

Article

The Impacts of Water Policies and Hydrological Uncertainty on the Future Energy Transition of the Power Sector in Shanxi Province, China

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Abstract: Water scarcity under climate change and increasingly stringent water conservation policies may trigger energy security concerns. The current study develops an optimization model to investigate the impacts of water conservation policies and hydrological uncertainties on the regional energy transition process in Shanxi Province, China. The dual-control policies on total water consumption and water intensity are systematically examined for their differential constraints and stimulative effects on various power generation types. Hydrological time series analysis methods are employed to project future water resource variations in Shanxi Province and evaluate their implications for power system optimization. The results indicate that (1) total water constraint policies are more stringent than water intensity constraint policies; (2) changes in water resource availability impose greater restrictions on coal power development than those imposed by current water conservation policies; and (3) when total water resources decrease by approximately 43.5% compared with 2020 levels, Shanxi Province may face electricity shortages. These findings suggest that water conservation policy formulation should be coordinated with regional power sector development planning, while also considering potential energy security risks posed by potential future reductions in water resources.

Keywords: power system optimization; water strategy; hydrological characteristics; climate change; water–energy nexus



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1. Introduction

The process of urbanization has accelerated under the trend of economic globalization. The process of economic development is further increasing the demand for all types of resources, such as water and energy, which will put enormous pressure on the Earth's limited resources [1]. Electricity is a fundamental safeguard for economic development and the backbone of the future energy system, while electrical power is a water-intensive and constrained sector [2]. Water resources are the foundation of power plant operation and can influence energy policy planning as well as power technology choices [3]. However, there may be a conflicting relationship between the growing demand for electricity and the tight supply of water resources [4]. Electricity and water are closely related [5], but most energy and water policies are set and implemented independently of each other [6]. On the

one hand, irrational power system schemes can aggravate the pressure on regional water resources, further exacerbating the risk of water scarcity [7]. On the other hand, changes in water quantity or quality can also affect the operation of power plants, further threatening the security of electricity supply [4]. As global warming continues, the evolution of the regional hydrological state becomes more complex, while increasing the sensitivity of the power sector to water availability [8]. In other words, water scarcity problems may increase the vulnerability of the power system, further threatening its reliability and leading to economic losses [9]. Therefore, the overall program of future power systems and the related policy formulation should pay attention to the changes in water resources under the influence of climate factors, with a view to avoiding or mitigating possible conflicts between water and electricity.

Electricity production consumes water in certain processes, such as those involved in obtaining materials [10] and processing them [11]. In particular, coal-fired power is a typically water-intensive power generation technology [12]. However, there is a significant mismatch in the spatial distribution of China's coal resources, water resources, power demand centers, and power supply centers [13,14]. Shanxi Province is a typical coal-rich but water-scarce region that also bears significant responsibility for transmitting electricity to other provinces. The expansion of power generation capacity, the high proportion of coal-fired power, and inter-regional electricity transmission may all contribute to regional water scarcity. However, strict enforcement of national or regional water conservation policies could potentially restrict the development of water-intensive coal power technology. Thus, whether local water resources can support the coal power industry's development remains a question that is worthy of in-depth exploration [15].

Currently, there is a growing interest in the study of water-related issues in the power sector. Many studies calculate water consumption in the power sector based on historical scenarios, including actual water consumption calculations [16], virtual water footprint calculations [17,18], and the lifecycle assessment of water resources for electricity production [19]. In order to characterize the conflict between water resources and electricity, some of the studies further assess the regional water stress caused by the power sector [20] or the vulnerability of power generation due to water scarcity [4]. However, simply analyzing and evaluating the water–electricity nexus over the past period is not sufficient to guide the region's future generation and water management. Therefore, some researchers have analyzed the future energy transition of the regional power sector in relation to policy requirements [21] and water resource conditions [22]. How constraints are selected and how future scenarios are characterized and constructed are key to this series of studies. Some research scenarios are built on specific assumptions that presuppose different possible future outcomes. For example, the scenarios are based on expectations of future renewable energy penetration and options for generation and cooling technologies in the study provinces [23]. Other related studies established research scenarios based on detailed predictions of optimization models [24,25]. Seasonal and interannual variability of precipitation is high in many areas of China, which may lead to a mismatch between incoming water and water demand [26]. Besides policy constraints, we should also be mindful of the challenges associated with changing hydrological conditions [27,28]. Most of these studies are based on future climate scenarios under specific greenhouse gas (GHG) emission patterns [29], and hydrological models (e.g., PCR-GLOBWB, CLHMS, etc.) [9,30] are usually used to analyze the water resources status under the influence of climate factors.

In the context of achieving climate goals, many scholars are concerned about the impacts of carbon emissions on the power sector. However, it has been demonstrated that water constraints are more restrictive than carbon emission constraints for the power sector in certain water-scarce regions of China [25,31]. The water conservation policies

considered in previous studies are mainly total water constraint policies, i.e., the “three red lines” policy. Currently, water conservation policies are being improved in order to address the more complex and severe water problems [32]. The total water constraint policy sets a cap on water consumption, while the water consumption per CNY 10,000 of gross domestic product (GDP) can further guide departments to improve their water consumption efficiency. The latest guidance document [33] also suggests that, in order to ensure the country’s water security, it is important to achieve the dual control of the total amount and intensity of water consumption. There is a relative lack of research on dual-control policies for water resources in the water–electricity conflict problem. Different from previous studies that only consider the total water constraint policy, this paper will consider dual-control policies on total water and water intensity. Although hydrological models can obtain high-resolution results, they require a large amount of data and find it difficult to update the data in time, while the accuracy of the simulation is also affected by parameters [34]. The data required for hydrologic time series analysis are more accessible, and the method can specify the hidden hydrological characteristics and the changing trend of a specific region over a period of time [35]. If the planning year is contained within a period of relatively flat interannual variability, the water projection for the planning year can be considered relatively representative. On the contrary, a forecast shift may occur when the planning year is in a period of large interannual variability, which can reduce forecast accuracy. The study requires further observation of fluctuations around the planning year, with attention to the location of peaks and troughs.

This paper selects Shanxi Province, China as the research area. It is a typical water-scarce, coal-rich province, and at the same time bears the important task of transmitting electricity to other provinces [36]. The overall layout of the article is as follows: Section 2 introduces the optimization model construction process, period identification method (Hilbert–Huang transform) and water resources time series fitting and forecasting methodologies. Section 3 introduces the sources of research data and the construction of study scenarios. Section 4 presents the power system optimization under water conservation policies and water resources changes, as well as comparing the strength of constraints for different conditions, and ultimately giving recommendations for adjustments to the water allocation scheme. Section 5 draws conclusions. Note that, in some articles, water intensity refers to water consumption per unit of electricity, but our study refers to water consumption per CNY 10,000 of GDP unless otherwise specified.

2. Research Methodology

2.1. Optimization Model

This study employs a power system planning optimization model, with the objective function of minimizing the economic costs of the power system during the planning period. The primary constraints consist of power sector water use limitations resulting from both water conservation policies and changing water resource conditions. To analyze water resource variations, we apply the Hilbert–Huang transform to identify both long-term trends and periods. These identified components of hydrological time series are then processed through nonlinear least squares fitting to project future water availability in Shanxi Province.

The objective function is to minimize the economic costs of the electric system over the planning period, which consist of total power plant construction cost, total fixed operational cost, total variable operational cost, and total fuel cost, while deducting various policy subsidies [5,25]. The objective function can be expressed as follows in Equation (1):

$$\min Ob = CONS + RUN_f + RUN_v + FUEL - SUB \quad (1)$$

where Ob is the total cost of the electric system; $CONS$ is the total construction cost of new installed capacity during the planning period; RUN_f is the total fixed operational cost for all types of electricity supply; RUN_v is the total variable operational cost for all types of electricity supply; $FUEL$ is the fuel cost, with fuels consisting primarily of coal, natural gas, and biomass; and SUB is the policy subsidy corresponding to different types of electricity generation. The economic cost components can be expressed as follows in Equations (2)–(6).

$$CONS = \sum_{k=1}^n \sum_{t=1}^T \left[CON_k \times (1 - \delta_k)^t \times \max(ELE_k - EB_k, 0) / (T \times OH_{max,k}) \right] \quad (2)$$

where n is the total number of power generation technologies; T is the length of the planning period, representing the time interval from the base year to the planning year; CON_k is the fixed construction cost per unit of installed capacity of electricity generation technology k in the base year; δ_k is annual reduction rate of CON_k ; ELE_k is the electricity output of electricity generation technology k assuming that all generating units operating at full load; EB_k is the power generation of technology k in the base year; and $OH_{max,k}$ is the maximum operational hours of technology k . Additionally, the study assumes that the installed capacity increases at a constant rate from the base year to the planning year to meet the social demand for electricity in the planning year.

$$RUN_f = \sum_{k=1}^n \left[CAP_k \times BF_k \times (1 - \theta_k)^T \right] \quad (3)$$

where CAP_k is the installed capacity of technology k in the planning year; BF_k is the average fixed operational cost of technology k in the base year; and θ_k is the annual reduction rate of the fixed operational cost.

$$RUN_v = \sum_{k=1}^n \left[ELE_k \times BV_k \times (1 - \theta_k)^T \right] \quad (4)$$

where BV_k is the average variable operational cost of technology k in the base year and θ_k is the annual reduction rate of the variable operational cost.

$$FUEL = \sum_{k=1}^n [ELE_k \times EC_k \times P_k] \quad (5)$$

where EC_k is the energy consumption per unit of electricity production for technology k in the planning year and P_k is the price of the fuel used by technology k .

$$SUB = \sum_{k=1}^n SUB_k \quad (6)$$

where SUB_k is the policy subsidy corresponding to technology k .

This is calculated according to different subsidy policies, mainly including feed-in tariff subsidies and fuel price subsidies.

The optimization model is subject to the constraints as expressed in Equations (7)–(10).

$$ELE_{in} + \sum_{k=1}^n [ELE_k \times (1 - \rho)] = ELE_{out} + SE \quad (7)$$

where ELE_{in} is the electricity delivered from the external area to the study area; ρ is the network loss ratio; ELE_{out} is the electricity delivered from the study area to the external area; and SE is the social demand for electricity in the planning year.

$$CAP_k \leq CAP_{k,max} \quad (8)$$

where CAP_k is the installed capacity of technology k in the planning year and $CAP_{k,max}$ is its theoretical maximum.

$$AAUH_{min,k} \leq AAUH_k \leq AAUH_{max,k} \quad (9)$$

where $AAUH_k$ represents the average annual operational hours of technology k and $AAUH_{min,k}$ and $AAUH_{max,k}$ are its theoretical minimum and maximum values, respectively.

$$\sum_{k=1}^n Water_k \leq Water_{lim,p} \quad (10)$$

where $Water_k$ is the water consumption of technology k in the planning year and $Water_{lim,p}$ is the limiting value of water consumption under different scenarios. Three scenarios are included in this study—total water limitation, water intensity limitation, and change in water resources under climate influence.

2.2. Hilbert–Huang Transform

This paper applies the Hilbert–Huang transform proposed by Huang et al. in 1998 [37] for hydrological time series trend analysis and implied period identification. This is a signal analysis method based on local features and is suitable for nonlinear and non-smooth time series analysis. It consists of two important parts, namely empirical mode decomposition (EMD) and the Hilbert transform. EMD can adaptively and efficiently decompose a signal into a series of intrinsic mode functions (IMFs), each of which is associated with a well-defined timescale. The Hilbert transform is applied to each IMF to obtain the Hilbert spectrum reflecting the relationship among time, amplitude and frequency. However, EMD may cause mode mixing due to signal intermittency and noise when dealing with some problems, so in this paper, ensemble EMD (EEMD), an improved algorithm of EMD, is used [38]. This method adds white noise of a specific amplitude to the original data, then processes the data with EMD several times, before finally averaging the results of the operation. This can effectively improve the modal mixing problem and enhance the stability and reliability of EMD.

The decomposition result of the hydrologic time series is shown in Equation (11):

$$X_t = \sum_{i=1}^p c_i(t) + r_p \quad (11)$$

where X_t represents the hydrological time series; $c_i(t)$, with i varying from 1 to p , represents a series of IMFs; and r_p is the residual. IMFs contain information about the local features of the signal and have obvious physical significance. For each IMF $A(\tau)$, its Hilbert transform $B(t)$ is shown as follows in Equation (12):

$$B(t) = 1/\pi \times P \int_{-\infty}^{\infty} [A(\tau)/(t - \tau)] d\tau \quad (12)$$

where P is the Cauchy principal value integral. The corresponding analytic signal is expressed as follows in Equation (13):

$$Y(t) = A(t) + iB(t) = a(t)e^{i\theta t} \quad (13)$$

where the instantaneous amplitude can be expressed as $a(t) = \sqrt{A^2(t) + B^2(t)}$; the instantaneous phase can be expressed as $\theta(t) = \arctan[B(t)/A(t)]$; and the instantaneous frequency can be further calculated by $\omega = d\theta(t)/dt$.

The specific process of the Hilbert–Huang transform and more details are described by Huang et al. [37].

2.3. Water Resource Projection

In the current study, the nonlinear least squares fitting is used to predict the future total water resources in the study area [39]. The study decomposes the total water resources time series into several IMFs with different characteristic timescales by EEMD, and then selects the appropriate fitting function to simulate each IMF. The relevant parameters of the fitting function are estimated by the nonlinear least squares fitting. The fitting results of all IMFs are summed up to obtain the fitting function for the total water resource time series. The fitting methods are expressed as follows in Equations (14) and (15):

$$W_{imf,y} = \sum_{r=1}^R q_{1,r} \times \sin(q_{2,r} \times t + q_{3,r}) \quad (14)$$

where $W_{imf,y}$ is the fitting result of an IMF; r represents the number of frequency components included in the analyzed IMF, totaling the number R ; and $q_{1,r}$, $q_{2,r}$ and $q_{3,r}$ represent the function parameters, which are amplitude, angular frequency and phase difference, respectively.

$$W_y = \sum_{imf=1}^M W_{imf,y} \quad (15)$$

where W_y is the fitting result of the total water resources time series and imf represents the number of IMFs, totaling the number M .

The fitted function can be further utilized for regional total water resource prediction.

3. Data Analysis and Scenario Design

3.1. Data

The current study is based on the year 2020, and the planning year is 2030. Shanxi Province is situated in northern China, spanning latitudes 34°34' N to 40°43' N and longitudes 110°14' E to 114°33' E. For precise geographical context, refer to the standardized map published by the Ministry of Natural Resources of China [40]. Figure 1 illustrates the coal reserves [41] and total water resources [42] of Shanxi Province in 2020, along with their corresponding proportions of the national total. This indicates that Shanxi Province represents a classic example of a region abundant in coal resources but limited in water availability. The installed capacity of coal power in Shanxi province in 2020 is 62.63 million kilowatts, accounting for about 60% of the province's total installed capacity. In addition, Shanxi undertakes the important task of sending electricity to north, east, and central China. The dual control policies on total water and water intensity have strictly constrained water consumption in Shanxi's power sector. Compared with renewable energy sources like wind and solar power, coal-fired power generation has much higher water intensity. Given the potential reduction in future water availability, continuing to develop water-intensive coal power technology would violate sustainability principles. Shanxi's coal-dominated power generation structure urgently needs transformation. Therefore, it is typical to study the relationship and conflicts between water and electricity in the power sector of Shanxi Province.

China sets standards and limits for specific water consumption targets for the power sector. Due to the lack of actual water consumption data for each power generation technology, this study will calculate the water consumption of the power sector based on the norm of water intake. Thus, the water consumption in this paper is a theoretical value based on relevant standards, not actual water consumption. The benefit is that the water intensity of different power generation technologies can be compared under the policy constraint, which can help to further analyze the impact of future technology combinations on water consumption in the power sector. The water consumption of the power generation sector mainly comes from the thermal power sector, of which the coal

power sector accounts for the largest proportion. Therefore, this paper collects the specific data of coal power units in Shanxi Province in 2020, mainly including the plant name, the number of units; the unit installed capacity, the corresponding generation technology and cooling technology. The list of coal power plants in the study comes from the Department of Ecology and Environment of Shanxi Province [43]. All of these power plants have been selected to participate in the national carbon emissions trading market for 2019–2020. The plants that are not selected are usually small and have relatively poor cooling technologies. The study uniformly treats undocumented plants as small plants using circulating cooling technology. The data collected in this study include 98 coal power plants with a total installed capacity of 57,385,500 KW, accounting for about 92% of the total installed capacity of coal power in Shanxi Province in 2020. Therefore, this study assumes that all of these coal power plants adopt recirculating cooling, and the installed capacity of each unit is less than 100 MW. Figure 2 shows the coal power plant statistics.

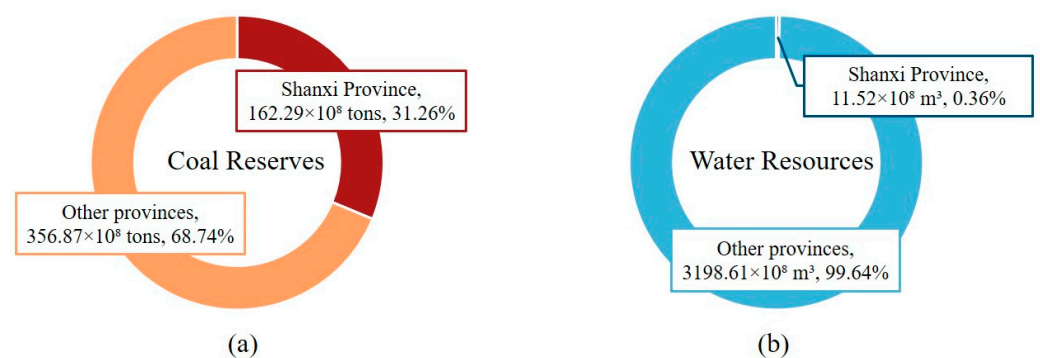


Figure 1. (a) Coal reserves in Shanxi Province, 2020 and national share. (b) Water resources in Shanxi Province, 2020 and national share.

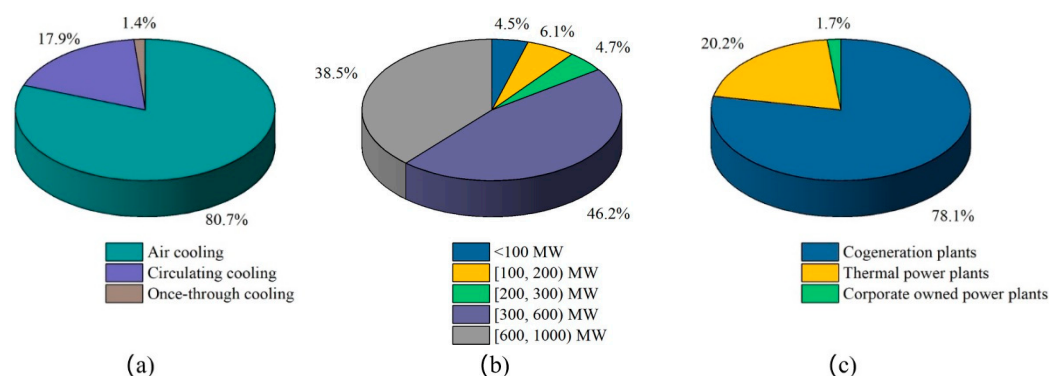


Figure 2. Classification of coal-fired power plants in Shanxi Province (2020) by cooling technology type (a), unit capacity (b), and power plant type (c).

The installed capacity and electricity generation data of different generating technologies are acquired from National Bureau of Statistics (NBS) [44]. Parameters related to the operation of the power plant are obtained from China Electric Power Yearbook [45] and the “14th Five-Year Plan” of Shanxi Electric Power Industry [46]. The norm of water intake for each power generation technology in Shanxi’s power sector can be found in “Shanxi Provincial Norm of Water Intake—Part 2: Industry”, published by the Shanxi Administration for Market Regulation [47], as well as in the “Norm of Water Intake—Part 1: Thermal Power Production” published by the State Administration of Market Regulation and National Standardization Administration [48]. Precipitation and water resources data are from the Shanxi Water Resources Bulletin issued by the Shanxi Provincial Department of Water Resources [49]. See the Supplementary Materials for more detailed data.

3.2. Scenario Design

This study examines the future restructuring of the power sector in Shanxi Province under the constraints of the existing water resources policy and considering the water resource variability under the influence of climatic conditions. As GDP affects not only electricity demand but also water intensity. Three scenarios of low GDP growth rate, medium GDP growth rate and high GDP growth rate are set in the study, with corresponding values of 6%, 7% and 8%. These are denoted by the symbols LS, MS, and HS, respectively. In order to study the impact of different water policies on the power sector, the paper further sets up relevant research scenarios. Overall, this paper sets up 15 scenarios, including three normal scenarios without water constraints, three scenarios for total water constraints and nine scenarios for water intensity constraints. Meanwhile, the power sector-related situation in 2020 is taken as the control group in this study and is recorded as BA. To simplify comparative studies, the normal scenarios without water constraints are denoted as NS in this paper, while such scenarios under the three GDP growth rates are denoted as NS_LS, NS_MS and NS_HS, respectively. All total water constraints are uniformly denoted as TS, and specifically as TS_LS, TS_MS, and TS_HS under the three GDP growth rates, respectively. At the same time, nine water intensity constraints in this paper are compounded by three degrees of decline targets and three levels of GDP growth rate. Referring to the decline target and actual decline in Shanxi's water intensity during 2016–2020, this paper assumes that water intensity in 2030 will be reduced by 20%, 25% and 30% compared with 2020. These are denoted by the symbols XS, YS, and ZS, respectively. Using 2005 as the base period, Shanxi's water intensity in 2020 is calculated to be 61.48 cubic meters per CNY 10,000 of GDP. The calculated water consumption limitation values in 2030 under different water intensity constraints are shown in Table 1.

Table 1. Water intensity restrictions in 2030 (Unit: BCM).

GDP Growth Rate	The Water Intensity Reduction Target		
	20% (XS)	25% (YS)	30% (ZS)
6% (LS)	0.480	0.450	0.420
7% (MS)	0.527	0.494	0.461
8% (HS)	0.579	0.542	0.506

According to the relevant documents, this paper takes the median of the national total water consumption limitation in 2025 and 2035 as the limitation in 2030. Based on the proportion of Shanxi's share of the national total water consumption limit in 2025, this paper calculates that Shanxi's total water consumption control target in 2030 will be 8.9 BCM. Assuming that future water consumption limitation in the power sector changes in equal proportion to the total limitation in the province, Shanxi's power sector water consumption control target in 2030 is 0.41 BCM. In fact, the total water constraint is not affected by the GDP growth rate.

Additionally, in order to investigate the impact of climate change on the power sector, this paper explores three different scenarios, each of which reflect future changes in water availability for the power sector in Shanxi Province under climate change. Details of the research scenarios under climate change are presented in Section 4.

4. Results and Discussion

4.1. Optimization Results Considering Water Conservation Policies

Under all water conservation policy constraints, the electricity generation of different power generation technologies of Shanxi Province in 2030 are presented in Figure 3.

Overall, coal-fired power generation is the main contributor to water consumption in Shanxi's electricity sector, and thus water conservation policies significantly constrain its development. In contrast, other types of power generation will expand in 2030. However, hydropower shows limited expansion across all scenarios, primarily due to severe water scarcity in Shanxi Province, which substantially restricts the development potential of the hydropower sector.

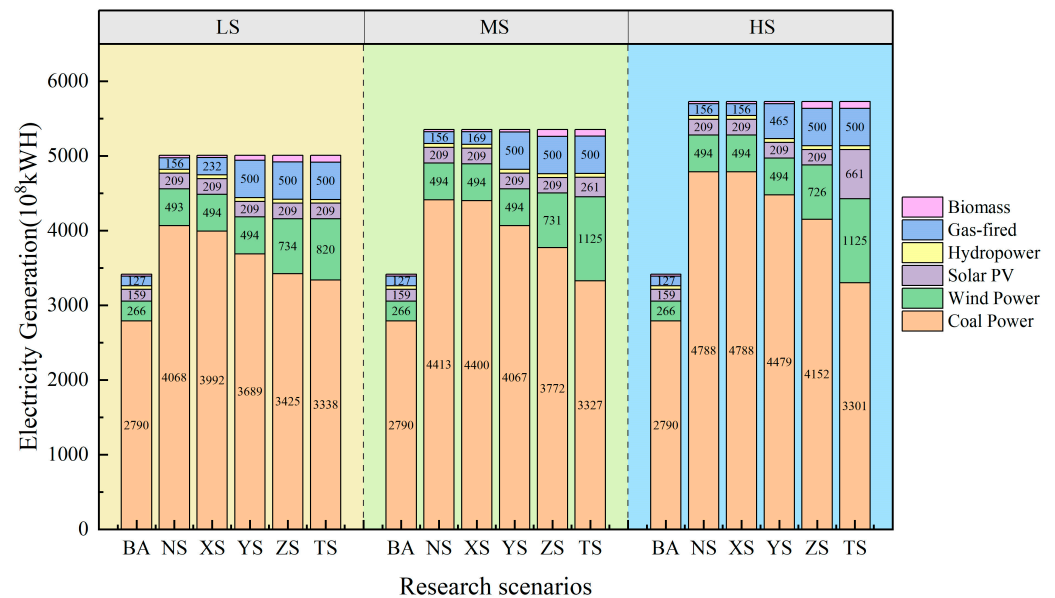


Figure 3. Shanxi's power mix transition under water dual-control policies: 2020–2030 comparison.

As shown in Figure 3, the most stringent water intensity constraint scenarios are ZS scenarios. Comparing the optimization results of ZS scenarios and TS scenarios. The results indicate that, subject to constraints from natural resource availability, local policy frameworks, and technical capacity limitations, while both gas-fired and biomass power generation exhibit considerable growth rates, they nevertheless maintain relatively small proportions within the total power generation portfolio. The primary differences in optimization outcomes lie in the development of coal-fired, wind, and solar power generation in 2030. Under TS scenarios, coal-fired power generation remains largely unaffected by GDP growth rates. Under ZS scenarios, coal-fired power generation shows increases of approximately 3% (GDP growth rate = 6%), 13% (7%), and 26% (8%) compared with TS scenarios. Meanwhile, in TS scenarios, the aggregate wind and solar power output exhibits positive correlation with GDP growth rates. Comparative analysis reveals that ZS scenarios demonstrate 8% (GDP growth rate = 6%), 32% (7%), and 48% (8%) reductions in total renewable (wind + solar) generation relative to TS scenarios. These results indicate that total water constraints prove more stringent than water intensity constraints across all economic growth conditions.

The water intensity constraint scenarios yield more complex outcomes under the combined influence of GDP growth rates and water intensity reduction targets. The following analysis focuses on different water intensity constraint scenarios. Table 2 presents the ratio of coal-fired electricity generation in 2030 to that in 2020 under various water intensity constraints. As shown in Table 2, coal-fired electricity generation demonstrates an increasing trend under all water intensity constraints. For the same economic growth rate, ZS scenarios can reduce coal-fired electricity generation by about 13–16% compared with NS scenarios, while XS scenarios only achieve a 0–2% reduction relative to NS scenarios. These results indicate that, with constant economic growth rates, larger water intensity reduction

targets correspond to smaller increases in coal-fired electricity generation. Conversely, with fixed water intensity reduction targets, higher economic growth rates lead to greater increases in coal-fired electricity generation.

Table 2. Coal-fired electricity generation in 2030 as a proportion of that in 2020.

GDP Growth Rate	Water Intensity Reduction Target			
	20% (XS)	25% (YS)	30% (ZS)	0% (NS)
6% (LS)	143.1%	132.2%	122.7%	145.8%
7% (MS)	157.7%	145.8%	135.2%	158.2%
8% (HS)	171.6%	160.6%	148.8%	171.6%

To analyze and compare the differences between water intensity constraint scenarios and the normal scenarios without water constraints in 2030, Table 3 presents the proportions of coal-fired electricity generation to total electricity generation under various scenarios. Under the normal scenarios without water constraints in 2030, Shanxi's power sector shows a slight decrease in coal-fired generation proportion in NS_LS scenario but increased proportions in both NS_MS and NS_HS scenarios. This occurs because under low GDP growth rates, the relatively slow growth of electricity demand can be met by reasonably increasing the operating hours of non-coal power generation technologies. As GDP growth rates rise, simply extending operating hours becomes insufficient to meet electricity demand growth, making economical and efficient coal power the preferred choice for the normal scenarios without water constraints. Additionally, Table 3 clearly shows significantly reduced proportions of coal-fired electricity generation to total electricity generation in both YS and ZS scenarios for 2030, demonstrating that the 25% and 30% water intensity reduction targets effectively constrain coal power expansion. It should be noted that the power system optimization results for XS scenarios closely resemble those of NS scenarios, with completely identical outcomes between XS_HS and NS_HS. This indicates that the 20% water intensity reduction target fails to limit coal-fired generation growth in Shanxi Province. Consequently, more careful calibration of water intensity reduction targets becomes essential in high GDP growth rate scenarios; otherwise, the water conservation goals for the power sector may prove difficult to achieve.

Table 3. The proportion of coal-fired electricity generation to total in 2030.

GDP Growth Rate	Water Intensity Reduction Target			
	20% (XS)	25% (YS)	30% (ZS)	0% (NS)
6% (LS)	79.7%	73.7%	68.4%	81.2%
7% (MS)	82.2%	76.0%	70.5%	82.4%
8% (HS)	83.6%	78.2%	72.5%	83.6%

4.2. Optimization Results Under Changing Water Resource Conditions

4.2.1. Characteristics of Regional Water Resources

The study adopts Spearman's correlation coefficient to analyze the relationship between total precipitation and total water resources in Shanxi Province. The time interval of the study data is 1994–2022, and the data unit is year. Total precipitation and total water resources in Shanxi Province during the study period are shown in Figure 4. The calculated Spearman's correlation coefficient is 0.9, which shows that there is a strong positive correlation between total precipitation and total water resources in Shanxi Province.

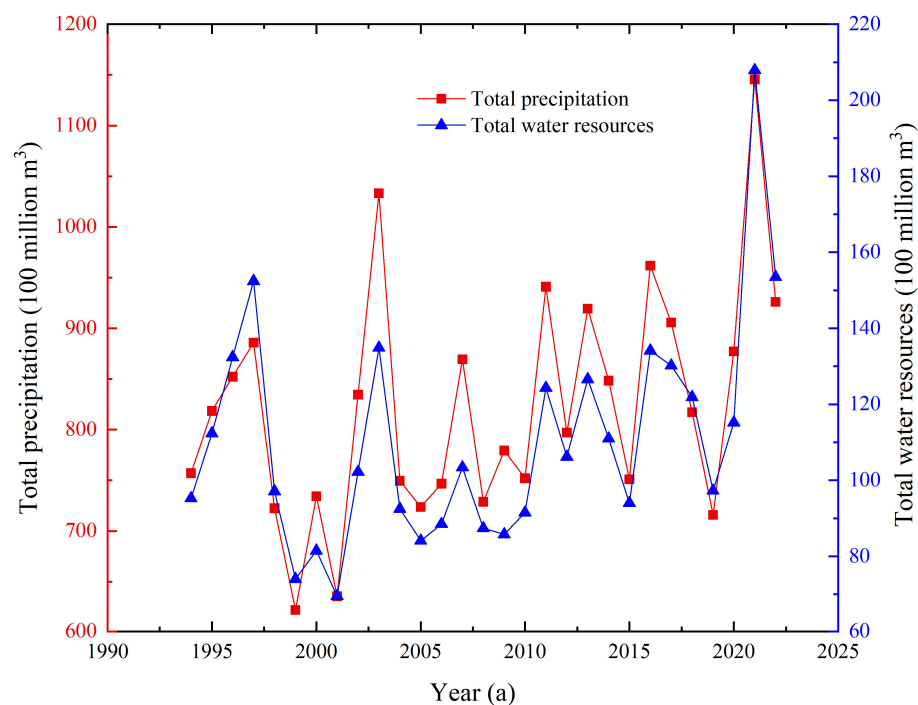


Figure 4. Total precipitation and total water resources in Shanxi Province during 1994–2022.

Abrupt change in hydrologic processes may affect the following research. The study adopts the sequential clustering method to test the possible abrupt change point of the total water resources time series, and the relevant result is presented in Figure 5. Calculating the statistic in U-test, the result is $|U| = 4.37 < U_{0.01/2} = 1.64$, which implies that the time series jumps significantly around 2020. This may be due to the fact that the average precipitation and temperature in Shanxi Province in 2021 broke the historical extremes, with the most precipitation and the highest temperature since 1961. Due to the lack of sufficient sample data for analysis after the identified change-point, we select data from 1994 to 2020 for subsequent study.

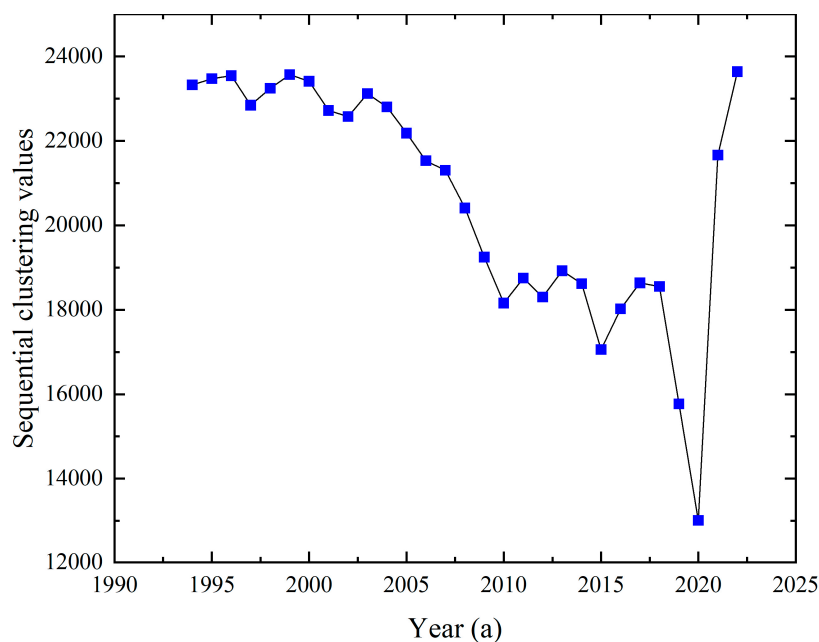


Figure 5. Sequential clustering curve of total water resources time series.

The total water resources time series is decomposed into a number of IMFs by EEMD method, including a trend and two periods, which are presented in Figure 6. It can be found that the trend of the total water resources in Shanxi Province during the study period is decreasing and then increasing. In order to obtain the center frequency and corresponding period of each IMF, the study applies the Hilbert transform to each IMF, and the Hilbert spectrum is shown in Figure 7. The results reveal that the water resources time series in Shanxi Province contains two significant periods of 4–5a and 7–8a. Analyzing the potential physical causes about the identified periods, which may be related to air–sea interactions [35]. For example, the Western Pacific subtropical high has a 3–4 year quasi-period and the polar–motion amplitude variation has the 6.5 years period.

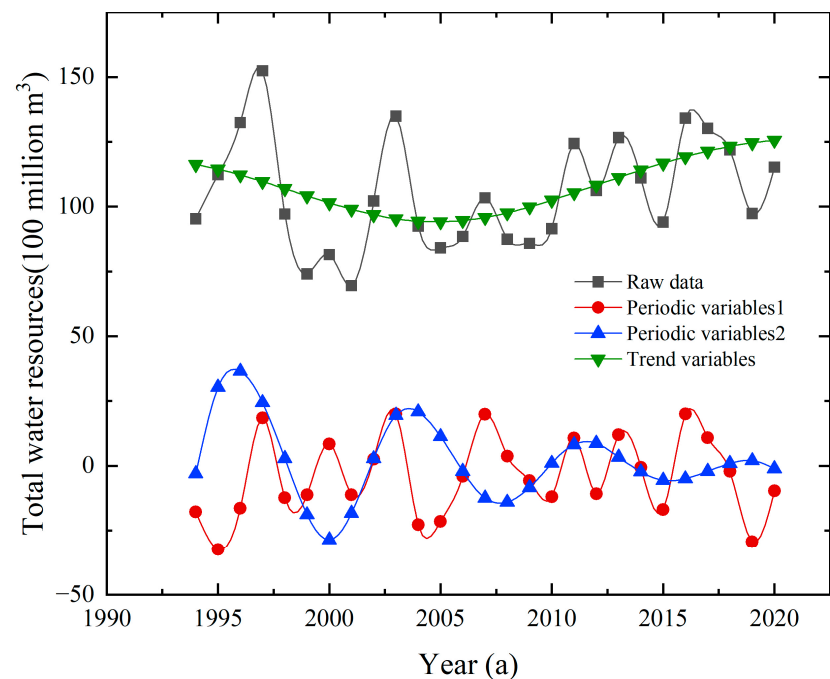


Figure 6. EEMD decomposition results of total water resources time series.

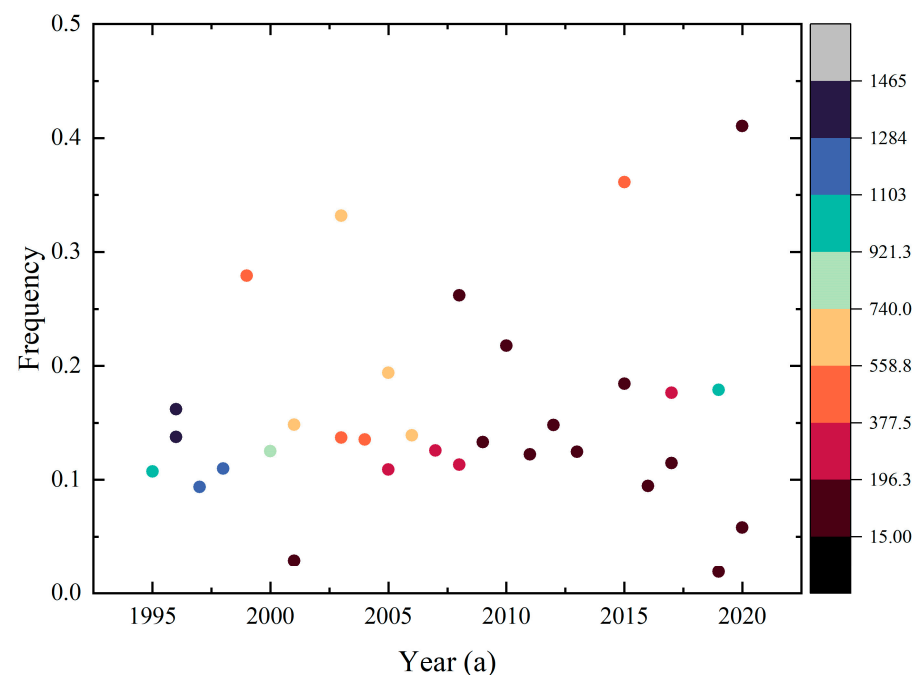


Figure 7. Hilbert spectrum of total water resources time series.

4.2.2. Projections of Regional Water Resources

In order to project the total water resources in Shanxi Province, this study fits each IMF. In this study, the data from 1994 to 2015 are selected as the fitting data, and the data from 2016 to 2020 are used as the validation data. Additionally, the mean absolute percentage error (MAPE) of the fitting and validation results are calculated simultaneously. The original data, fitting data and prediction results of the total water resource time series in Shanxi Province are shown in Figure 8. Calculations demonstrate that the MAPE is 5.5% for the fitting data and 7.8% for the validation data, both of which are within 10%, making it feasible to use fitting results for the subsequent prediction. The calculation results show that the total water resources of Shanxi Province in 2030 will be 11.11 BCM, which is 410 million cubic meters less than those of 2020.

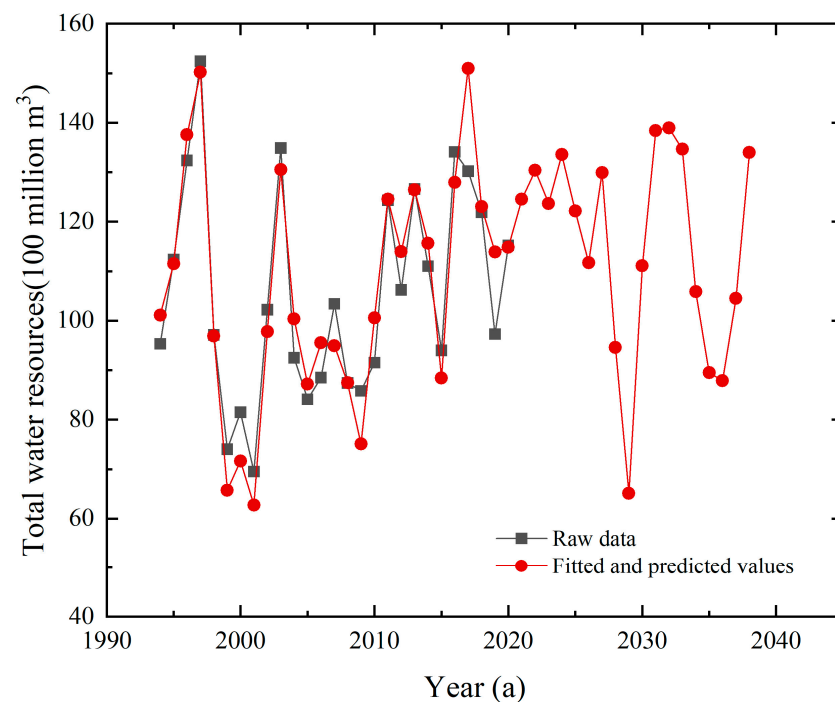


Figure 8. Fitting and prediction results of total water resources in Shanxi Province.

By observing the characteristics around point 2030, we can see that the time series from 2027 to 2034 basically reflects a relatively complete period for 8 years. This period has a peak in 2032 and a valley in 2029, while the total water resource projections vary significantly around 2030. In order to more comprehensively reflect the changes in the total water resources of Shanxi Province under future climate change, three data points are selected as model constraints in this study, namely, 6.51 BCM, 11.11 BCM, and 13.84 BCM. Compared with 2020, the total water resources of Shanxi Province in 2030 under these three scenarios decreases by 43.5%, decreases by 3.6%, and increases by 20.1%, respectively. We assume that the proportion of available water resources to total water resources remains constant, and that the proportion of water allocation between sectors in the region remains constant. The water resources allocated to the power sector of Shanxi Province in 2030 are 0.189 BCM, 0.323 BCM, and 0.402 BCM, labeled as CL, CM, and CH. The above data will be used in this study as water constraints for subsequent power system optimization studies.

4.2.3. Optimization Results

The power system optimization study is carried out at each economic growth rate, considering the water constraints calculated separately in Section 4.2.2. The optimization results of the electricity generation portfolio in 2030 under changing water resource

conditions are presented in Figure 9. Compared with the normal scenarios without water constraints, coal-fired power generation in 2030 shows significant reductions under changing water resource conditions, decreasing by approximately 37–48% (CM scenarios) and 20–33% (CH scenarios). When compared with 2020 levels, coal-fired generation in 2030 decreases by about 8–10% under CM scenarios but increases by approximately 16–17% under CH scenarios. By comparison, electricity generation from non-coal power shows an increasing trend. The sum of wind and solar electricity generation of Shanxi Province in 2030 grows by 300–500% (CM scenarios) and 160–340% (CH scenarios) compared with 2020. Developments in the hydropower, gas-fired and biomass power generation sectors are consistent with TS scenarios. In summary, the CM scenario imposes a more stringent constraint compared with the CH scenario. Furthermore, when compared with water intensity and total water consumption constraints, the changing water resource conditions demonstrate more pronounced limiting effects on future coal-fired power generation.

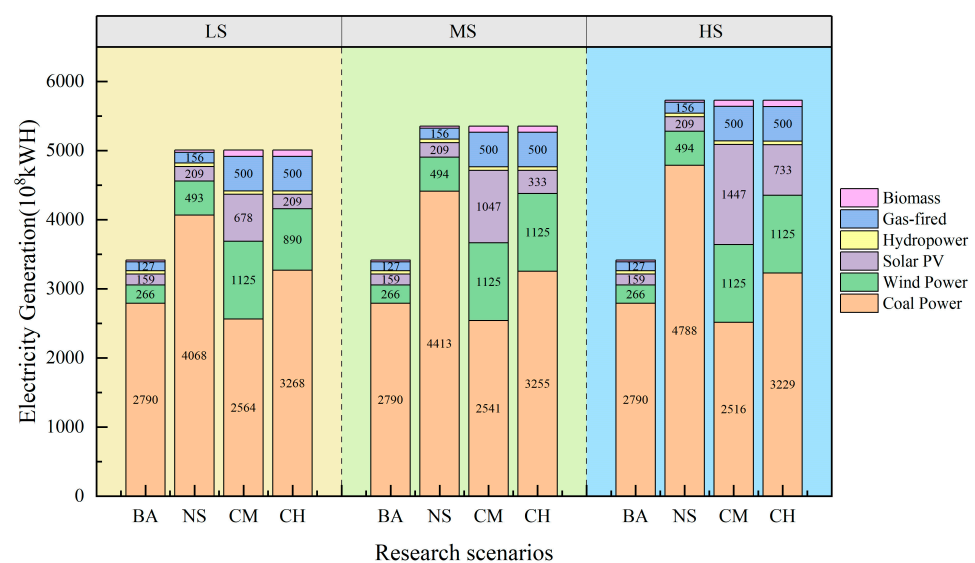


Figure 9. Electricity generation of Shanxi Province in 2030 under climate impacts.

However, for CL scenarios, the model cannot satisfy all constraints and the solution fails. The main reason for this is that the model cannot meet the limitations of the installed capacity as well as the operating hours of each power generation technology. This suggests that CL scenarios are too stringent for the future development of the power sector in Shanxi Province. If water resources in Shanxi Province decrease significantly in the future compared with 2020, the current water allocation model may not be able to fully meet the water demands of all users in the region. In other words, without modifying current water allocation schemes, the projected decrease in Shanxi's water resources by 2030 may lead to electricity supply challenges. The following section will further discuss feasible solutions.

4.2.4. Water Allocation Scheme Discussion

In water-rich regions, drought events can affect the power system primarily by reducing hydroelectric generation. Consequently, thermoelectric power is more reliable as a supplemental source of electricity [3]. However, in some water-scarce regions where thermoelectric power is the primary source of electricity, the cooling water shortage during drought conditions may affect energy security. Although the accelerated construction of wind and solar power can alleviate the problem, the expansion rate of new energy generation, as well as its construction capacity, is limited by the constraints associated with the construction period and by technical and resource factors, among others. As a result, power outages are still possible during extreme weather events without adequate preparation.

Timely and targeted adjustments to water allocation schemes can help mitigate potential energy risks associated with extreme weather events.

The study provides three possible solutions based on the regional water balance equation [50]. Solution 1 is to increase the amount of water available for allocation in the region by reducing the amount of water leaving the region, but this approach may reduce the amount of water available to downstream water users. Solution 2 is to use regional water storage to supplement water consumption for socio-economic development, which mainly includes water storage in water conservancy projects, water storage in rivers and underground water storage. Specific dispatch programs and water allocation plans need to be decided on a case-by-case basis. However, Solution 2 may also be accompanied by problems during implementation, these problems include the following: (a) reducing the amount of water available for dispatch may affect other functions of the reservoir; (b) reducing the ecological and environmental water for a river channel may negatively affect regional ecological conservation and sustainable development; and (c) over-abstraction of water may lead to problems such as over-extraction of groundwater and water table depression. Solution 3 is to change the proportion of water allocation to each water user in the region to further meet the growing water demand of the power sector. While this approach may alleviate the power sector's vulnerability to water resources, it may at the same time exacerbate water stress in other sectors. In specific scenarios, it is necessary to comprehensively consider the relationship between the supply and demand of water resources, as well as to study reasonable water resource allocation scheme to mitigate the problem of water resource reduction caused by climate change.

5. Conclusions

Shanxi Province, characterized by abundant coal reserves but severe water scarcity, confronts the challenge of balancing power system expansion with water policy limitations and fluctuating hydrological conditions. This study develops a power system optimization model integrated with water resource projection based on the Hilbert–Huang transform, systematically evaluating electricity development pathways in Shanxi Province under diverse water resources policies and hydrological variability conditions.

The results illustrate that policy factors and climate factors will reduce water consumption in the power sector primarily by limiting the development of the coal power sector, while other power generation technologies will be further developed. Wind and solar power have relatively high development potential, while other power generation technologies are more constrained by natural resources, local policies, and technological capabilities. Therefore, excessive curtailment of coal-fired power generation may lead to insufficient power supply under stringent water constraint scenarios. When implementing water intensity constraints, it is crucial to consider the combined effects of water intensity reduction targets and economic growth rates. At a 20% water intensity reduction target, Shanxi's coal power sector development remains largely unaffected. Under identical water intensity reduction targets, the constraining effect weakens as GDP growth rates increase. However, under total water consumption constraints, coal power sector development shows minimal sensitivity to GDP growth rate variations, with constraints remaining consistently stringent across all economic scenarios. Comparative analysis reveals that total water consumption policies impose significantly stricter constraints than water intensity policies, and this gap widens progressively with higher GDP growth rates.

Shanxi Province exhibits significant interannual precipitation variability, with regional water resource uncertainties potentially causing electricity supply reliability challenges. It is projected that the total water resources of Shanxi Province may decrease by 43.5%, decrease by 3.6%, or increase by 20.1% around 2030. Climate-induced reductions in water

resources can similarly constrain coal power sector development, and in our study scenarios such constraints are more stringent than those arising from water conservation policies. In particular, the optimization model has no solution when the water resources decrease by 43.5%, which indicates that energy security in the study region cannot be guaranteed. Therefore, in order to alleviate the future conflicts between water and electricity, it is necessary to further improve the water resource policies and strengthen water conservation efforts. To mitigate the vulnerability of the power sector to changes in water resources, this study considers the possibility of increasing the proportion of water allocated to the power sector, using in-region water storage, or reducing regional outflows. Specific water allocation programs need to take into account not only the water demands of different sectors within the study region, but also the water allocation related to transregional rivers. Therefore, the detailed schemes have yet to be further analyzed and determined in the light of specific regulations and actual user needs.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en18092281/s1>, Table S1: Electricity portfolio and installed capacity of Shanxi Province in 2020; Table S2: Economic parameters related to power technologies; Table S3: Norm of water intake for power industry in Shanxi Province; Table S4: Evaluation criteria for MAPE; Figure S1: Electricity consumption and GDP of Shanxi Province from 2005 to 2020. References [5,25,44,47,48,51] are cited in supplementary file.

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