Prioritizing climate change adaptation needs for hydropower sector in China

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Abstract
Differentiating spatial–temporal hydropower risk triggered by climate change is crucial to climate adaptation and hydropower programming. In this research, we use a fixed-effect model on 5082 plants in China to estimate how the revenue of hydropower plants responded to climate change over 16 years, and project the revenue change and fit the damage function driven by 42 climate realizations. Results show that the revenue change of the hydropower sector demonstrates substantial regional variation and would reduce by 9.34% ± 1.21% (mean ± s.d.) yr⁻¹ on average under RCP 8.5 by 2090s as compared to 2013, about four times larger than that under RCP4.5. Carbon leakage caused by thermal power substitution reaches 467.56 ± 202.63 (112.49 ± 227.45) Mt CO₂e under RCP8.5 (RCP4.5). Different climatic conditions manifest locally, and different climate resilience makes the response function regionally heterogeneous. Southwest China is identified as the priority region for adaptation through integrated evaluation of historical climate sensitivity, future climate variability, and regional hydropower importance, informing more adaptation and investment needs of further hydropower development in the area.

1. Introduction

Hydropower resource has been vigorously tapped to meet the growing electricity demand while mitigating environmental impacts. The share of hydropower in global electricity generation has climbed to 16.6% in 2015 [1], propelled by its advantage of lower operational expenditure, minor environmental externalities, mature technology, and multiple uses of dams (e.g. flood control, navigation, and irrigation) [2, 3]. As more countries and regions claimed net-zero or other low-carbon emission goals in the future [4], hydropower is supposed to continuously tick up in future energy portfolios [5].

However, as one of the pillars of future renewable energy, hydropower is highly sensitive to changing climate [6]. The impacts of climate change, for example, the changing water availability and temperature [7–10], on usable capacity [7, 11], output [12], and revenue [13–16] of hydropower plants are worsening worldwide [17, 18], hence adaptation strategies should be well integrated into hydropower planning and management in advance [19–21]. Effective adaptation strategies (e.g. new construction, reconstruction, technology advancement, etc) require substantial resource inputs, many of which are limited and scarce [22]. Prioritizing adaptation and investment needs, through the evaluation of climate risk hotspots, is crucial but remains understudied [22].

In this study, we choose China as our study area and prioritize climate adaptation needs in the hydropower sector. As a huge country, China has diversified meteorological features, which helps to depict the climatic-zone heterogeneity of climate change response. In addition, China has accounted for ~29% of the worldwide hydropower generation to date [23] and therefore plays a key role in the development of global hydropower [24]. Efforts to improve climate
adaptation of the hydropower sector in China may help to achieve global goals of renewable energy development and greenhouse gas (GHG) reduction [25].

The crux of prioritization is temporal and spatial characteristics of hydropower sensitivity, which subjects to the long-standing responses to regional climate conditions [26, 27]. Multiple studies have revealed the regionally heterogeneous relationship between climate and hydropower [28–31], approaches of which can be categorized into two types: process-based modeling and statistical regression analysis. While process-based models [7, 12] simulating various stages of hydropower generation may perform better with more refined spatial scales and more detailed data [32–34], black-box models (e.g. econometric models) have the advantage of more simplified structure, less dependence on parameter calibration, and higher simulation efficiency [35, 36]. Among others, fixed-effect models controlling the individual variables that remain unchanged as time moves on (e.g. construction scale and location of each plant) could unbiasedly estimate the effects of climate change [37, 38]. At the provincial level, Fan et al. are among the first attempt to explore climate impacts on hydropower in China based on fixed-effect models [39]. Research on prioritizing climate adaptation needs for the hydropower sector based on a large-scale plant-level statistical inference is still vacant. Besides, it is still unclear at the statistical level whether adaptation measures such as pumped storage are effective against droughts. More importantly, current studies put more emphasis on capturing the shock of climate change to the hydropower sector, but ignoring the reduced hydropower will form a gap in electricity supply, which is highly possible to be substituted by thermal power [6] and cause carbon leakage.

In this paper, we develop an evaluation framework and analyze the impacts of multi-dimensional climate change on economic performance (i.e. revenue for the main business, which is called for more attention [39–42]) of China’s hydropower plants by constructing fixed-effect models based on 5082 hydropower plants from 1998 to 2013. Regional heterogeneity is also estimated through grouped regression by divided climatic zones. Economic damage functions, which associate economic loss in the 21st century with the changes of average temperature or precipitation, are fitted using 42 climate realizations. We also quantify carbon leakage caused by loss of hydropower and replacement of thermal power. Implications for prioritizing climate change adaptation combined with regional hydropower importance and the effectiveness of pumped storage are then put forward to safeguard the hydropower development in China.

2. Methods

2.1. Fixed-effect model

We establish a fixed-effect model with panel data entailing hydropower plants and the corresponding meteorological conditions. The marginal effect of climate change on the revenue of hydropower plants can be estimated as follows:

\[
\ln(\text{rev}_{it}) = \beta_1 P_{10i} + \beta_2 P_{100i} + \beta_3 P_{toti} + \beta_4 T_{\text{max}i} + \beta_5 Z_{it} + u_i + \mu_{it} + \varepsilon_{it}
\]

where \text{rev}_{it} represents the main business revenue of the hydropower plant \(i\) in year \(t\); \(P_{10i}\) captures the no-rain days of the city where the hydropower plant \(i\) is located in year \(t\); \(P_{100i}\) captures the heavy-rain days of the city where the hydropower plant \(i\) is located in year \(t\); \(P_{toti}\) represents the total rainfall of the city where the hydropower plant \(i\) is located in year \(t\); \(T_{\text{max}i}\) captures the average daily maximum temperature of the city where the hydropower plant \(i\) is located in year \(t\); \(Z_{it}\) represents the control variables including the main business cost, total assets, and the number of employees; \(u_i\) represents plant-level fixed-effect, which controls all the unobservable plant-related factors (individual heterogeneity) that remain unchanged over time, for example, geographical location, size, holdings, etc.; \(\mu_{it}\) represents province–year interaction fixed-effect, which is used to exclude the intervention of time-varying provincial heterogeneity (e.g. the impacts of economic fluctuations on the revenue of hydropower plants). \(\varepsilon_{it}\) represents random error term. The dependent variable is taken the natural logarithm to be normally distributed.

2.2. Heterogeneity analysis

Given China’s vast territory, it is necessary to construct the region-specific climate response function. Under the long-term climatic influence, hydropower plants in different regions have formed clustered management and operation processes that adapt to local climatic conditions, adding to the necessity of heterogeneity analysis. We conduct precipitation zoning, and temperature zoning is excluded since the performance of hydropower plants is insignificantly related to temperature according to the national estimation (table 1).

Rotated empirical orthogonal function (REOF) [43] is usually employed to divide climate zones. EOF method (see equation (2)) can separate the major spatial types and their time coefficient matrix from the meteorological observations [44]. It is more objective because it has no fixed function. Based on EOF, we further perform the maximum variance rotation transformation on the loading eigenvector matrix, which overcomes the defect whereby the EOF
decomposition only highlights the global correlation but ignores the regional correlation [45]. After REOF transformation, the high load is concentrated in the small scope with more significant regional characteristics [43, 46].

\[ Z(x, y, t) = \sum PC(t) \times EOF(x, y). \]  

(2)

where \( Z(x, y, t) \) represents the precipitation space-time field composed of the time \((t)\) and the space \((x, y)\). \( \sum PC(t) \) and EOF\((x, y)\) represent orthogonal time function and spatial loading eigenvector matrix respectively.

We calculate the eigenvectors and eigenvalues of daily precipitation data of 318 prefecture-level cities over 20 years. Similar to Xiong et al [43], we select the first six major precipitation distributions with large eigenvalues to represent the original precipitation space-time field. The maximum variance rotation transformation is then carried out. Finally, we set the load value as the threshold to divide China into seven precipitation sub-regions. According to similarities among adjacent regions, we further merge the seven sub-regions into three ones, namely wet regions, moderate regions, and dry regions. More details are in section 2 in SI (available online at stacks.iop.org/ERL/17/034040/mmedia).

In addition, we iterate through the names of all the plants to pick out the pumped storage plants recorded in the Hydropower Yearbook [47]. We set up a dummy variable to distinguish the type of each plant. If the power plant is a pumped storage one, then it is 1 and the others are 0. We interact the dummy variable with four climate variables respectively to examine whether and how much the impact of these climate variables on the revenue of pumped storage plants is different from that of traditional hydropower plants.

### 2.3. Damage function

We estimate the changes of main business revenue in the hydropower sector over the 21st century (2013–2100) based on climate-revenue response functions and climate projections. Setting 2013 as the baseline year is mainly because the historical observation data compiled through a large-scale plant-level survey is updated to 2013. We first calculate the average daily temperature and precipitation for each day in each year of each model in the period from 2013 to 2100 under RCP4.5 and RCP8.5. Using these integrated daily city-level climate data, we calculate four yearly climate variables—no-rain days, heavy-rain days, total precipitation, and maximum temperatures for each of 42 climate realizations (21 models × 2 scenarios) in each of 87 years (2013–2100).

The minimum temperature is not incorporated in the prediction model due to its poor capture of high-temperature shock. Next, we calculate the differences of climate variables between the baseline year (2013) and all the other years (2014–2100) in each city under 42 climate realizations. We then employ the coefficients from our estimated region-specific fixed-effect models to project future changes of main business revenue under 42 climate realizations. We separate the impacts of precipitation and temperature on the revenue of hydropower plants. The percentage change in annual main business revenue between the baseline year and each of other years during the projection period is calculated as:

\[
\frac{\Delta \text{rev}_{\text{inp}}}{\text{rev}_{\text{inp}}} = e^{\beta_3 (P10^c_t - P10^c_0) + \beta_4 (P10^p_t - P10^p_0 - P10^c_0) + \beta_5 (Pmax_t - Pmax_0) + \beta_6 (Tmax_t - Tmax_0)} - 1
\]

(3)

where, \(i, t, c, \) and \(p\) denote plant, time, city, and province respectively. \(C^c\) and \(C^p\) denote the climate variables of the first and other years respectively. \(\Delta \text{rev}_{\text{inp}}\) is the percentage change in main business revenue due to climate change representing as multiple dimensions of changes from \(C^c\) to \(C^p\). Fixed-effects and other plant characteristics variables, including main business cost, total asset, and employee numbers, are implicitly assumed unchanged at the baseline year level.

Finally, damage functions that depict the percent change of main business revenue due to climate change varying with future national mean surface temperature (NMST), or national mean precipitation (NMP), can be fitted through a set of 7308 data points (21 models × 2 scenarios × 87 years × 2 dimensions).

### 2.4. Potential carbon leakage

The gain or loss of the revenue largely reflects the variation of hydropower generation in each plant. We adopt random forest, a widely-used non-parametric machine learning model, to estimate the corresponding change of hydropower generation. Combining Hydropower Yearbook, National Electric Power Enterprise Price Supervision Notice, with the panel data used in regression, we compile a dataset including hydropower generation, revenue, on-grid price, line-loss rate, and the location of 1046 plants. Recursive Feature Elimination algorithm calculates the
optimal number of variables (figure S16(a)) and we determine the best subset of variables according to Variable Importance simulated by random forest (figure S16(b)). \( R^2 \) of the model is 0.83 and the partial dependence plots show the nonlinear relationship between hydropower generation and revenue (figure S16(c)).

As electricity demands surge, the hydropower loss must be filled by other ways of generating electricity. Although renewable energies are developing rapidly, thermal power generation is still the most stable way of electricity supply. Therefore, we assume that hydropower losses would be replaced by thermal power [6], and the proportion of coal, oil, and natural gas (the three most commonly used fuels) in each year refers to the energy structure of RCP4.5 and RCP8.5 over the 21st century [5]. As equation (4), we quantify the potential GHG leakage due to climate impacts on the hydropower sector. If the value is larger than zero, it indicates that climate impacts on the hydropower industry are positive and that the GHG emissions generated by thermal power substitution are avoided, while a negative value illustrates that the adverse impacts brought by climate change may, in turn, exacerbate global warming.

\[
\text{GHG}_{i,j,t} = \sum_{\text{coal, oil, gas}} (E \times P_{i,j}) \times \Delta \text{Gen}_{i,j,t}. \tag{4}
\]

where, \( \text{GHG}_{i,m,t} \) denotes GHG performance in model \( i \) under scenario \( j \) in year \( t \). \( E \) denotes emission factors of coal, oil, and natural gas, and the emission factors for each fuel come from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [48]. \( P_{i,j} \) denotes the proportion [5] of each fuel in year \( t \) under scenario \( j \). \( \Delta \text{Gen}_{i,j,t} \) denotes the change in hydropower generation in model \( i \) under scenario \( j \) in year \( t \), simulated through the random forest. More details are in section 4 in SI.

Data processing and uncertainty analysis related to sections 2.1–2.4 are completely reported in section 1 in SI.

3. Results

3.1. Climatic factors influencing the hydropower sector

Model 1 (table 1) including all 25 199 samples across China shows significant impacts of precipitation, no-rain days, and heavy-rain days on the revenue of hydropower plants. Climate conditions and sensitivity in different regions draw forth the regionally heterogeneous climate response functions. We divide China into three regions, namely wet, moderate, and dry regions (figure S15), based on REOF. Model 2, 3, and 4 (table 1) use plant samples in three regions respectively to depict diversified nexus among hydropower, water availability, and temperature.

Each region has its dominant influencing factors. For the wet region (table 1), droughts and temperature may not impact the revenue of hydropower plants while the total precipitation and heavy-rain days do. One more heavy-rain day contributes to a 0.2% increment in revenue. With a 1% level significance, each 1 mm increment in precipitation also gives rise to a 0.01% increase in revenue. Extreme-rain day (>20 mm each day) also shows similar effects, seen in section 3 in SI.

For the moderate region (table 1), one more heavy-rain day increases the revenue by 0.4% while one more degree Celsius decreases the revenue by 5.6%. Temperature impacts on hydropower mainly manifest in the moderate region. Acceleration of water evaporation caused by high temperature will reduce water availability, which directly impairs the capacity of hydropower generation. Adding to the tough circumstance is that high water temperature may impose an extra cooling burden on water turbines and reduce the efficiency of hydropower generation.

For the dry region (table 1), with limited precipitation, the revenue of hydropower plants is mainly subject to droughts (i.e. no-rain days in this study) and one more no-rain day reduces the revenue by 0.1%. Droughts fail to significantly shock the hydropower supply in other regions endowed with plentiful water resources. It is likely that once plants in regions more dependent on hydropower were affected by droughts before, they would take pre-adaptive measures such as turning to reliable water resources [28].

Electricity demand continuously grows, but the conventional hydropower might work intermittently [49] constrained by climate variability (table 1). Pumped storage is conceptually helpful to mitigate the vulnerability of the supply-side by pumping water into higher reservoirs when electricity is surplus and releasing the stored water into lower reservoirs to drive water turbines for peak-hour demands [41, 50–53]. The estimates on interactions of no-rain days and pumped storage show a significantly positive impact in all three sub-regions, which indicates that pumped storage relieves the negative impacts caused by lack of rainfall (table 2). The dry region is of high interest because the number of no-rain days has a significant negative impact on revenue (table 1). The coefficient shows that, with pumped storage, the hydropower plant can even benefit 0.1% with one more no-rain day (table 2). Hence, electricity generation with pumped storage is thus statistically much less vulnerable and more climate-resilient compared to traditional ways, especially in the dry region.

3.2. Time trends

Based on 2013, the national aggregated revenue of hydropower plants is projected to decrease by 1.52% ± 0.99% in the 2050s and 2.46% ± 1.08% in
the 2090s under RCP4.5. Circumstances under high-concentration emission scenario RCP8.5 turn out to be more severe, with a decrease by 4.71% ± 0.95% in the 2050s and 9.34% ± 1.21% in the 2090s. The impacts on the revenue under two climate scenarios are close to each other before the 2060s, but the gap broadens in the latter half of the 21st century (figure 1(a)). Over the 21st century, the revenue loss can go up to 980.94 ± 67.58 billion CNY under RCP8.5, nearly four times larger than that under RCP4.5. The differences between 21 climate implementations are so significant that some models estimate that climate change has a positive impact on hydropower, which runs counter to the average of the 21 models. For instance, in 2100, the upper bound estimation of the relative change in revenue reaches 4.24% under RCP4.5 and 3.59% under RCP8.5. Such uncertainty (the positive impact) is not enough to make us any less wary of climate change, because the more credible predictions (the distribution of the impacts between 25 percentile and 75 percentile) still indicate a negative shock on the hydropower industry, and if not mitigated or adapted, the impact would be considerable. As for comparing the results with other studies [12], our results reveal more serious consequences from climate change since we incorporate extreme climate events into the model, in addition to average climate variability.

### 3.3 Prioritizing climate change adaptation needs

Revenue in the wet region, such as south-east of China, would experience a 2.57% ± 6.63% (5.44% ± 5.44%) increment until 2100 under RCP8.5 (RCP4.5) (figure 1(b)). The relative revenue increases simulated by 21 global climate models (GCMs) are slight in the wet region even with a high sensitivity to heavy-rain days (table 1), since this climatic indicator remains stable over the 21st century (figure S1(f)). An important hydropower plant (Xin Feng Jiang) in the wet region will gain 1.28% ± 2.80% more revenue under RCP8.5 in the 2090s and most hydropower plants in this region are not at risk of massive revenue decline.

The revenue of hydropower plants in the moderate region (the south-west, north-east, and cent-

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**Table 1.** The effect of climatic variables on the revenue of hydropower plants at national and regional level.

| Dependent variable: ln (revenue) | (Model 1) National | (Model 2) Wet region | (Model 3) Moderate region | (Model 4) Dry region |
|----------------------------------|--------------------|----------------------|--------------------------|----------------------|
| No-rain days (d)                | −0.001***          | −0.000               | 0.000                    | −0.001*              |
|                                  | (−2.43)            | (−0.03)              | (0.13)                   | (−1.66)              |
| Heavy-rain days (d)             | 0.002**            | 0.002**              | 0.004**                  | 0.002                |
|                                  | (2.54)             | (2.00)               | (2.00)                   | (1.11)               |
| Precipitation (mm)              | 0.000***           | 0.000***             | 0.000                    | 0.000                |
|                                  | (4.66)             | (4.73)               | (0.18)                   | (0.96)               |
| Max. temperature (°C)           | −0.014             | −0.031               | −0.056***                | 0.030                |
|                                  | (−1.22)            | (−1.41)              | (−2.63)                  | (1.54)               |
| Control variables               | Yes                | Yes                  | Yes                      | Yes                  |
| Province–year fixed effects     | Yes                | Yes                  | Yes                      | Yes                  |
| Plant fixed effects             | Yes                | Yes                  | Yes                      | Yes                  |
| Number of plants                | 5,028              | 2,490                | 1,355                    | 1,183                |
| Observations                    | 25 199             | 13 150               | 6,573                    | 5,476                |
| Number of plants                | 0.746              | 0.695                | 0.734                    | 0.830                |

Note: Robust t-statistics in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.

**Table 2.** Impacts of the number of no-rain days on traditional hydropower plants and pumped storage plants.

| Dependent variable: ln (revenue) | (Model 1) National | (Model 2) Wet region | (Model 3) Moderate region | (Model 4) Dry region |
|----------------------------------|--------------------|----------------------|--------------------------|----------------------|
| No-rain days (d)                | −0.002***          | −0.001***            | −0.001**                 | −0.001*              |
|                                  | (−6.05)            | (−3.46)              | (−2.26)                  | (−1.85)              |
| No-rain days # pumped            | 0.006***           | 0.005***             | 0.023***                 | 0.002***             |
|                                  | (4.03)             | (3.59)               | (3.34)                   | (2.88)               |
| Control variables               | Yes                | Yes                  | Yes                      | Yes                  |
| Province–year fixed effects     | Yes                | Yes                  | Yes                      | Yes                  |
| Plant fixed effects             | Yes                | Yes                  | Yes                      | Yes                  |
| Number of plants                | 5,028              | 2,490                | 1,355                    | 1,183                |
| Observations                    | 25 199             | 13 150               | 6,573                    | 5,476                |
| Number of plants                | 0.745              | 0.693                | 0.734                    | 0.830                |

Note: Robust t-statistics in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1.
ral of China) would suffer from a long-term and increasingly massive loss from $-0.60\% \pm 2.84\%$ ($-0.32\% \pm 4.13\%$) in 2014 to $-23.19\% \pm 7.26\%$ ($-8.31\% \pm 4.51\%$) in 2100 under RCP8.5 (RCP4.5) (figure 1(c)). This is mainly because the moderate region is negatively impacted by maximum temperature (table 1) and this climatic indicator rises notably in the 21st century, from $18^\circ C$ to $24^\circ C$ (figure S1(l)). Located in the moderate region, China’s critical Three Gorges Hydropower Station might experience significant loss up to $25.40\% \pm 12.48\%$ by 2100 under RCP8.5, which indicates a huge reduction in hydropower generation. By contrast, hydropower plants in Guangxi province are predicted to turn from losses in the 2050s to gains in the 2090s (figures 2(a) and (b)).

For the dry region, the predicted revenue remains stable over the 21st century (figure 1(d)). The dry region is mainly subjected to the no-rain days (table 1), but climate models do not demonstrate any dramatic growth or decline in annual no-rain days either under RCP8.5 or RCP4.5. However, it is worth noting that some hydropower plants in Sinkiang may turn gains in the 2050s to losses in the 2090s, which perhaps is a reminder for them to respond by increasing the flexibility and availability of hydropower, or other forms of power generation.

Different spatial–temporal priorities can be derived from hydropower importance, historical climate sensitivity, and future climate variability. Sichuan and Yunnan Province in the moderate region (south-west China) are listed on the top two hydropower-generation provinces, which become priorities among priorities with the additional effects of historical temperature-sensitivity and significantly consistent rise of future temperature (figure 2(c)). Besides, time-scale priority could also inform adaptation management. For example, Guangxi Province in South China might receive priorities before the 2050s and give away at the end of the 21st century, because precipitation there probably will experience a turning point from less to more according to future GCMs. Noting that regions with high-probability but low-impact and regions with low-probability but high-impact might be distributed disproportional priorities when it comes to policy-makers with different risk management attitudes and preferences. In any case, the necessity of adaptation in South-west regions keeps robust, where significant climate-induced hydropower decline may shock the southern power grid in the long term which serves Guangdong, Guangxi, Yunnan, Guizhou, Hainan provinces, and increase pressure on electricity transmission across regional power grids.
3.4. Damage function

Similar to Li et al. [36], we fit damage function over the 21st century by using 21 different GCMs under RCP4.5 and RCP8.5 to construct a relationship between change in NMST, or NMP, and relative NMST-induced (or NMP-induced) change in the revenue of hydropower plants. Fitted lines in figure 3 show that revenue rises by 0.01% and 0.02% for each 1 mm precipitation increase in NMP under RCP4.5 and RCP8.5 respectively, and decreases by 2.27% and 2.11% for each 1 °C increase in NMST. When considering temporal variation and model uncertainties, damages caused by NMP range from −6.15% to 9.35% under RCP4.5 and from −5.79% to 12.99% under RCP8.5. Damages caused by NMST range from −8.60% to 3.76% under RCP4.5 and from −14.49% to 1.63% under RCP8.5.

3.5. Potential carbon leakage

The adverse effects of climate change tend to have potential knock-on effects. If the future climate ends up with RCP8.5, the estimated hydropower loss would amount to 1.47 ± 1.33 TWh yr⁻¹ on average. Furthermore, demands for electricity are soaring while renewable energy sources such as hydropower and wind power largely depending on weather conditions are fraught with uncertainties. Electricity generation lost in the hydropower sector would most likely be substituted by the thermal power sector [6], which is bound to consume a large amount of coal, oil, and natural gas. In 2100, the proportion of coal-burning is ~15% lower under RCP4.5 than that under RCP8.5. The resulting carbon leakage could reach 9.86 ± 5.09 Mt CO₂e yr⁻¹ by the end of the 21st century under RCP8.5.
Figure 3. Damage function. The y axis shows the predicted relative change (based on 2013) in revenue of hydropower plants caused by precipitation change under RCP4.5 (a) and RCP8.5 (b), or caused by temperature change under RCP4.5 (c) and RCP8.5 (d). Each color represents one set of simulation results derived from one GCM.

Climate change mitigation not only relieves the hydropower risk but also further reduces the carbon leakage from $467.56 \pm 202.63$ Mt CO$_2$e to $112.49 \pm 227.45$ Mt CO$_2$e throughout the 21st century thanks to a cleaner energy structure.

4. Discussion

Our results emphasize the role climate change mitigation plays in improving the performance of hydropower plants, as avoided revenue loss in the sector throughout the whole 21st century reaches $738.65 \pm 94.57$ billion CNY when we manage to achieve a more stringent mitigation target from the current scenario (RCP8.5) to RCP4.5. Besides, carbon leakage due to the hydropower loss under RCP4.5 is numerically negligible compared to $9.86 \pm 5.09$ Mt CO$_2$e yr$^{-1}$ at the end of the 21st century under RCP8.5, and the avoided social carbon cost [54] is approximately $516.57 \pm 36.11$ billion CNY.

Climate change adaptation strategies are deemed necessary in both this study and others, in which a hydropower crisis in the coming decades has been reasonably foreseen. Van Vliet et al [7] found that increasing the efficiency of hydropower plants by 10% could completely offset the hydropower loss due to water constraints in most regions, such as Asia and Africa. Higher efficiency can be achieved by removing aging turbines, generators, and other equipment, as well as recruiting high-quality staff, and increasing the installed capacity. Pumped storage can also regulate the temporal and spatial distribution of water resource endowment, in response to the increasingly frequent droughts and the peak electricity demands [49]. It is also suggested that enhancing the reliability and attack-resistance features of infrastructure (e.g. dams) prone to climatic extremes could contribute to reduced vulnerability while improving resilience.

Regional heterogeneity of climate impacts navigates and dominates the adaptation priorities. For example, we find that future hydropower plants had better be constructed in the southeast of China,
including Hunan, Jiangxi, Zhejiang, Guangdong, and Fujian Provinces. In contrast, we advocate the promotion of adaptive technologies (such as pumped storage) that are less dependent on the timing of water availability among provinces in the north-east (e.g. Heilongjiang, Jilin, Liaoning Provinces, etc) and south-west (e.g. Yunnan, Guizhou, Chongqing, Sichuan Provinces, etc) to mitigate their vulnerability to climate conditions. Major hydropower provinces such as Sichuan and Yunnan Provinces [55] should be especially mindful of the potentially significant reduction in future hydropower generation (figure 2). We also prove that effective climate change mitigation helps relieve the urgency of adaptation measures since only ~1% hydropower generation on average will be reduced under RCP4.5.

More case studies are required to capture and quantify uncertainties that are hard to be addressed in large-scale macro studies. Firstly, although the fixed-effect model is useful to control all plant-specific characteristics, provincial time-varying factors, etc, it fails to track the future change of these variables. For example, the decrease in reservoir capacity due to sediment accumulation is likely to have significant implications for long-term hydropower analysis [56]. We deal with this problem by assuming that these influencing factors (e.g. plant size, assets, and technique) remain unchanged in the 21st century. This will overestimate the adverse impacts on the performance of hydropower plants, especially when adaptation measures upgrading existed technology or adopting new technology are gradually taken with people's increasing awareness of climate change's far-reaching influences. Secondly, despite abundant plant-level observation data, we cannot estimate the monthly condition due to data unavailability. Fan et al's study [39] made up for this short-age by using monthly panel data at the province level, revealing that hydropower generation is more vulnerable during the summer season in China. Thirdly, high levels of uncertainty among different GCMs exist, especially in the long term. The predicted revenue change at the end of the 21st century driven by 21 GCMs can range from −19.21% to 3.58% under RCP8.5. Furthermore, climate models show much smaller changes in precipitation than temperature. Whether model simulations lay sufficient emphasis on precipitation, another important factor characterizing climate change, remains a tough question.

In conclusion, by compiling a large dataset with over 5000 hydropower plants across 16 years and developing a climate risk evaluation framework, we find that by the 2090s, the relative revenue loss would reach 9.34% ± 1.21% under RCP8.5, with the moderate region (including major hydropower provinces) suffering the most, up to 25.40% ± 12.48% decrease. If we end up with RCP8.5, the national revenue loss over the 21st century would amount to 980.94 ± 67.58 billion CNY. The corresponding estimated hydropower reduction would be 127.89 ± 115.71 TWh. Carbon leakage caused by thermal power substitution could go up to

![Figure 4. Potential GHG leakage due to the reduced hydropower substituted by thermal power with different energy structures under RCP4.5 and RCP8.5. Solid lines present the average of 21 models. Ribbons show the results ranging from the minimum estimates to the maximum. Dotted lines present the 25 percentiles and 75 percentiles.](image-url)
Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no competing financial interest.

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