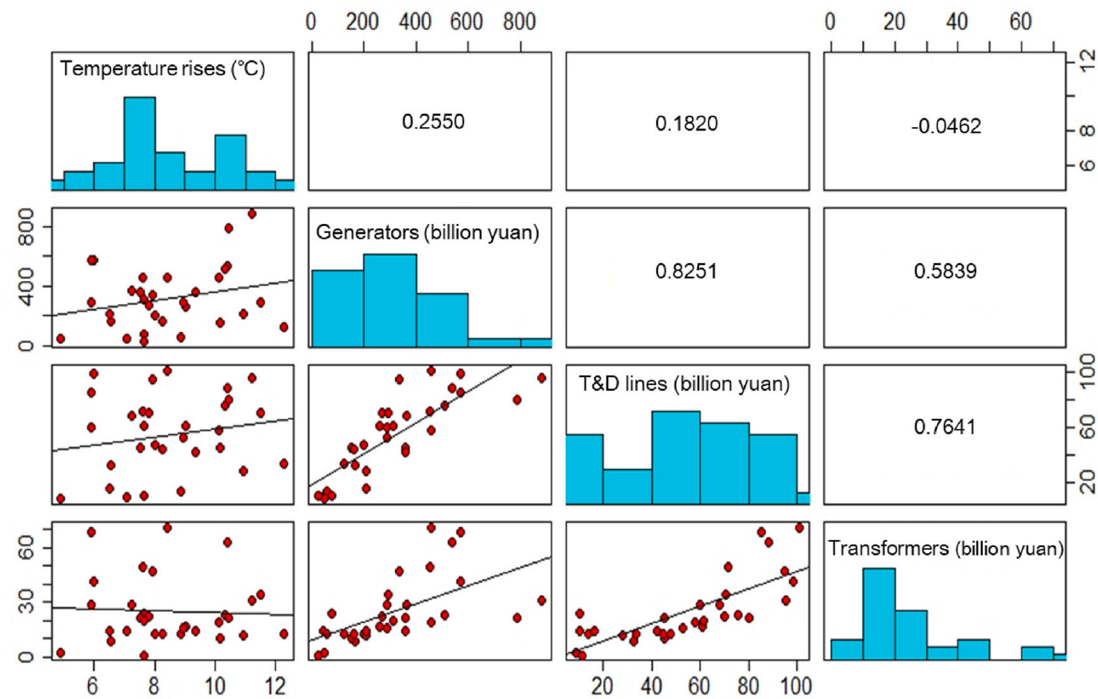

Fig. 5. The correlation relationships between temperature increases and ESI assets.
Notes: The de-rating factors of transmission lines are the average values of different provinces.

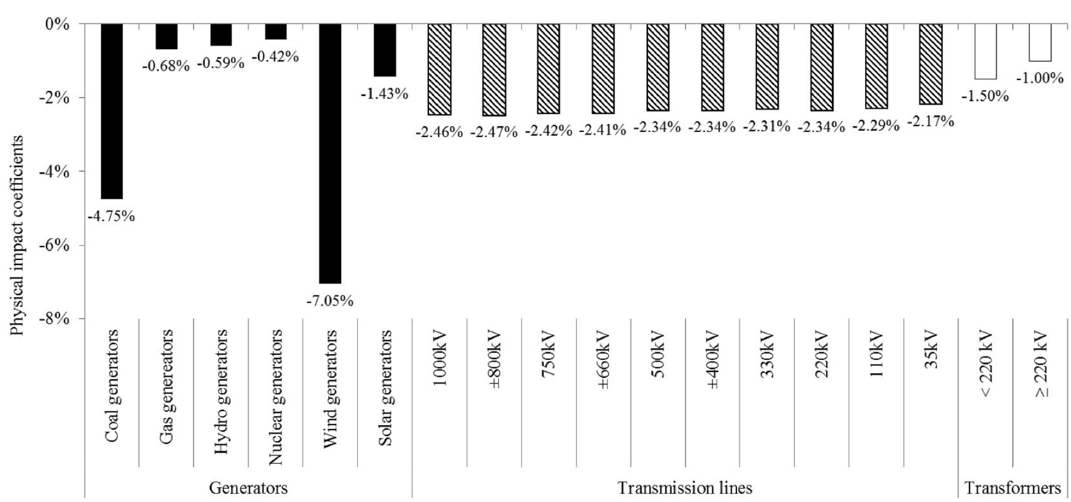

Fig. 6. De-rating factors of different ESI components under 1 °C temperature rise.
Notes: The estimated physical impacts are ranked among 31 provinces regarding the generators (a), grid lines (b) and transformers (c) respectively.

distributions of ESI damages are shown in Fig. 8. The economic values of existing ESI assets at risk of outage are forecasted to be 1741 billion yuan (around 258 billion US dollars), representing 14.2% of the total electricity assets and 2.1% of the Chinese GDP in 2017.[3] Xinjiang and Inner Mongolia have the largest economic assets at risk of outage among all the provinces, while Tibet and Hainan are affected the least. Considering the large quantities of these economic damages, it will be promising to achieve a large amount of benefits when these damages are reduced or eliminated. Furthermore, the generators will be affected most (1217 billion yuan) among the three components, which are equal to 70% of the total economic values of damaged ESI assets. However, the estimation results are based on the existing ESI in China and may be affected by the low-carbon transition of China's electricity system. With more wind generators and solar generators built to achieve the new carbon neutrality target of China, the major asset types affected by climate change will change from fossil fuel generators to renewable generators.

3.3. Sensitivity analysis

A challenge to this impact estimation is the significant uncertainty of climate change in the future and its impacts on the ESI. Uncertainty can arise from several sources, such as how quickly different countries will decarbonize their economies, whether the models accurately simulate the climate change and how much the performance of different ESI

[3] This figure is calculated according to the average exchange rates in 2017 (1 US dollars = 6.7518 Chinese yuan).

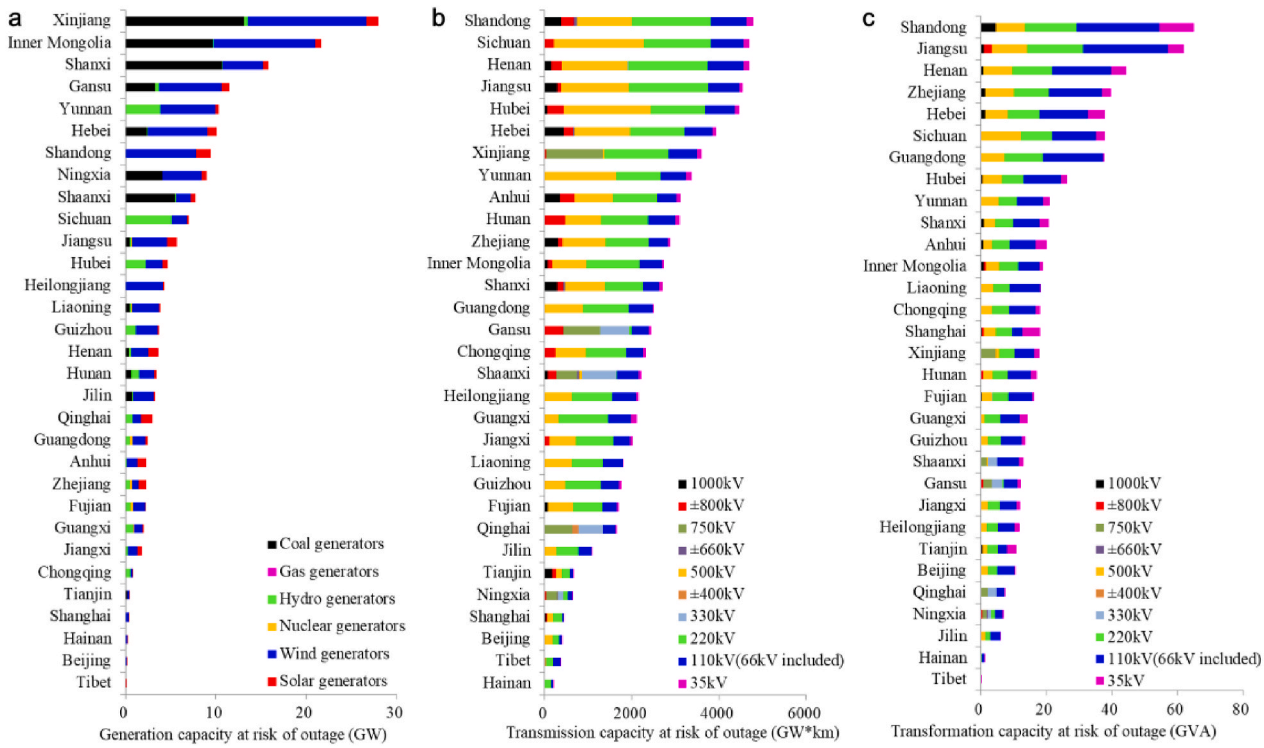

Fig. 7. The estimated physical impacts on different ESI components.

components will be influenced by the temperature rise. This section analyzes how these uncertainties will affect the estimated climate damages. In the sensitivity analysis results, the shares of ESI economic values at risk of outage are chosen as the dependent variables, and the estimation results using BCC-CSM1.1 under RCP 8.5 are served as a Business as Usual (BAU) scenario for comparison.

3.3.1. Climate system models

The impacts of temperature rise on ESI rely on the output of future temperature paths from CSMs. To explore the sensitivity of the estimated climate damages, four popularly used CSMs have been selected from the Coupled Model Intercomparison Project, Phase 5 (CMIP5), see Table 4.

The results from four CSMs are compared with the BAU, see Fig. 9. We can see that most of the models have similar results, exhibiting the robustness of our results when using different CSMs. The average share of ESI assets at risk of outage from the four models is 12.7%, which is similar to the results estimated in our study using BCC-CSM1.1. Moreover, the impacts are the biggest using HadGEM (17.7%), while the influences are the least via CNRM (9.9%).

3.3.2. Representative concentration paths

Given the same CSM, the projected temperature paths in the planning horizon will be influenced by the selection of RCPs. RCPs are consistent projection sets of the radiative forcing pathways, based on which the time-dependent projections of atmospheric greenhouse gas (GHG) concentrations can be obtained. RCPs are proposed by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and are frequently used as input for climate modeling, pattern scaling and atmospheric chemistry modeling. There are four RCPs published by AR5 and their descriptions are shown in Table 5. The economic impacts of climate changes on ESI are estimated for different RCPs and compared with the BAU scenario, see Fig. 10.

We can see that higher radiation values of RCPs will cause larger shares of ESI at risk of outage in China. This is because the projected temperatures will be higher when the radiation values of RCPs are bigger. The total economic values of ESI at risk of outage under RCP 8.5 are two times of the results under RCP 2.6. Therefore, it is important to reduce the atmospheric greenhouse gas emissions in order to mitigate the climate change impacts on ESI.

3.3.3. De-rating factors

The de-rating factors used in this study are drawn from existing case studies conducted for China. However, considering the large differences in both the ESI materials and their working environment in China, there may be differences in the estimated de-rating factors. To analyze the sensitivity of de-rating factors, we have surveyed the de-rating factors from case studies conducted in other countries. The maximum values, minimum values and average values of these de-rating factors are used as inputs for the climate damage estimations, see Table 6.

The sensitivity analysis results of de-rating factors are shown in Fig. 11. The shares of ESI asset at risk of outage range from -10.6% to 39.5%. The big differences among the results indicate that the estimations of ESI vulnerabilities are sensitive to the choices of de-rating factors. To improve the accuracy of the climate impact estimations, more efforts are needed to obtain the de-rating factors by considering the heterogeneity in different regions and among different technologies. With a comprehensive set of the ESI de-rating factors, the risks of climate damages on the ESI can be better understood. In addition, the international evidences of climate damages on ESI can be served as useful references when there is a lack of Chinese de-rating factors. This is because the results calculated based on the average de-rating factors from international studies are similar to the results estimated in the BAU scenario.

4. Conclusions and policy implications

4.1. Conclusions

Developing a spatially explicit quantitative understanding of electricity infrastructure vulnerabilities to the climate change is critical for the electricity system reliability. To provide guidance for the long-term

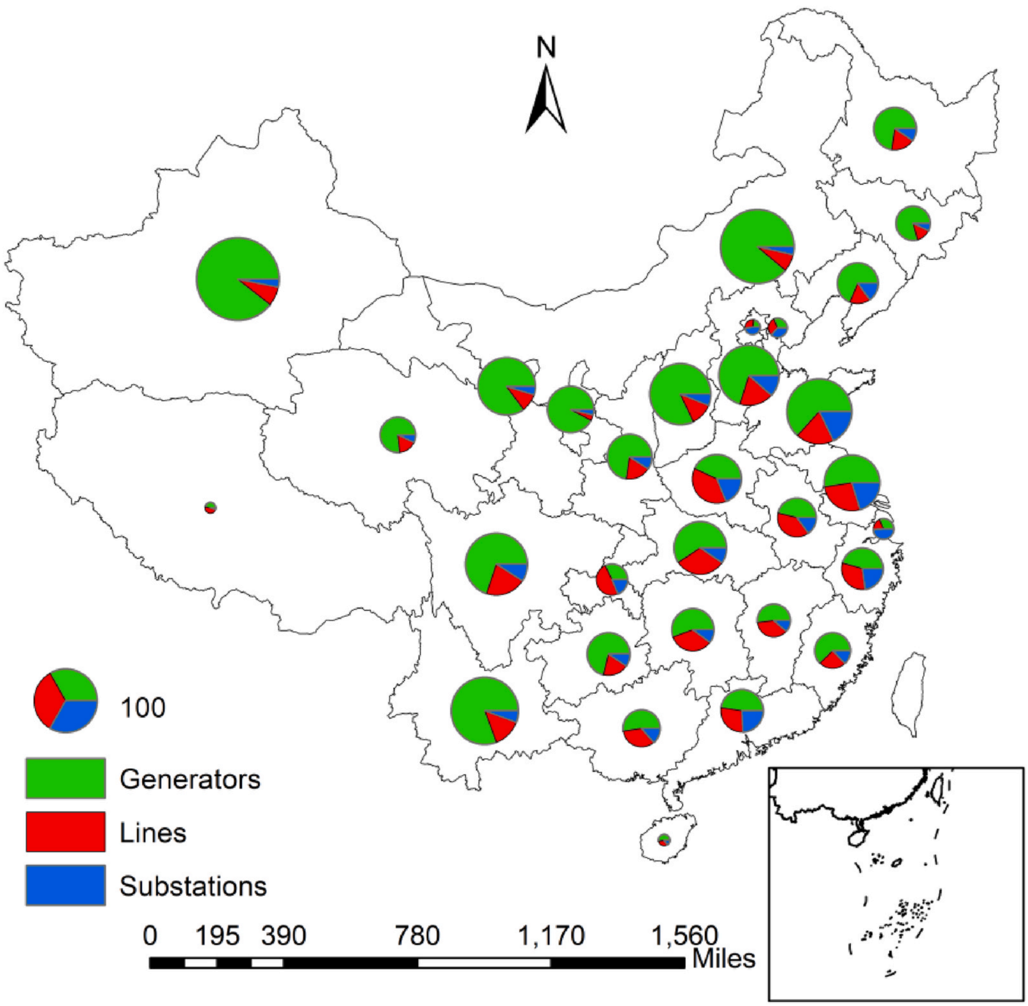

Fig. 8. The economic impacts of climate change on the ESI (billion yuan).

Table 4
Model descriptions of the four CSMs.

CSM model	Modeling group
CanESM2	Canadian Centre for Climate Modeling and Analysis
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
HadGEM2-ES	Met Office Hadley Centre

Table 5
The descriptions of different RCPs.

RCP	Description
RCP 2.6	Peak in radiative forcing at ~3 W/m^2 before 2100 and decline to 2.6 W/m^2 in 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100
RCP 6.0	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100

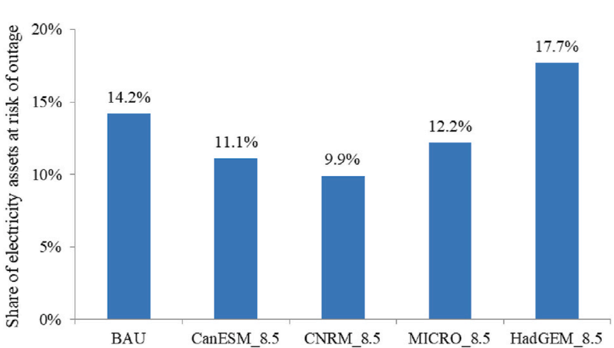

Fig. 9. The climate change impacts under different CSMs.

planning, investment, mitigation and abatement measures, this study firstly employs a downscaled CSM to project the future temperature paths. Then, a methodology is established to quantify both the physical and economic impacts of long-term future temperature rise on the existing ESI components. Finally, China's electricity system is taken as a case study to analyze both the magnitude and the spatial distributions of climate-attributable impacts on ESI. During this process, we have obtained the following major conclusions.

(1) There is a significant increasing trend of annual peak temperatures in China until the end of this century, and the largest temperature rise will likely to be seen in 2096. Moreover, the average value of provincial peak temperature increase is 8.5 °C from 2018 to 2099. However, the temperature increases vary substantially

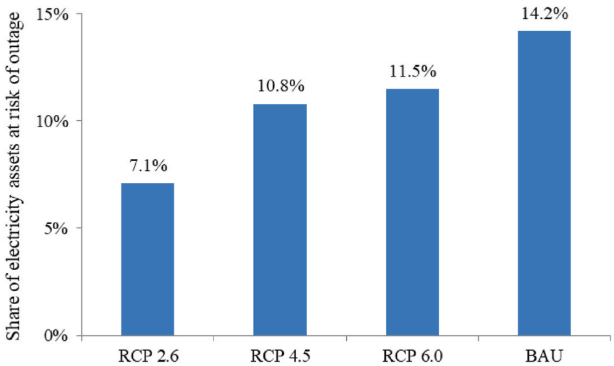

Fig. 10. The climate change impacts under different RCPs.

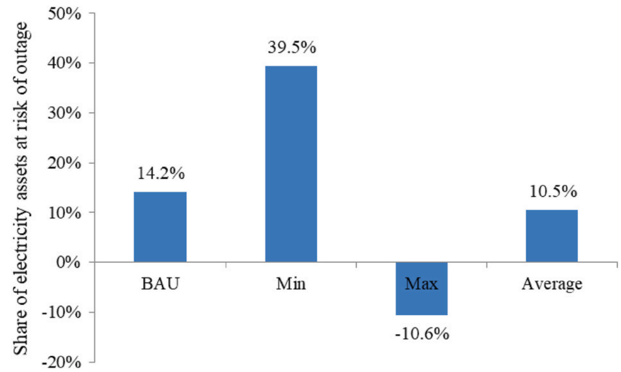

Fig. 11. The estimated results using surveyed de-rating factors from other countries.

Table 6
The surveyed de-rating factors from international studies.

ESI components	Min	Max	Average	Sources
Coal generators	-11.37%	-0.10%	-2.08%	(CCP, 2013; Dowling, 2013; Li et al., 2016; Linnerud et al., 2009; Liu et al., 2017; Miara et al., 2017; Ouvrard, 2018; Parkpoom et al., 2005; Rousseau, 2013; Sieber, 2013; Van Vliet et al., 2016)
Gas generators	-2.00%	-0.20%	-0.69%	(Arrieta and Lora, 2005; Burillo et al., 2019; Daycock et al., 2004; Dowling, 2013; John and Michael, 2006; Li et al., 2016; Linnerud et al., 2009; Sathaye et al., 2013; Schaeffer et al., 2012; Sieber, 2013; Tyusov et al., 2017)
Hydro generators	-7.21%	2.40%	-2.05%	(Boehlert et al., 2016; Guerra et al., 2019; Hamlet et al., 2010; Turner et al., 2017; Van Vliet et al., 2016)
Wind generators	-8.48%	4.00%	-1.25%	(Harrison et al., 2008; Karnauskas et al., 2018; Ouvrard, 2018; Pasicko et al., 2012; Tobin et al., 2016; Wachsmuth et al., 2013)
Solar generators	-1.75%	2.22%	-0.22%	(ADB, 2012; Burillo et al., 2019; Crook et al., 2011; Fidje and Martinsen, 2006; Gaetani et al., 2014; Ioanna et al., 2014; Muriel et al., 2004; Li et al., 2016; Pasicko et al., 2012; Patt et al., 2013; Phillip et al., 2014; Radziemska, 2003; Szabo, 2010; Wild et al., 2015)
Nuclear generators	-11.37%	-0.10%	-1.57%	(ADB, 2012; Durmayaz and Sogut, 2006; Forster and Lilliestam, 2010; Koch et al., 2014; Linnerud et al., 2009; Linnerud et al., 2011; Parkpoom et al., 2005; Rousseau, 2013; van Aart and Ploumen, 2004; van Vliet et al., 2012)
Transmission lines	-2.73%	-0.29%	-1.27%	(ADB, 2012; Bartos et al., 2016; Burillo et al., 2019; Cradden and Harrison, 2013; Li et al., 2016; Sathaye et al., 2011; Sathaye et al., 2013)
Transformers	-1.21%	-0.40%	-0.80%	(Burillo et al., 2016, 2019; Hashmi et al., 2013; Sathaye et al., 2013; Swift et al., 2001)

among different provinces. Chongqing has the largest increase of annual peak temperature, while Hainan has the smallest rise of annual peak temperature. Moreover, generators and T&D lines are more exposed to the predicted temperature rise when compared with the transformers.

(2) The climate-attributable impacts on ESI in China are substantial from both the physical perspective and the economic perspective. Owing to the temperature rise during the period from 2018 to 2099, 10.2% of the generator ratings, 17.8% of the transmission and distribution line ratings and 10.0% of the transformer ratings will be at risk of outage. Moreover, the monetary values of these physical impacts are equal to around 258 billion US dollars, representing 14.2% of the existing total ESI assets in China. Among the three ESI components, generators will be affected most and their impact values account for 70% of the total damaged ESI values. Moreover, Xinjiang and Inner Mongolia will suffer the largest impacts, while Tibet and Hainan are affected the least. However, the estimation results are obtained based on the existing ESI and may be influenced by the low-carbon transition of China's electricity system in the future.

(3) The magnitude of ESI assets at risk of outage is highly uncertain due to the climate model choices, the projected future emission pathways and the selections of de-rating factors. The de-rating factors are found to have the largest impacts among the three sensitivity analysis factors, but only a small number of studies have estimated the climate damages on different ESI components in China. Therefore, a comprehensive parameter set of de-rating factors considering the regional, technological and material differences is of imperative need to accurately estimate the climate change impacts.

4.2. Policy implications

Based on the conclusions obtained above, some policy implications can be drawn as follows:

First, the climate change impacts should be well integrated into the power system planning in the future, such as the Five-Year-Plan (FYP) and the Long-term Climate Change Action Plan in China. The quantified impacts of climate change on the ESI are substantial, so neglecting them will significantly overestimate the ability of ESI to meet future electricity demands. Moreover, it will also result in higher risks for the electricity system reliability as the climate change accelerates. Therefore, the government can modify the standards of security operating reserves of electricity system based on the estimated results in this study, so more back-up generators and transmission lines can be invested to improve the system reliability. The budget plan of ESI investment can also be adjusted according to the estimated regional impacts, and more electricity resources can be allocated to the most fragile regions.

Second, considering the substantial impacts of climate change on the

ESI, both the supply side resources and the demand side resources can be used to mitigate the climate change impacts. From the supply side, more mitigation and adaption measures can be promoted by the government to safeguard the ESI from climate change risks. The potential measures include developing heat-resistant conductors, deploying more climate-resilient technologies, upgrading the infrastructure to be more thermal resistant and switching to recirculating cooling. The large-scale adoptions and applications of climate-resilient technologies in the electricity sector will enhance the abilities to cope with the climate change damages. From the demand side, it is good for the government to take various measures to increase the demand response (DR) potentials and capability. DR can greatly improve the flexibility and reliability of electricity system, and many developed countries have accumulated rich experiences in utilizing the demand side resources. The current DR potential is 3.2% in Texas, 3.6% in the United Kingdom and 9.1% in Pennsylvania-New Jersey-Maryland (PJM) (Pollitt et al., 2017). However, the DR potential in China only accounted for 0.4% of the national peak load in 2018, which is far below the potentials of other countries.[4] Therefore, it is necessary to establish well-functioning ancillary service markets and to promote more intelligent information technology for the large-scale application of DR.

Third, considering the significant impacts of de-rating factors on the magnitude of estimated ESI vulnerabilities, it is good for the Chinese government to help to establish a platform to synthesize the results from relevant experiments and academic studies, which can promote a sustained and continuously improved modeling of the ESI vulnerabilities. Many developed countries have published the periodical reports of climate change impacts on the ESI. For example, the United States has published four versions of National Climate Assessment Reports, while the United Kingdom has published Climate Change Risk Assessment Reports every five years from 2012.[5] A well-structured database of ESI vulnerabilities under the climate change can be produced from these reports, thus the investors can adopt electricity technologies more wisely and the government can design more targeted climate abatement policies.

This study has addressed several important questions regarding the climate change impacts on ESI in China, and the conclusions obtained can provide support for mitigating the climate change impacts. However, some limitations of this study can be improved in the future. First, this study focuses on the supply side of the electricity system, which can be further extended to quantify the outage risks when the demand side impacts are included. Climate change can not only put the ratings of ESI at risk of outage but also result in higher peak loads. A systematic modeling of the whole electricity system is necessary to comprehensively estimate the impacts, based on which more coordinated measures can be worked out. Moreover, the mitigation or adaptation efforts can be integrated into the model to obtain more accurate estimation results. This is because the deployment of climate-resilient technologies will reduce the amount of temperature rise impacts on the ESI, so it is necessary to analyze how the technologies will affect the impact estimation results and update the used de-rating factors accordingly. In addition, this study only analyzes the largest impacts of predicted temperature rise on the ESI, so the temporal effects can be further explored to provide guidance for the optimal planning and investment of ESI in the future. At last, the current results can be updated if new data are available. For example, more customized input parameters (de-rating factors and threshold temperatures) can be used in the future impact estimations, and the water-resource/precipitation impacts on the ESI through temperature rise can also be explored in the future studies. All these improvements can contribute to a more accurate estimation of the climate damages, thus offering better guidance for the abatement measures and climate policies.

[4] This data can be obtained from http://www.nea.gov.cn/policy/zxwj.htm.

[5] The National Climate Assessment Report of Unites States can be seen from https://nca2014.globalchange.gov/, and the Climate Change Risk Assessment Report can be seen from https://www.theccc.org.uk/publications/third-uk-climate-change-risk-assessment/.

CRediT authorship contribution statement

Hao Chen: Conceptualization, Methodology, Writing - original draft. **Simin Liu:** Data curation. **Qiufeng Liu:** Software. **Xueli Shi:** Software. **Wendong Wei:** Methodology. **Rong Han:** Visualization. **Sinan Küfeoğlu:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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