

Article

A Water–Energy–Carbon–Economy Framework to Assess Resources and Environment Sustainability: A Case Study of the Yangtze River Economic Belt, China

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Abstract: Developing a comprehensive research framework that integrates the water–energy–carbon (WEC) system with economic development is crucial to fostering sustainable development. However, common evaluation indicators for sustainable development fail to cover the most up-to-date climate objectives and policies comprehensively and also lack a decoupling analysis between various subsystems and economic development. By incorporating the Tapio model and the coupling coordination degree model (CCDM), we introduce a novel water–energy–carbon–economy (WECE) framework to evaluate the sustainability of regional resources and the environment. Taking the Yangtze River Economic Belt (YREB) as an example, we have constructed a comprehensive water–energy–carbon (WEC) indicator system that aligns with China’s sustainable development objectives and its most recent carbon emission reduction strategies. Employing the indicator system, we conducted an assessment of the sustainable development within the YREB from 2010 to 2019. The results reveal that the YREB has yet to achieve full decoupling between water use, energy consumption, carbon emissions, and economic development, with a prevailing trend towards weak decoupling (WD). The WEC system within the YREB exhibited coordination from 2010 to 2019. Notably, only the WEC system in Sichuan attained good coordination in 2019, indicating the imperative for more extensive initiatives in resource and environmental development to realize sustainable objectives. Finally, we delve into the driving mechanism of the coupling coordination degree (CCD) of the WEC system. Our findings suggest that, from the perspective of system collaborative management, the integrated approach of the WEC system offers superior benefits compared to individual management components. Consequently, it is imperative to bolster collaboration and institute a comprehensive set of policies to ensure sustainable development within the region.

Keywords: sustainable development; coupling coordination; water–energy–carbon; decoupling; economic growth



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1. Introduction

Intensive human activities pose significant challenges to the sustainability of the economy and the environment [1]. The expansion of urbanization, which fosters economic growth and population increase, instigates ecosystem degradation [2]. This expansion also necessitates a significant demand for resources such as water and energy [3], and it directly or indirectly generates greenhouse gases, thereby intensifying climate change [4]. A marked rise in water and energy deficits has emerged due to the escalating demand for these resources [5]. Furthermore, the destruction of ecosystems is intensified by climate

change, which is induced by greenhouse gas emissions [6]. It is an indisputable fact that more than 70% of total global emissions stem from greenhouse gas emissions produced during energy consumption [7]. In particular, the energy consumption associated with water supply and wastewater treatment processes significantly contributes to indirect carbon emissions [8]. To address these challenges, the United Nations has established a train of sustainable development goals (SDGs) to promote advancements in resource management, and environmental conservation [9,10].

China is recognized as one of the most rapidly expanding economies globally. Despite only accounting for 6% of freshwater resources, it consumes 24.3% of the primary energy and emits 28.8% of carbon dioxide worldwide [11]. In 2020, China formally pledged to achieve peak carbon emissions by 2030 and transition to carbon neutrality by 2060 [12]. To achieve this objective, China proactively implemented a policy in 2021 that imposes dual control over the amount and intensity of carbon emissions. This action demonstrates China's dedication to balancing environmental protection with sustainable socio-economic development while ensuring the security of energy and water supply [11]. Nevertheless, it also intensifies the tension between economic growth, resource consumption, and environmental conservation in China. Coordination is a fundamental principle of sustainable development, underscoring synergistic growth across economic, social, and ecological dimensions. This principle stipulates that economic advancement should not be achieved at the cost of environmental degradation [13]. It aligns with the concept of decoupling resource consumption, environmental pollution, and economic growth. Thus, it is essential to clarify how the water–energy–carbon (WEC) system corresponds to the SDGs, specifically SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), and SDG 13 (climate action).

The fundamental premise of sustainable development is to attain a decoupling between resources and the environmental elements and economic development. The Tapio model has been extensively employed to investigate the decoupling between environmental pollution or resource utilization and economic development [14,15]. In the field of WEC, it is primarily used to examine the relationship between the economy and multiple factors such as energy consumption, embodied greenhouse gases, and water utilization. For example, Chen et al. [16] used the Tapio model to assess the decoupling of energy consumption, greenhouse gas emissions, and economic growth in Macao. They found that there was a decoupling between energy consumption and economic growth, but a continued coupling between carbon emissions from energy sources and economic growth. Gong et al. [17] examined the decoupling relationship between water consumption and GDP within the Chengdu–Chongqing dual-city economic circle from the perspective of “production–living–ecological” based on the Tapio model. Their findings indicated a weak decoupling in Chongqing and a strong decoupling in Chengdu between economic growth and water consumption.

The coupling coordination degree model (CCDM) is commonly utilized to evaluate multiple systems' interactions. Previous studies have shown that the coordination relationship between multiple systems can be depicted with greater accuracy when the CCDM is used in conjunction with evaluation methods such as the entropy weight method [18,19]. This was widely used in the assessment of coordination between the environment, economy, carbon emission, and other subsystems. For example, Li et al. [20] evaluated the economic–social–environmental systems of nine central Chinese cities using the CCDM and found that the coordination was in a suboptimal state, except for Beijing, where significant coordination was observed. Zhang et al. [21] employed the CCDM to analyze the coupling coordination between carbon emissions and economic development in the Pearl River Basin of China, revealing a gradual transition from a state of discoordination to one of general coordination over time.

Previous studies have sought to examine the WEC nexus from a coupling perspective, conducting analyses at both national and urban scales using various methodologies such as system dynamics [22], a life cycle analysis [23], and an input–output model [24], etc.

There is an escalating focus among legislators on environmental sustainability and related resource concerns. To address the issue of inter-system sustainability, researchers have increasingly turned their attention to the nexus of WEC from a synergistic viewpoint. To comprehensively analyze the synergistic relationship of WEC systems, scholars have developed an integrated index system to evaluate the interaction and impact of various sub-elements. Some researchers have combined indicators from water, energy, food security, and carbon emissions to establish a comprehensive WEC system index. The CCDM was subsequently used to assess system coordination [25]. Other studies have incorporated key indicators from the water, energy, food, and environmental systems with local government document requirements. This resulted in the development of a WEC system index evaluation system that aligns with local management and strategic goals. The CCDM was then used for a quantitative analysis of system coordination [26].

Despite extensive research conducted by scholars on the evaluation of the WEC system and yielding promising results, there are still notable inadequacies present within the following: (1) The majority of research has predominantly concentrated on the decoupling between one or two variables and economic expansion [16,17]. However, a paucity of studies analyzes this correlation relationship among multifaceted elements from a synergy perspective. (2) There are limited studies on the coordination assessment of WEC systems. Moreover, a systematic evaluation framework guided by SDGs and key strategic goals is still lacking in existing research on the coordination of WEC systems [25,26]. (3) Currently, the construction of the WEC system indicator system is often confined to a literature review, which fails to fully reflect important strategic objectives and the latest national policy orientations, resulting in a lack of comprehensiveness in the assessment of system coordination. This limitation may hinder the sustainable development of resources and the environment, as well as the achievement of long-term carbon emission reduction targets [27].

To bridge the above gaps, the contributions of this paper are mainly reflected in the following aspects: (1) A novel water–energy–carbon–economy (WECE) system framework for regional sustainability assessment is proposed. (2) The WEC system and economy are incorporated into the same evaluation framework to evaluate synergy between systems and trade-offs outside the system from the perspective of sustainable development. (3) A WEC system evaluation indicator system oriented by sustainable development goals, dual carbon goals, and carbon emission dual control policy is developed.

2. Research Framework

The core challenge of resource and environmentally sustainable development lies in the balanced interaction between water resources, energy, carbon emissions, and the economy [28,29]. To promote sustainable development, it is crucial to coordinate the relationship between water, energy, carbon, and economic growth, that is, to reduce water consumption, optimize energy utilization, and lower carbon emissions while enhancing economic benefits. This involves decoupling between the WEC system and economic growth as well as enhancing coordination within the WEC system [16,17] (Figure 1). Analyzing the decoupling status between water resource consumption, carbon emissions, and economic growth, as well as the coordination among the WEC system, is conducive to promoting the sustainable development of resources and the environment. The detailed technical roadmap is provided in the Supplementary Materials (Figure S1).

SDGs, dual carbon goals, and dual control policies on carbon emissions are all aimed at promoting global sustainable development and mitigating climate change. These policies and goals actively promote the synergy between economic growth, resource-efficient use, and environmental protection by implementing a series of comprehensive strategies and measures. SDGs draw a grand blueprint for the sustainable development of resources and the environment through four core dimensions: water, energy, economy, and climate. Among them, the water dimension (SDG 6) is dedicated to ensuring that all people around the world have access to safe and affordable drinking water, with key initiatives including

ensuring the stability of the water supply, improving water resource utilization efficiency, and improving water quality. The energy dimension (SDG 7) focuses on popularizing affordable and reliable modern energy services while optimizing the energy structure and improving energy use efficiency [30]. The climate action dimension (SDG 13) emphasizes a rapid and extensive response to climate change and its impacts, with particular emphasis on implementing measures to mitigate climate change. The economic dimension (SDG 8) aims to promote durable, inclusive, and sustainable economic growth, focusing on per capita income growth based on national conditions in each country, and working towards effective decoupling of economic growth from environmental degradation. China's '30·60' decarbonization goal highlights the imperative need for comprehensive control over carbon emissions. This entails mitigating the intensity of carbon emissions and enhancing carbon sinks. The two aspects of the carbon system are also emphasized: the reduction in carbon emission and the increase in the carbon sink. The dual control policy, which concurrently regulates both the quantity and intensity of carbon emissions, is engineered to enhance energy utilization efficiency. This policy further propels the evolution of industrial structures, with its impetus being driven by energy, carbon emissions, and intensity control.

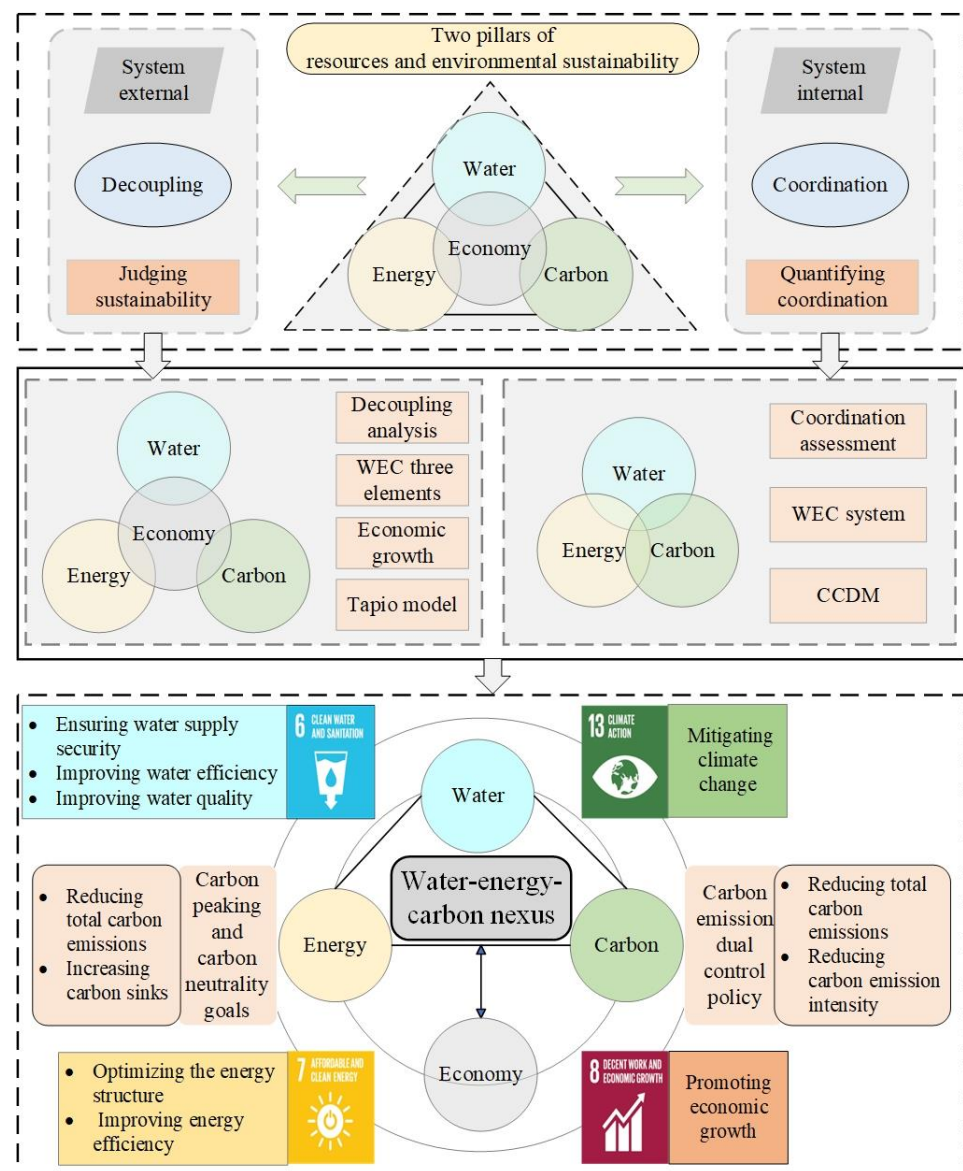


Figure 1. Research framework.

3. Materials and Methods

3.1. Study Area

The YREB is situated in the southern region of China, divided into upper (including Sichuan, Chongqing, Yunnan, and Guizhou), middle (including Jiangxi, Hunan, and Hubei), and lower (including Shanghai, Jiangsu, Zhejiang, and Anhui) reaches (shown in Figure S1). The belt, characterized by its robust comprehensive strength and significant strategic support, holds a prominent position within China. Nevertheless, notable disparities exist in the spatial distribution of economic development patterns, strategic resources, and cumulative carbon emissions across the belt. In 2019, the provinces and municipalities of Zhejiang, Jiangsu, and Shanghai collectively accounted for 40% of the GDP within the YREB. According to the China Statistical Yearbook, China Energy Statistical Yearbook, and China Carbon Emission Accounting Databases (CEADs) [12,31,32], these regions contributed to approximately 10% of the regional water resources, generated roughly 7% of the total primary energy produced, and emitted 35% of carbon dioxide within the belt. Therefore, YREB offers a typical case for studies on the sustainable development of resources and the environment, and it can provide references for other regions in China and worldwide.

3.2. Indicator System Construction and Data Sources

The WEC system is characterized by its significant coupling features, which include three interrelated subsystems (Figure 1 and Table 1). This study developed a holistic evaluation indicator system for the WEC system, achieved by integrating the SDGs, dual control policy over the amount and intensity of carbon emissions, dual carbon goals, and the WEC nexus. In alignment with the policy mentioned above and objectives (Figure 1), we developed a comprehensive index system for WEC systems (Table 1). More specifically, within the water resources sector, we established indicators for subsystems based on three primary dimensions: security, utilization structure, and efficiency. In the energy sector, corresponding subsystem indicators were formulated from the vantage points of energy security, utilization structure, and efficiency. For the carbon management sector, we devised an index system for subsystems that considered both carbon emissions and carbon sinks.

The data about the WEC system's indicators were gathered from the statistical yearbooks of provinces and municipalities within the YREB (2010–2019), the China Statistical Yearbook, the China Environmental Statistical Yearbook, the China Energy Statistical Yearbook, and the CEADs [12,31,32]. Some data were sourced from Supplementary Material of reference [33]. Some indicator values were calculated according to their respective definitions. Furthermore, the missing values, mainly concentrated in two key indicators, the proportion of ecological water utilization and the proportion of oil consumption, with roughly 10 data points missing for each indicator, were filled using varied strategies for imputation. Specifically, the data with linear trends were imputed by linear interpolation, while those without a linear trend were substituted with the mean value across years. We observed a close alignment between the CCD computed from the original data and the results derived from the interpolated data, with a root mean square error (RMSE) of 0.01325 and maximum error of 0.02389. Therefore, the small effect of interpolation on the outcomes confirmed the validity and reliability of the data obtained by this approach. However, to ensure the continuity of data series and an effective time series analysis, this study still uses interpolated data for its investigation.

Table 1. WEC indicator system.

Subsystem	First-Level Indicator	Second-Level Indicator	Reference	Number	Weight (Direction)
Water resource subsystem	Water resources security	Total water resources per capita (m^3/person)	[30]	X1	0.155 (+)
		Total water consumption per capita (m^3/person)		X2	0.072 (−)
		Development and utilization rate of water resources (%)	[34]	X3	0.016 (−)
		Water production modulus ($10^4 \text{ m}^3/\text{km}^2$)		X4	0.122 (+)
	Water use structure	Proportion of agricultural water use (%)	[35]	X5	0.186 (−)
		Proportion of industrial water use (%)		X6	0.065 (−)
		Proportion of domestic water use (%)		X7	0.081 (−)
		Proportion of ecological water use (%)		X8	0.189 (+)
	Water use efficiency	Water consumption per CNY 10,000 of GDP ($\text{m}^3/\text{CNY } 10^4$)	[30]	X9	0.045 (−)
		Urban wastewater treatment rate (%)		X10	0.042 (−)
		Water consumption per CNY 10,000 of value-added use by industry ($\text{m}^3/\text{CNY } 10^4$)	[34]	X11	0.027 (+)
Energy subsystem	Energy security	Energy self-sufficiency rate (%)	[36]	X12	0.254 (+)
		Primary energy production per capita (ton of standard coal (TSC)/person)		X13	0.077 (−)
		Energy consumption per capita (TSC/person)	[30]	X14	0.055 (+)
	Energy utilization efficiency	Elasticity consumption per capita ($10^4 \text{ kW}\cdot\text{h}/\text{person}$)		X15	0.063 (−)
		Share of oil consumption (%)		X16	0.076 (−)
		Share of coal consumption (%)	[37]	X17	0.055 (−)
		Share of natural gas consumption (%)		X18	0.253 (+)
		Elasticity ratio of energy consumption	[33]	X19	0.071 (−)
		Energy consumption per CNY 10,000 of GDP (TSC/CNY 10^4)		X20	0.046 (−)
	Energy utilization efficiency	Elasticity ratio of electricity consumption	[38]	X21	0.022 (−)
		Electricity consumption per CNY 10,000 of GDP ($\text{kW}\cdot\text{h}/\text{CNY } 10^4$)	/	X22	0.026 (−)
Carbon subsystem	Carbon emission	Total carbon emissions (106 t)		X23	0.050 (−)
		Carbon emissions per CNY 10,000 of GDP ($\text{t}/\text{CNY } 10^4$)	[13]	X24	0.095 (−)
		Carbon emissions per capita (t/person)		X25	0.145 (−)
	Carbon sink	Greening coverage rate of urban built-up area (%)	[26]	X26	0.070 (+)
		Forest stock per unit area (m^3/km^2)	/	X27	0.346 (+)
		Percentage of forest cover (%)	[39]	X28	0.294 (+)

3.3. Methodology

3.3.1. Tapio Model

The Tapio model has gained popularity in disciplines such as economics, environmental studies, and resource management [16,17,40], due to its uncomplicated computational process irrespective of scale. The formula [40] is as follows:

$$DE = \frac{\Delta S/S}{\Delta G/G} = \frac{(S_t - S_{t-1})/S_{t-1}}{(G_t - G_{t-1})/G_{t-1}} \quad (1)$$

where DE denotes the decoupling index. ΔS denotes the variation in the subsystem's comprehensive index. ΔG indicates the change in GDP. S_t and S_{t-1} represent the subsystem's comprehensive index in the area for years t and $t - 1$, respectively. G_t and G_{t-1} show the GDP in the area for years t and $t - 1$, respectively. The types of decoupling [41] and their practical implication are shown in Supplementary Materials (Figure S3).

3.3.2. Entropy Weight Method

The indicators are initially standardized to mitigate the influence of the inter-indicator scale. The entropy weight method is based on the variability of data, and it is sensitive to the original data distribution. The min–max normalization technique can effectively maintain the distribution characteristics of the original data and avoid excessive compression of the data. At the same time, it can also capture the inherent variability of the data. Therefore, the min–max normalization method is very suitable for data processing in the entropy weight method. In this paper, we use the min–max normalization method to standardize the data so that the entropy weight method can calculate the weights more accurately. The formulas [37,42] are as follows:

For positive indicators,

$$Y_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \quad (2)$$

For negative indicators,

$$Y_{ij} = \frac{\max(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \quad (3)$$

where Y_{ij} and X_{ij} represent the standardized and initial values of variable j in the i -th year, respectively, and $\max(X_{ij})$ and $\min(X_{ij})$ represent the maximum and minimum values of variable j across all years, respectively.

The entropy weight model is utilized to determine the weights assigned to each standardized variable and compute the value of each subsystem comprehensive index. The detailed procedures [30] are as follows:

- (1) Calculate the proportions of the i -th sample in the j -th indicator:

$$P_{ij} = Y_{ij} / \sum_{i=1}^n Y_{ij} \quad (4)$$

- (2) Calculate the information entropy of each indicator. The formula for information entropy is

$$Q_j = -\frac{1}{\ln n} \sum_{i=1}^n P_{ij} \times \ln P_{ij} \quad (5)$$

where $0 \leq Q_j \leq 1$; when $P_{ij} = 0$, $P_{ij} \times \ln P_{ij} = 0$.

- (3) Calculate the weights of the indicator j . The weight assigned to each indicator is calculated by dividing the indicator by the aggregate value of the system indicators:

$$W_j = \frac{1 - Q_j}{\sum_{j=1}^m (1 - Q_j)} \quad (6)$$

- (4) Calculate the comprehensive evaluation values for each subsystem. The comprehensive value of the subsystems is determined by the product of the standardized indicator values and their respective weights:

$$g = \sum_{i=1}^n \sum_{j=1}^m (W_j \times Y_{ij}) \quad (7)$$

where P_{ij} indicates the proportion of the indicator j in year i ; Q_j denotes the entropies' value of indicator j , when $P_{ij} = 0$ and $P_{ij} \times \ln P_{ij} = 0$; W_j represents the weight of indicator j ; and g is the comprehensive value.

3.3.3. CCDM

The CCD can effectively reflect the interaction relationship between various subsystems, as well as the coordination level within these systems [43]. Utilizing the subsystem synthesis index, as derived from the entropy weight method, the CCD of the WEC system can be calculated through the CCDM. The formulas [30] are as follows:

$$C = \left\{ \frac{g_1 \cdot g_2 \cdot g_3}{[(g_1 + g_2 + g_3)/3]^3} \right\}^{\frac{1}{3}} \quad (8)$$

$$T = ag_1 + bg_2 + cg_3, \text{ CCD} = \sqrt{C \times T} \quad (9)$$

where C denotes the coupling degree. g_1 and g_3 are the evaluation values of subsystems, respectively. T represents the comprehensive index of the WEC system. a , b , and c show the determinant coefficients. In this paper, it is assumed that all three systems have equal status [30,42,43], so $a = b = c = 1/3$.

The types of coupling coordination corresponding to the CCD at different levels have been classified in the Supplementary Materials (Figure S4) according to previous study [37].

3.3.4. Spatial Auto-Correlation Model

Geographical elements exhibit correlation spatially [44]. This spatial correlation can be measured using Moran's I , which consists of the global Moran's I and local Moran's I . The global Moran's I test quantifies the similarity and dissimilarity (spatially positive and negative correlation) of characteristics between neighboring areas across a given region. This is represented by the following equation [44]:

$$GI = \frac{n \sum_{i=1}^n \sum_{j=1}^m \omega_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^m \omega_{ij} (x_i - \bar{x})^2} \quad (10)$$

where GI shows the global Moran's I , and $-1 \leq GI \leq 1$. $GI > 0$, $0 < GI$, and $GI = 0$ indicate positive, negative, and uncorrelated spatial relationships among different provinces, respectively. n is the number of provinces and municipalities. x_i and x_j denote the CCD of provinces i and j , respectively. $\bar{x}$ is the mean of the CCD. ω_{ij} represents the spatial weight matrix.

The local Moran's I quantifies the correlation intensity between variables within each province and those in adjacent provinces. The formula [44] is as follows:

$$LI = \frac{n(x_i - \bar{x}) \sum_{j=1}^n \omega_{ij} (x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (11)$$

where LI represents the local Moran's I . The other variables are identical to those in the formula above.

4. Results

4.1. Decoupling between WEC Elements and Economic Growth

Using Equation (1), we determined the decoupling relationship between water use, energy consumption, carbon emission, and economic growth, respectively. As depicted in Figure 2, the types of decoupling observed were strong decoupling (SD), weak decoupling (WD), expansive coupling (EC), and expansive negative decoupling (END). Notably, the top two ideal decoupling states were dominant, namely, SD and WD, between resource utilization, environmental degradation, and economic expansion, respectively. From 2011 to 2019, four types of decoupling between water utilization and economic growth were observed. The states of SD and WD accounted for 51.52% and 44.44%, respectively, whereas the states of EC and END only occurred three times and once, respectively. However, only Zhejiang and Chongqing maintained an SD state from 2014 to 2019. Between 2011 and 2019, the YREB witnessed a decoupling of energy consumption and economic growth, as indicated by the presence of only SD and WD states, with WD accounting for 84.85% and SD representing just 15.15%. In the period from 2011 to 2019, 67.68% of carbon emissions in the YREB were primarily due to WD, with SD (29.29%), EC (2.02%), and END (1.01%) contributing less significantly. However, as economic constraints intensified, the SD state, which was characterized by a correlation between carbon emissions and economic growth across YREB, became unstable. Only Sichuan exhibited a stable five-year decoupling period.

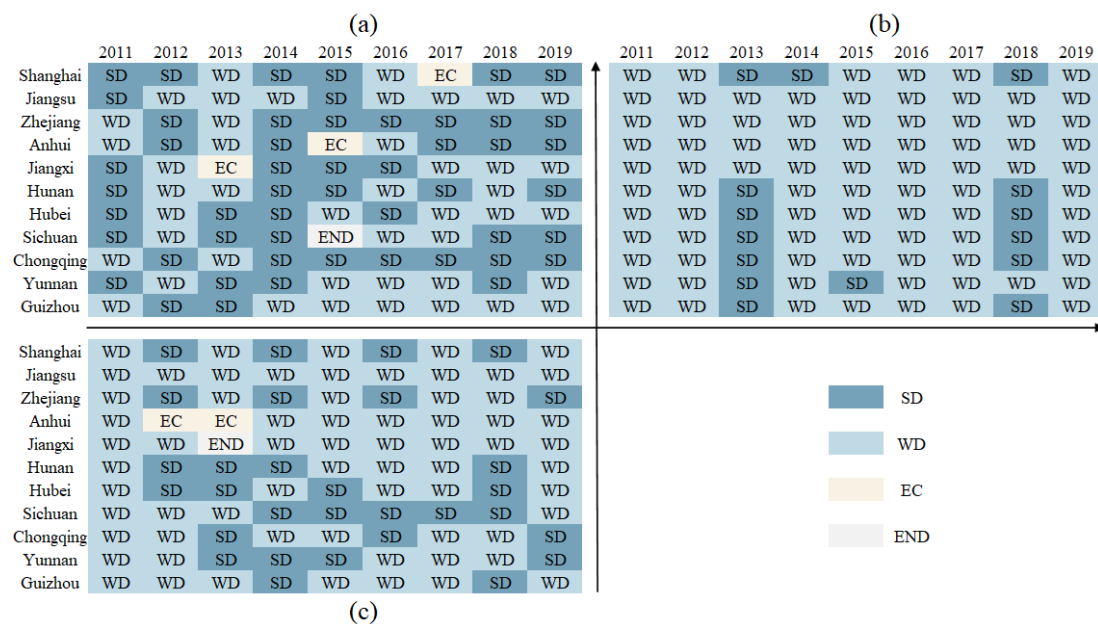


Figure 2. The decoupling relationship between water use (a), energy consumption (b), carbon emissions (c), and economic growth in the YREB from 2011 to 2019. Note: The years shown in the figure represent those in which the non-base years are located.

4.2. Analysis of the Comprehensive Evaluation Index in the WEC System

The entropy weight model was employed to obtain the comprehensive index of water resources (WCI), energy (ECI), and carbon (CCI) subsystems in the YREB from 2010 to 2019 (Figure 3). The WCI (Figure 3a) and ECI (Figure 3b) were relatively concentrated, fluctuating mainly between 0.3 and 0.7, while CCI (Figure 3c) showed more variability with significant regional differences.

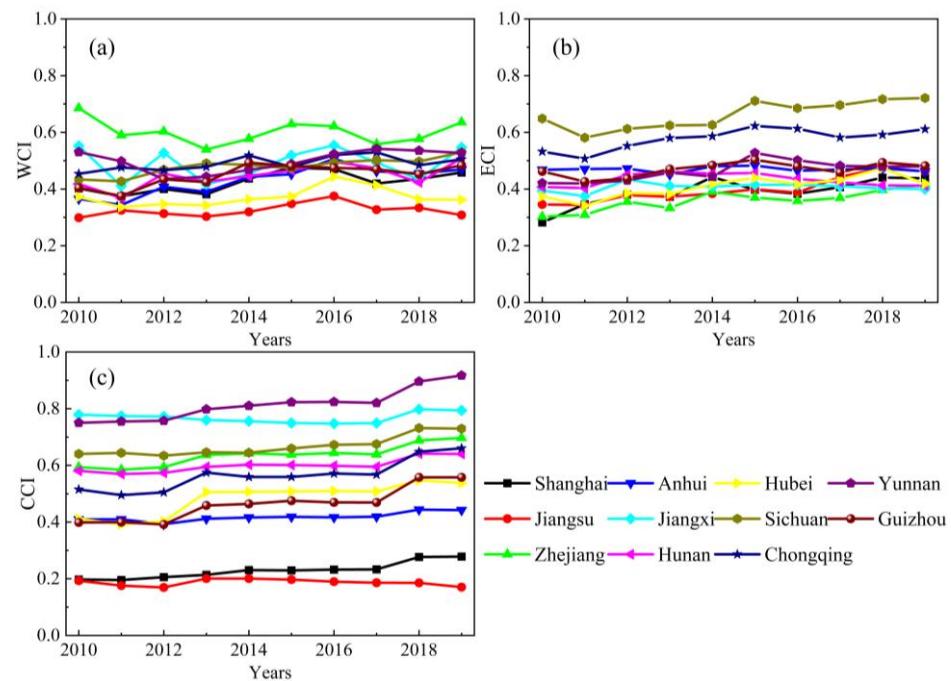


Figure 3. The composite indices of WEC subsystems in the YREB from 2010 to 2019. (a) WCI. (b) ECI. (c) CCI.

In terms of water resources and energy subsystems, it is apparent that there were significant variations in WCI across YREB from 2010 to 2019. The ECI of most regions showed an upward trend, while a few regions exhibited fluctuating ECI values. Specifically, the WCI of Zhejiang had a clear advantage, while the WCI of Jiangsu was always at the bottom of the YREB. The WCI values in other regions were more concentrated, with varying rankings. Sichuan and Chongqing ranked in the top two, respectively, among the YREB in terms of ECI values. The substantial impact of the energy self-sufficiency rate had typically resulted in a decrease in the initial value for ECI in the lower regions of the YREB. However, with advancements in energy structures and utilization efficiency, there has been a consistent increase in the ranking of ECI within regions such as Jiangsu, Shanghai, and Zhejiang. Within the carbon subsystem, it was observed that the CCI for the majority of provinces and municipalities in 2019 showed an increase when compared to that from 2010. This suggests that most regions have been actively working on enhancing their environmental quality while simultaneously growing economically. Between 2010 and 2019, Yunnan consistently exhibited the highest CCI value in most years, with Jiangxi closely trailing. In 2019, the respective CCI values for Yunnan and Jiangxi were 0.92 and 0.79. In contrast, the majority of years witnessed Jiangsu registering the lowest CCI value (0.17), whereas Shanghai recorded a marginally higher one (0.28).

4.3. The Spatiotemporal Characteristic of the WEC System's CCD

The CCD of the WEC system, as calculated using the CCDM in the YREB, exhibited an increase from 2010 to 2019 (Figure 4b). It rose from 0.66 to 0.71, reflecting a growth rate of 7.58%. We noted substantial spatial disparities in the CCD within the YREB. Specifically, the upstream region exhibited a larger CCD compared to the middle reaches, whereas the downstream region displayed the smallest CCD. As illustrated in Figure 4c, the CCD has been increasing in most provinces and municipalities. The coupling coordination relationship (Figure 4a) within the WEC system in the YREB has witnessed significant improvements from 2010 to 2019. These enhancements can be largely attributed to the optimization of the resource environment [35].

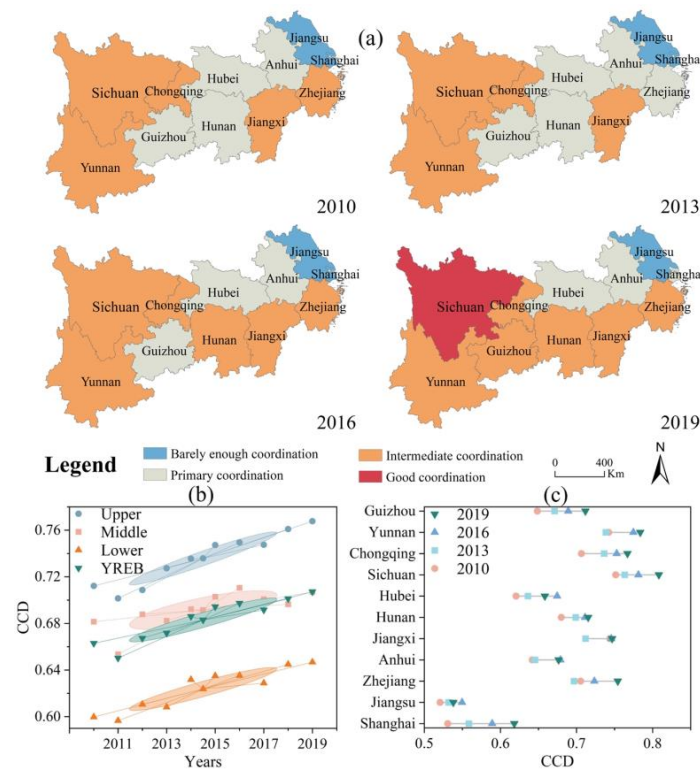


Figure 4. The spatial pattern of the coupling coordination type (a) and CCD (b,c) of the WEC system in the YREB from 2010 to 2019.

In 2010, the CCD of 11 provinces and municipalities was at a low level. Specifically, Sichuan, Jiangxi, and Yunnan exhibited the highest CCD in the YREB, with values of 0.75, 0.74, and 0.74, respectively. Conversely, Jiangsu had the lowest CCD among all provinces and municipalities, measuring at 0.52. The mean value of the CCD decreased from upstream to downstream in the YREB. The CCD increased in all provinces and municipalities in 2013 compared with that in 2010, except for Zhejiang, Jiangxi, and Yunnan. Excluding Zhejiang, the coupling coordination type was consistent across the remaining ten provinces and municipalities. The CCD in Zhejiang exhibited a decrease from 0.71 in 2010 to 0.70 in 2013, signifying a shift from an intermediate type to a primary coordination type. The observed spatial disparities in CCD are consistent with those reported in 2010. In 2016, the CCD of provinces and municipalities experienced a significant increase. Notably, only Hunan experienced a transition from primary to intermediate coordination levels. The mean value of CCD decreased from the upstream to the downstream of the YREB. In 2019, the CCD recorded the peak across provinces and municipalities, except for Hubei, Anhui, and Jiangsu. Compared to 2016, Guizhou has seen an increase in the coupling coordination type by one level, thereby achieving intermediate coordination. Sichuan was the only province where this type of coordination escalated to high levels. Conversely, Jiangsu maintains its worst position among all provinces and municipalities. The spatial pattern of the coupling coordination type mirrored that observed in 2016. The mean CCD value consistently demonstrated a declining trend from upstream to downstream within the YREB.

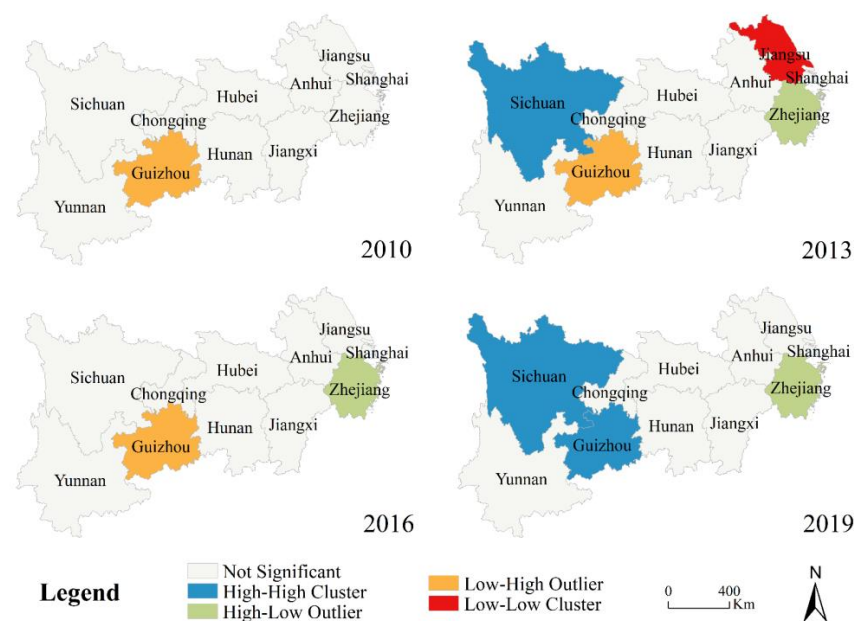
4.4. Spatial Correlation Analysis of the WEC System's CCD

The global Moran's I across all years was calculated by Equation (9), as presented in Table 2. Global Moran's I except for 2011 and 2012 (z-score less than 1.65, p-value more than 0.1) passed the significance test successfully, which indicates that there existed some spatial correlation in CCD in most years. This suggests a robust positive correlation between the WEC subsystems' CCD in the YREB.

Table 2. Global Moran’s I of the WEC systems’ CCD in the YREB from 2010 to 2019.

Years	GI	z-Score	p-Value
2010	0.226	1.682	0.093
2011	0.208	1.572	0.116
2012	0.175	1.422	0.155
2013	0.347	2.336	0.020
2014	0.279	2.061	0.039
2015	0.314	2.201	0.028
2016	0.317	2.220	0.026
2017	0.345	2.356	0.018
2018	0.336	2.334	0.020
2019	0.262	1.948	0.051

To explore the characteristics of local CCD, we calculated local Moran’s I of the CCD of the regional WEC system, as shown in Figure 5. The four clustering methods of the local auto-correlation of CCD in the YREB’s WEC system from 2010 to 2019 were all observed. In 2010, only Guizhou was observed as a cluster, which was a low–high outlier. This indicated that the CCD of Guizhou was significantly lower than other provinces and municipalities with high CCD values. In 2013, four clusters were identified due to the variation in CCD. Sichuan and Guizhou were high–high clusters and low–high outliers, respectively. This indicated that the CCD of provinces and municipalities around Sichuan was relatively high except for Guizhou. Zhejiang and Jiangsu were high–low outliers and low–low clusters, respectively. This indicated that only the CCD of Zhejiang was higher than those of other provinces and municipalities. The clustering results of Guizhou and Zhejiang for 2016 are consistent with those obtained in 2013. In 2019, the CCD of most provinces and municipalities reached its peak. In particular, the CCD of Guizhou transformed the low–high outlier into high–high cluster features from 2016 to 2019. The clustering results of Sichuan and Zhejiang were similar to those obtained in 2013. Over time, the spatial correlation of CCD across various provinces and municipalities has consistently improved. This suggests that regions characterized by high–high clusters and high–low outliers have positively influenced each other through regional cooperation, factor flows, and technology diffusion. Consequently, this has promoted the coordination of the WEC system in adjacent regions.

**Figure 5.** The spatial clustering of CCD in the YREB from 2010 to 2019.

5. Discussion

5.1. Decoupling Analysis between WEC Elements and Economic Growth

Investigating the decoupling between water utilization, energy consumption, carbon emission, and economic development can help water conservation, the enhancement in energy efficiency, and carbon reduction. Although the YREB has made great efforts to achieve sustainable development (Figure 6), we found that the decoupling states were still dominated by WD. Between 2011 and 2019, the WD state represented approximately 50% of decoupling states between water utilization and economic expansion. In terms of decoupling states between energy utilization, carbon emissions, and economic progression, both of them constituted over 65%. This indicated that a considerable inconsistency existed between these three variables in the YREB. With the escalating demands on resources and increasing environmental pressures, the YREB will confront a substantial challenge in achieving a balance between resource utilization, environmental conservation, and economic development. Therefore, regional sustainable development can be realized only by comprehensively considering the interrelationships among the WEC system from a synergy perspective [45,46].

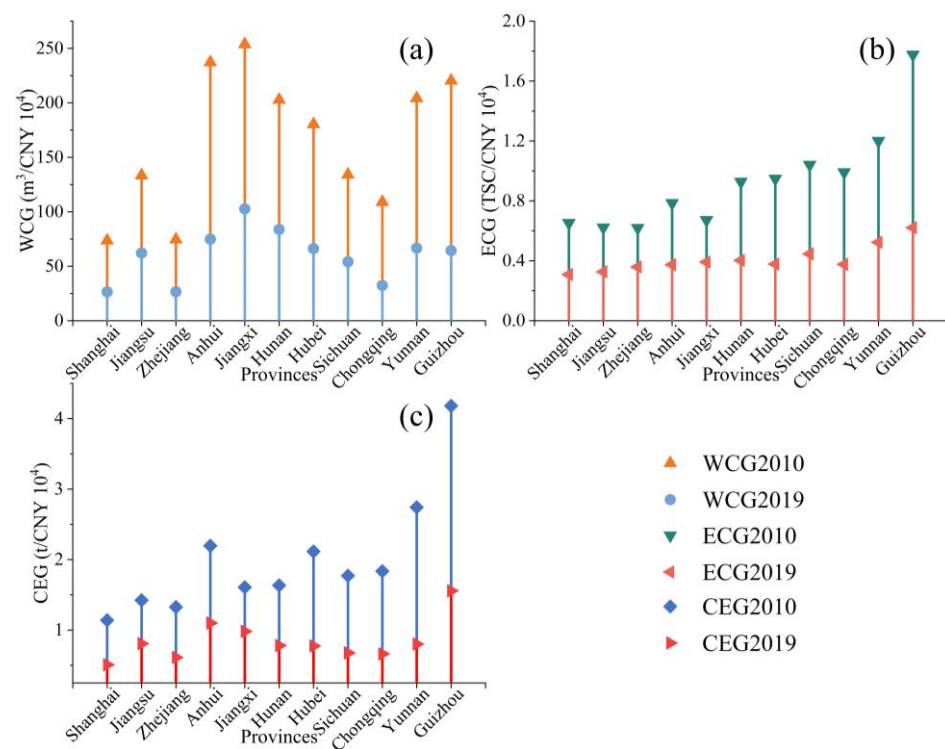


Figure 6. Water utilization, energy consumption, and carbon emission intensity in the YREB, in 2010 and 2019. (a) Water consumption per CNY 10,000 of GDP (WCG); (b) energy consumption per CNY 10,000 of GDP (ECG); (c) carbon emission per CNY 10,000 of GDP (CEG).

5.2. The Drivers of the WEC Subsystem Composite Indices

As depicted in Figure 4 and Figure S6b (refer to Supplementary Materials), the CCD of the WEC system exhibits a negative correlation with the GDP trend in YREB. Combining the empirical results of decoupling three WEC elements from economic growth (Figure 2), economic levels of provinces and cities (Figure S6a), and CCD results (Figure 4c), it can be found that the CCD of provinces and cities is not directly determined by the economic level, but is affected by sustainable development goals and carbon emission constraint policies (Figure 1, Figure 3, Figure 6, and Figure 7 and Table 1). For example, compared with Jiangsu, Zhejiang has more water resources and less water consumption, while Zhejiang has instituted the most rigorous water resource management system and developed

five distinct water treatment plans since 2013, strictly controlling water withdrawal and greatly improving water use efficiency [47]; thus, the WCI of Zhejiang maintained an absolute advantage. Similar to the regional differences in WCI, regions with higher energy self-sufficiency rates and favorable energy consumption structures (such as Sichuan and Chongqing, based on statistical data and measurements) had higher ECI levels (Figure 3b). The rate of forest coverage and the per unit area of the forest stock dominated the CCI (Figure 7c), with Yunnan and Jiangxi, which have low levels of urbanization, ranking in the top two, and Shanghai and Jiangsu, which have high levels of urbanization, ranking in the bottom two (Figure 3c) [48].

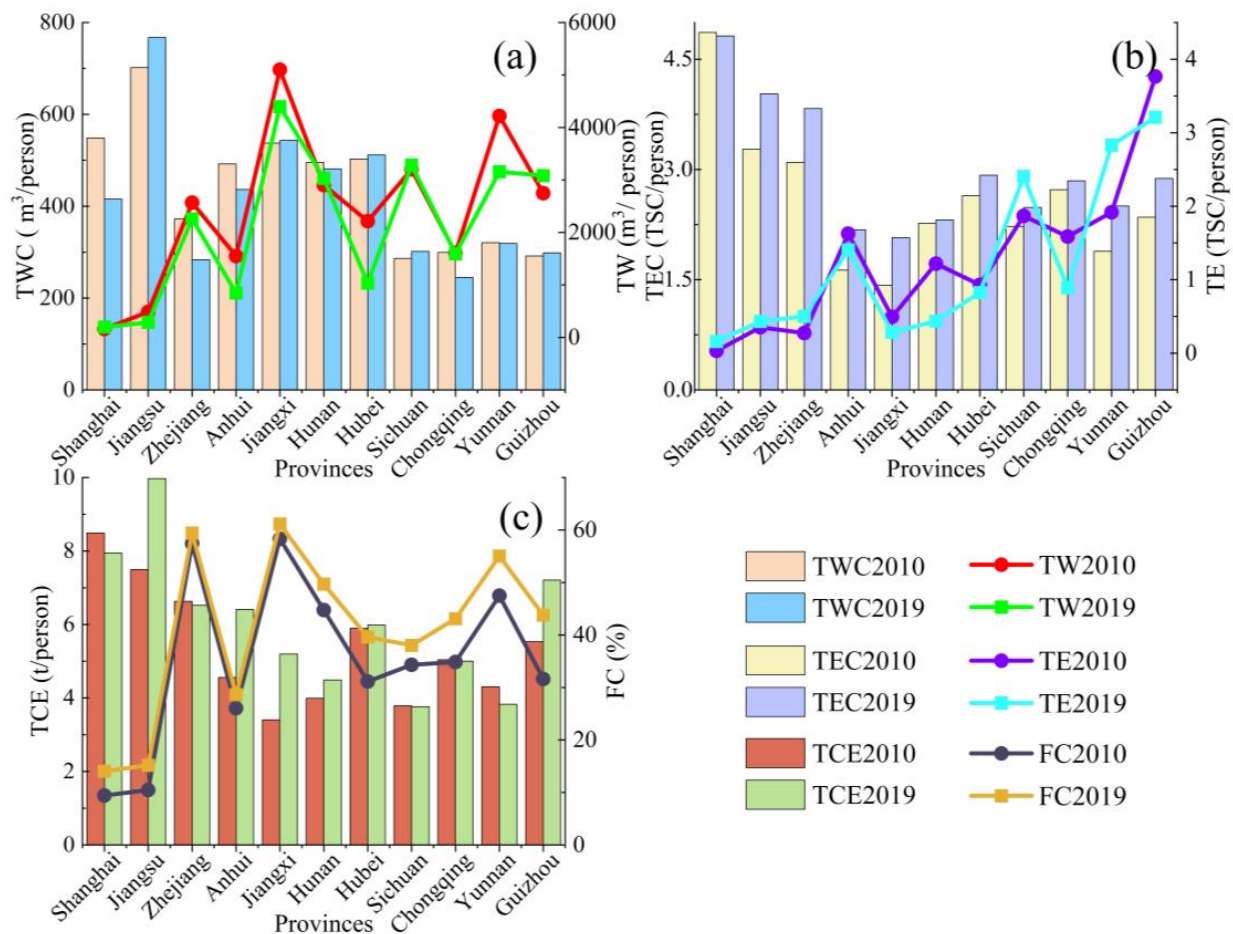


Figure 7. Per capita consumption and possession of water resources, energy, and carbon in YREB from 2010 to 2019. (a) Total water consumption per capita (TWC) and total water resources per capita (TW). (b) Total energy consumption per capita (TEC) and total primary energy production per capita (TE). (c) Total carbon emission per capita (TCE) and percentage of forest cover (FC).

5.3. Driving Mechanism of CCD and Additional Benefits under WEC Synergy

Figure 8 illustrates the driving mechanism of each indicator on the CCD of the WEC system, where X1-X27 has been described in Table 1. As can be seen from Figure 8, the CCD of the WEC system is mainly driven by the comprehensive index of three subsystems: water resources, energy, and carbon (see Equations (8) and (9) for details). Among the subsystems, the security of hydropower resources (contributing 36.5% and 52.1%, respectively), the use structure (contributing 44.9% and 38.4%, respectively), and the function of the carbon sink (contributing 71.0%) are key elements to drive the CCD. These elements are affected by regional resource endowments (such as water resources, energy, and forest resources) and their utilization strategies.

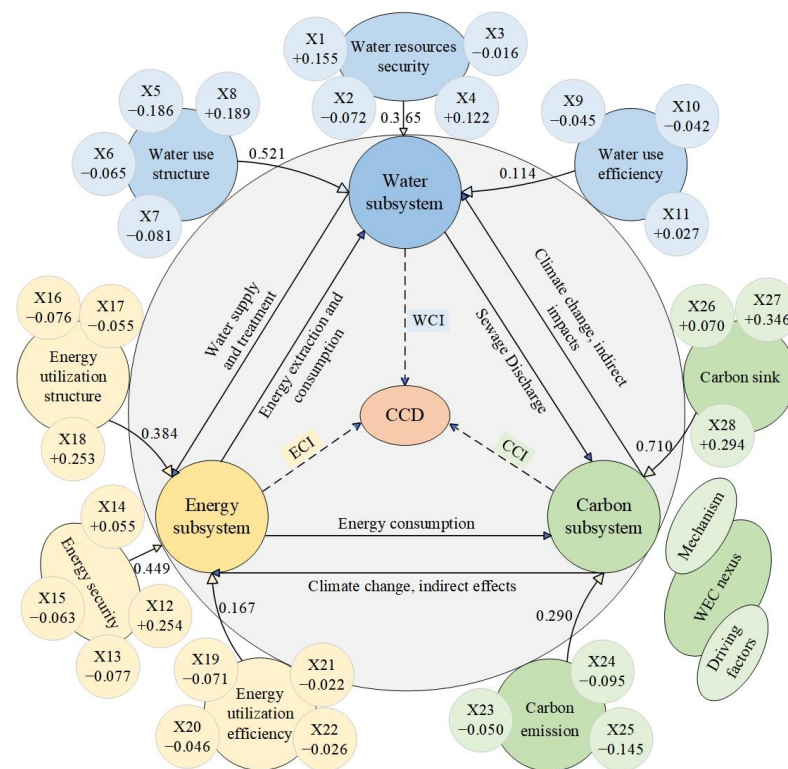


Figure 8. Driving mechanisms of CCD in the WEC system.

However, due to the differences in the geographical location and regional development level, YREB shows significant differences in resource endowments, resource consumption, utilization structure, and environmental pollution degree (see Figure 7, Sections 3.1 and 5.2). This leads to regions with rich resources, superior water–energy utilization structure, and lower development levels having a natural advantage in WEC system CCD. Given that the resource difference and development level caused by the region are difficult to change, the key to improving the WEC system CCD is to optimize water–energy utilization structure, improve resource use efficiency, and enhance carbon sink capacity.

Compared to managing a single element, coordinated management of WEC elements offers additional benefits for the sustainability of resources and the environment. Within the WEC nexus, the entire water resource life including the development, supply, use, and treatment, requires significant amounts of energy [49]. Meanwhile, wastewater discharge produces large quantities of carbon dioxide emissions [50]. Therefore, optimizing the water use structure to reduce overall consumption coupled with advances in wastewater treatment technologies to reduce wastewater discharge can together lead to reductions in both energy consumption and carbon emissions. The entire life cycle of energy, which includes energy production, conversion, treatment, and utilization, necessitates the use of water resources. This process generates a significant amount of wastewater and contributes to the release of carbon dioxide [24]. Therefore, the development of renewable energy and the enhancement in energy consumption efficiency throughout the life cycle can reduce water consumption and carbon emissions. Climate change, which is attributed to elevated levels of carbon emissions, intensifies the occurrence of natural disasters such as heat waves [6], floods [51], and droughts [52]. However, the increasing frequency of natural disasters presents a substantial threat to water resources, energy infrastructures, and economic progress. These events, such as ice cap melting, sea level elevation, floods, and droughts, profoundly affect the water resource system and hinder economic growth [53]. Conversely, natural disasters such as hurricanes and heat waves can cause significant damage to infrastructure, including energy and electricity systems, thereby increasing the risk of energy insecurity and causing economic losses [54]. However, improvements in

energy infrastructure and advancements in wastewater treatment technologies can reduce additional carbon emissions. This, in turn, reduces the frequency of natural disasters caused by climate change. Simultaneously, these improvements increase water resource availability, enhance energy system security, and promote economic growth.

5.4. Comparison with Existing Studies

In this study, we explored the decoupling relationship between WEC elements and economic development. Then, an integrative indicator system of the WEC system across YREB was established, which enabled us to investigate the spatiotemporal dynamics of the WEC system's CCD at the provincial scale. Compared with existing studies [25,26,39] that have calculated the WEC system's CCD, this paper mainly differs in the following: (1) A WEC system framework for assessing sustainability is proposed. (2) This paper formulated a composite indicator system for the WEC system, considering the SDGs, dual carbon targets, and dual control policy of carbon emissions. (3) We have proposed a driving mechanism for CCD in the WEC systems. These distinctions fill knowledge gaps in the study of WEC relationships from a synergistic perspective, providing a foundation for the synergistic management of the WEC system and economies.

5.5. Characteristics and Applicability of the Framework in This Paper

This study constructs a framework of the WECE system and takes YREB as a case for an empirical analysis. The framework shows significant advantages and high adaptability in achieving regional sustainable development goals, thereby confirming its important value in guiding the optimal allocation of regional resources and promoting coordinated development of the environment and economy. The framework exhibits the following characteristics:

(1) The method not only focuses on the coordinated development of regional resources and environmental systems but also comprehensively evaluates sustainability by integrating internal and external factors, fully taking into account the needs of regional economic development. This framework organically integrates the resource–environment system with the regional economy, overcoming the limitations of traditional methods that only focus on coordination within the system and ignore the needs of economic development. It takes multiple factors such as resources, environment, economy, and society into consideration, providing comprehensive, balanced, and sustainable guidance for regional development, which is conducive to achieving harmonious coexistence between the economy and environment.

(2) This framework establishes an index system for the WEC system by integrating the main SDGs with the National Resource Environment Strategy. The system combines both international advanced concepts and China's unique national conditions and developmental needs, thereby ensuring its scientific validity and practical applicability. As a result, it provides an effective tool for assessing and guiding regional sustainable development.

(3) The framework proposed in this paper has a wide range of applicability to evaluate the resource and environment policies and targets of different countries or regions in WEC. Based on the framework, both indicators that are consistent with SDGs can be retained, and other indicators can be flexibly adjusted to adapt to local resource and environment policies, constructing a WEC system indicator system that conforms to local reality. This customization ensures that the framework can provide targeted policy recommendations for various regions and effectively support their sustainable development of resources and the environment.

6. Conclusions, Policy Recommendations, and Research Limitations

6.1. Conclusions

This paper proposes a framework of the water–energy–carbon–economy system applicable to different countries or regions, aiming at evaluating the sustainable development of regional resources and the environment, and conducts an empirical analysis of the Yangtze

River Economic Belt based on the framework. The findings indicated that the Yangtze River Economic Belt has not yet attained a comprehensive decoupling of water use, energy consumption, carbon emissions, and economic development. Instead, there was a predominant trend towards weak decoupling. The water–energy–carbon system in the Yangtze River Economic Belt showed coordination from 2010 to 2019, and only the water–energy–carbon system in Sichuan exhibited good coordination in 2019. The coupling coordination degree of the water–energy–carbon system was correlated with regional economic levels, but its intrinsic driving force comes from water and energy resource security, water and energy resource utilization structures, and carbon sinks. On this basis, we proposed a driving mechanism for the coupling coordination degree of the water–energy–carbon system. This provides a theoretical foundation for the coordinated administration of the water–energy–carbon system. In addition, we found that water–energy–carbon co-governance will yield additional benefits to both the water–energy–carbon system and economic development. Consequently, a coordinated approach to the management of the water–energy–carbon system is imperative for achieving sustainable development of both resources and the environment.

6.2. Policy Recommendations

Drawing upon the aforementioned analysis, we put forth several recommendations for the sustainable development of resources and the environment within the YREB, and more broadly, in China.

- (1) In regions with abundant water resources, it is essential to develop water-saving and wastewater treatment technologies throughout the energy life cycle. This strategy will promote efficiency in water resource utilization. Due to the large proportion of agricultural water use in total water consumption, reducing agricultural water use or improving its efficiency in water-scarce regions will contribute to reducing pollution and carbon emissions. In addition, wastewater treatment technologies in the energy life cycle process should also be developed to improve the resilience of the water resource system.
- (2) In regions with abundant energy resources, it is crucial to prioritize the promotion of energy efficiency and the development of energy conversion technologies throughout the entire life cycle of water utilization. For regions with limited energy, it is crucial to reduce the proportion of coal and oil use, increase the proportion of natural gas use, and enhance the efficiency of sustainable energy use, such as solar, hydrogen, wind, etc., and the progression of energy conversion technologies throughout the life cycle of water use.
- (3) For forest resource-rich and undeveloped areas, local governments should prioritize economic development and introduce advanced carbon reduction technologies to reduce carbon emissions. Local governments should prioritize the development of carbon reduction technologies for forest resource-rich and developed areas. It is necessary to increase carbon sinks through afforestation for regions with scarce forest resources and simultaneously balance economic development and environmental protection.

6.3. Research Limitations

Although there has been some progress regarding the regional WECE nexus in this paper, certain limitations should be addressed.

- (1) Data accessibility issues, such as the absence of evaluative metrics for agricultural water use efficiency, constrain the selection of indicators. This limitation hampers the ability of the WEC subsystem to incorporate a broader range of factors. Addressing this gap in indicators will significantly enhance the evaluation of the WEC system.
- (2) Given that various normalization techniques can influence the computation of index weights, employing different normalization methods on raw data may result in discrepancies in the CCD.

- (3) Though the driving mechanism that can also aid in proposing effective management strategies for the WEC system's CCD based on the identified driving mechanisms has been identified, the factors influencing it have not yet been quantified. Further exploration could quantify the specific contribution rate of each factor to the CCD.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en17133143/s1>, Figure S1: Flowchart; Figure S2: The YREB geographical location; Figure S3: A schematic diagram of the WEC indicator system construction criterion; Figure S4: Decoupling types; Figure S5: The types of coupling coordination; Figure S6: GDP of YREB, 2010–2019.

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