

Article

Is the Economy, Environment and Energy (3E) System Sustainable?—An Analysis of the Coordination Degree of Carbon Decoupling and Energy Equity in the Yangtze River Economic Belt

Chun Fu ^{1,2}, Chuanyong Luo ^{1,2,*}  and Yezhong Liu ³

¹ School of Public Policy and Administration, Nanchang University, Nanchang 330031, China

² Jiangxi Provincial Institute of Regional Economy, Nanchang University, Nanchang 330031, China

³ School of Infrastructure Engineering, Nanchang University, Nanchang 330031, China

* Correspondence: lcyong2019@outlook.com

Abstract: As the climate crisis intensifies, the low-carbon transition seems to be the necessary path to maintain the sustainability of the 3E system. However, does it no longer pose potential threats to sustainability? In the context of the low-carbon transition, this study reveals hidden worries about the sustainability of the 3E system from an energy equity perspective, specifically focusing on the coordination between carbon decoupling and energy equity. This study innovatively calculates the level of carbon decoupling and energy equity in China's Yangtze River Economic Belt from 2008 to 2019 and explores the degree of coordinated development between carbon decoupling and energy equity by employing the coupling coordination model and bivariate local Moran index. The results show the following: (1) from 2008 to 2019, the energy equity in the Yangtze River Economic Belt showed steady improvement, but the overall level was still not high, being below 0.5; (2) the upstream and downstream regions showed more obvious resistance in maintaining the coordinated development of carbon decoupling and energy equity, but there are structural differences among them; (3) inter-basin differences were an important feature of the low-carbon economy and equitable energy development in the Yangtze River Economic Belt in the past. This study provides policy implications and research insights for promoting the sustainability of the 3E system in transition countries from an energy equity perspective.

Keywords: low-carbon economy; energy transition; energy equity; coupling coordination degree



Citation: Fu, C.; Luo, C.; Liu, Y. Is the Economy, Environment and Energy (3E) System Sustainable?—An Analysis of the Coordination Degree of Carbon Decoupling and Energy Equity in the Yangtze River Economic Belt. *Sustainability* **2024**, *16*, 5817. <https://doi.org/10.3390/su16135817>

Received: 11 June 2024

Revised: 5 July 2024

Accepted: 5 July 2024

Published: 8 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Under the threat of the greenhouse effect, the development of low-carbon energy has become a common path for countries to promote energy transition. However, can a low-carbon approach truly eliminate concerns about the sustainability of the 3E system? In reality, when countries implement energy transition policies for carbon reduction, they inevitably face the difficult problem of balancing goals: energy security, energy equity and environmental sustainability. In 2022, the World Energy Council released the Energy Trilemma Index report, which evaluated energy security, energy equity, environmental sustainability and national contexts [1]. This energy trilemma reflects the balanced challenges that countries encounter in addressing energy supply-chain security, energy acceptability and low-carbon emissions. It also highlights the potential threats to the sustainability of the 3E system under the low-carbon transition, which may expose vulnerabilities related to energy poverty and energy equity. Nevertheless, compared to energy poverty, the issue of energy fairness resulting from decarbonization is often overlooked by policymakers due to its hidden and gradual nature, which could potentially cause irreversible damage to the sustainability of the 3E system. In 2017, driven by the promotion of clean heating

policies, the Beijing–Tianjin–Hebei region launched the “coal-to-gas” project. However, due to overly radical plans, some residents encountered insufficient gas supplies. Consequently, the Ministry of Environmental Protection temporarily suspended the policy in December 2017. Despite this setback, local governments are still grappling with increasing environmental pressures, and the “coal to gas” project has a faint trend of expanding to rural areas [2].

In 2020, the Chinese government put forward the “3060” dual-carbon target to encourage the development of clean energy and promote clean production, aiming to reduce carbon emissions and improve the energy structure, but there are disputes among scholars about the impact of clean production on energy equity. Many scholars have affirmed the role of renewable energy in promoting energy diversification and the low-carbon energy transition, which has a positive impact on energy equity. Through the case study of Nepal, Shakya et al. found that the long-term net-zero emission strategy has good co-benefits for reducing air pollutant emissions and enhancing energy security and equity [3]. Ying et al. established a differentiated carbon pricing scheme based on the principle of cost equity, and found that the scheme was conducive to promoting carbon equity and reducing carbon emissions [4]. However, some scholars also expressed concerns that cleaner production would lead to a series of negative issues for energy equity, such as the affordability of renewable energy, carbon transfer, green plunder, etc. [5,6]. Monyei et al. contended that incorporating more renewable energy into the grid in Germany, California and Australia did not necessarily result in cheaper electricity prices or improved energy equity. In fact, it may even have led to energy poverty for vulnerable groups [7]. Johnson et al. believed that when marginal groups were not fully considered in low-carbon energy transition decision-making, the existing unequal energy structure might become more permanent [8]. Emilien et al. studied the impact of France’s low-carbon strategy on social equity and found that targeting architectural revamps and electric vehicles at the largest energy consumers can minimize carbon emissions but increase inequality [9]. Therefore, whether China’s current low-carbon energy transition process can bring the coupling of carbon emission reduction and energy equity, or how to weaken their possible trade-off relationship, is of great research significance.

The World Energy Council provides an accounting system for energy equity and environmental sustainability. Energy equity is evaluated by factors such as the proportion of the population with electricity access, electricity prices and gasoline prices [10], which strongly promotes research on world energy equity. Based on the 2018 Energy Trilemma Index (abbreviated as “ETI”) data, Majed et al. applied the fuzzy TOPSIS method to study the energy efficiency of various countries in the world [11]. However, some scholars still question the rationality of the evaluation of energy equity and believe that the definition of energy equity is too narrow, which leads to the phenomenon of biased evaluation. Polona et al. applied Pearson correlation analysis and a Kronbach’s alpha test to argue that the energy trilemma cannot be considered reliable without comprehensive improvements [12]. Abidah made an in-depth analysis of the impact of Indonesia’s energy transition policies on energy equity and found that the policies focused narrowly on distributional equity in energy accessibility and affordability, ignoring procedural equity and recognition equity in energy justice [13]. Lara and Kirsten pointed out that the fairness of energy policy is often easily simplified to energy poverty or affordability, causing a disconnect between the concepts of energy justice in academic literature and practice [14]. It can be seen that the cost–benefit analysis of energy has become the focus of current research on energy equity, while other energy equity issues, such as risk exposure and energy democratization, have been ignored [15,16]. Hence, it is necessary to further explore a more comprehensive assessment of energy equity based on the ETI.

Since China’s accession to the WTO in the 21st century, it has not only become the second largest economy in the world, but also achieved remarkable results in its energy security construction, which is supported by abundant energy security studies [17,18]. In stark contrast, energy equity has not received sufficient attention from practical activities

and academic research. Local governments pay more attention to carbon efficiency in the decision-making of energy transitions, thus ignoring carbon inequality [19]. In addition, the current research on energy equity in China is in the stage of theoretical exploration, focusing on the qualitative analysis of energy equity through system definition, problem analysis, system guarantee and so on. Zhang and Xiong interpreted China's rural energy justice from the perspective of multiple values and analyzed four dimensions of rural energy justice: distributive justice, procedural justice, corrective justice, and social justice [20]. Shi et al. believed that although new energy vehicles technically used cleaner energy, their vigorous development may lead to a series of equity issues: international equity, domestic equity, intergenerational equity and ecological equity [21]. In order to safeguard energy justice in the process of energy transition, Ning and Yang explored the legal mechanisms of energy transition from multiple approaches, such as livelihood guarantees, procedural guarantees and justice restoration [22].

Although some scholars have empirically analyzed the coordination of China's 3E system and established a system framework for the coordinated development of the 3E system, they have paid less attention to the sustainability of the 3E system from the perspective of equity and justice. Yu and Gong evaluated the energy system from the dimensions of energy production and consumption and empirically estimated the coupling coordination of economy, energy, environment and technology in Northeast China. They found that the coupling degree basically maintained steady growth in Northeast China [23]. It can be seen that on the one hand, China's current energy system evaluation pays more attention to efficiency, such as the economic and environmental benefits of energy transition, but ignores fairness issues. On the other hand, many studies focus on the positive effects of low-carbon transition on the 3E system, while the negative effects of the low-carbon transition process lack consideration. Based on Chinese provincial panel data, this study estimates the coupling coordination degree between carbon decoupling and energy fairness during the energy transition process, and it reveals threats to the sustainability of the 3E system in the Yangtze River Economic Belt from the perspective of energy equity, aiming to fill the current research gap through a study coupling equity and efficiency. This study provides policy implications for the coordinated development of low-carbon economy and energy equity and helps to maintain energy justice and the 3E system's sustainability in the process of energy transition.

The marginal contribution of this study is as follows: (1) utilizing the energy trilemma index as a reference, the evaluation system of energy equity is reconstructed, and the evaluation method of regional energy equity in China is perfected; (2) it innovatively reveals the threat to the sustainability of China's 3E system from the perspective of energy equity, filling the empirical research gaps on the negative impact of low-carbon transition; (3) it provides policy implications for maintaining energy justice and sustainability of the 3E system in the process of China's energy transition.

2. Theoretical Analysis and Research Area

2.1. Equity and Efficiency Coupling

A multitude of studies have explored how to develop regional economy sustainably while maximizing carbon emission reduction [24,25]. These studies essentially analyze the coupling between economic performance and carbon emission reduction. Nevertheless, if energy equity is ignored, these coupling realization paths with efficiency as the core may cause damage to people's energy consumption. In other words, sacrificing the energy rights and interests of vulnerable groups may become a negative effect of low-carbon transition policies. Consequently, from the perspective of maintaining social welfare and the 3E system's sustainability, it is of significant practical importance to analyze the coupling relationship between a low-carbon economy and energy equity.

Although there are some academic controversies regarding the relationship between green energy and energy justice, this study theoretically analyzes the coupling relationship between a low-carbon economy and energy equity, taking carbon intensity as an interme-

diary factor and drawing on scenario analysis methods [26–28]. As depicted in Figure 1, assuming a positive linear relationship between energy equity and carbon intensity, carbon intensity is represented as the ratio of carbon emissions to GDP. The carbon-energy baseline indicates that when regions rely on resource consumption to pursue economic growth, energy equity and carbon intensity tend to maintain steady growth. With the constraints of environmental regulation and energy transition, the carbon-energy baseline shifts left to the low-carbon energy line, and carbon intensity decreases when energy equity is ensured (direction: the arrow “a”). Therefore, theoretically, developing countries can transition from a high-emission carbon-energy baseline to a low-carbon energy line, but the external environmental drivers need to be continuously strengthened.

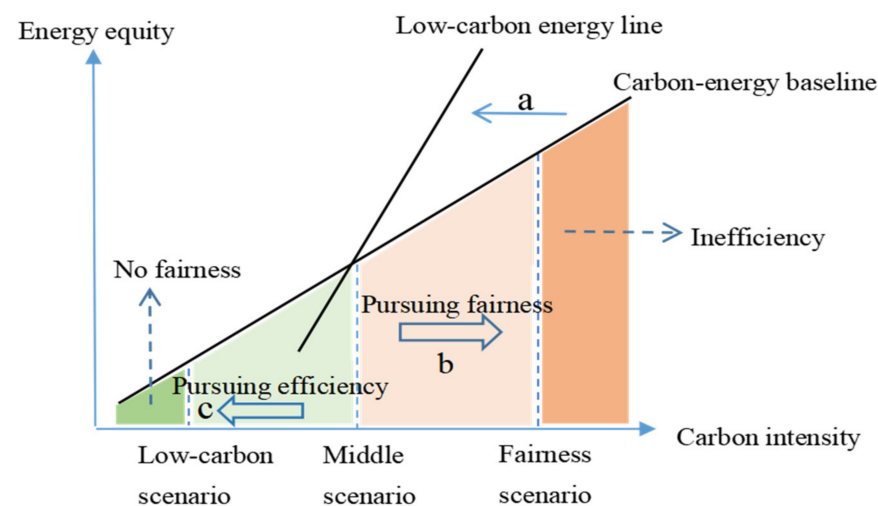


Figure 1. Coupling relationship between a low-carbon economy and energy equity.

Through a scenario analysis of the carbon-energy baseline, the coupling relationship between the low-carbon economy and energy equity is illustrated. When the carbon intensity of the regional economy is higher than the carbon emission level in the energy scenario of the fair state, it indicates that the energy supply and consumption in the region fully meet the demands of economic development and stimulate the rapid growth of the regional economy. However, the high carbon intensity of emissions leads to the inefficient or ineffective transition of the low-carbon economy, and the decoupling between the low-carbon economy and energy equity is serious (direction: the arrow “b”). When the carbon intensity of the regional economy is lower than the carbon emission level in the low-carbon scenario of the efficiency state, it indicates that although the regional economy has achieved the maximum promotion of a low-carbon economy, the carbon intensity of excessively low emissions will reduce energy equity (direction: the arrow “c”). At this time, the low-carbon economy and energy equity are still seriously decoupled. This model of low-carbon economic development without energy equity will also become unsustainable [29]. Assuming that the carbon intensity of the regional economy is in the middle scenario of the baseline, it indicates that energy justice is ensured as far as possible on the basis of promoting the development of a low-carbon economy, and a moderate balance between efficiency and fairness is achieved. In this case, a low-carbon economy and energy equity exhibit a high degree of coupling.

2.2. Study Area

In September 2016, China issued the Outline of the Development Plan for the Yangtze River Economic Belt, establishing a new development pattern based on the golden waterway of the Yangtze River. The Yangtze River Economic Belt covers 11 provinces (97°21′ E–123°10′ E, 21°08′ N–35°08′ N), accounting for more than 40% of the country’s population and GDP. It is a major national strategic development area, as detailed in Figure 2.

According to the ninth national inventory of forest resources, the forest coverage rate of the Yangtze River Economic Belt reached 44.4 percent in 2020, 21.4 percentage points higher than the national average. According to the China Water Resources Bulletin, the total water resources in the Yangtze River basin in 2020 were 1286.293 billion cubic meters, accounting for about 40.7% of the national total. It can be seen that the Yangtze River Economic Belt has the top forest resources and water resources in China, and can play a key role in the development of forest carbon sinks and renewable energy. Furthermore, based on the official statistics, the total carbon emissions of the Yangtze River Economic Belt in 2019 amounted to 402.367 million tons, with coal consumption reaching 975.17 million tons and oil consumption totaling 202.87 million tons. Therefore, the study of the coupling relationship between low-carbon economy and energy equity in the high-consumption Yangtze River Economic Belt is of great practical significance for China's future economic transition and energy welfare safeguarding.

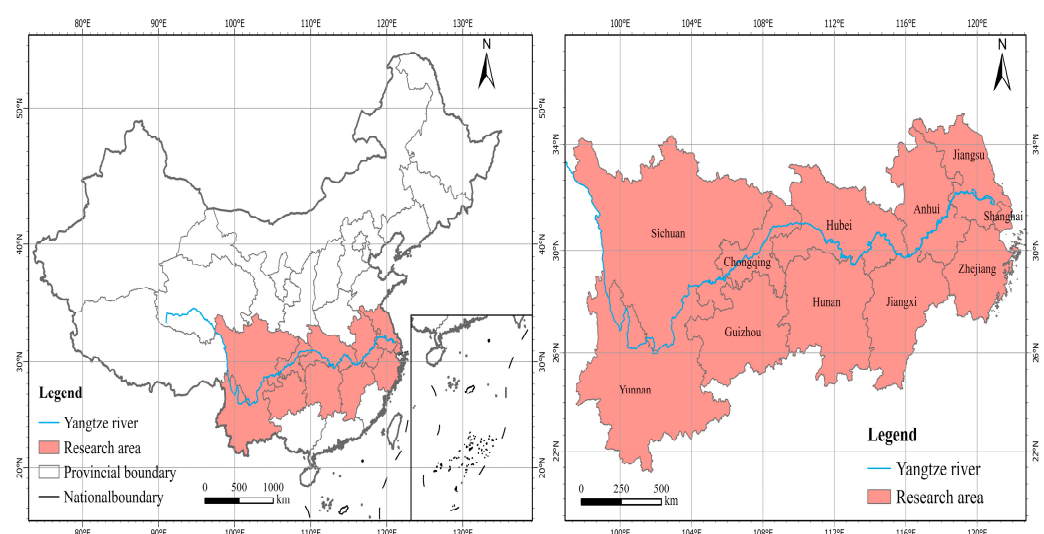


Figure 2. Study area: the Yangtze River Economic Belt.

3. Data and Methodology

3.1. Calculation Method of Carbon Decoupling with Economic Growth

Studies have shown that economic growth and the greenhouse effect seem to go hand in hand, and economic growth even has a direct stimulating effect on the greenhouse effect [30,31]. In the history of the modernization process, many countries have experienced a process of double growth in gross social product and carbon emissions, especially in developing countries during periods of rapid economic growth. However, with the constraint of environmental carrying capacity, the extensive pattern of economic growth began to be abandoned, and many countries turned to developing sustainable economies. With the increasingly serious greenhouse effect, many scholars and policymakers, driven by the concept of green economic growth, have paid attention to the low-carbon economy. To explore how to promote the development of a low-carbon economy, it is necessary to first analyze the dynamic change relationship between the current regional or industrial gross product and carbon emissions and identify the change trend of the two. This can be achieved by using the decoupling model to measure the spatial-temporal accompanying characteristics of economic growth and carbon emissions and to explore the inflection point of economic growth and carbon decoupling.

The decoupling model was first measured by the OECD for the blocking relationship between economic growth and environmental pressure. In recent years, many scholars have used the decoupling model constructed by Tapio to study the decoupling relationship between resource utilization, economic growth and carbon emissions. In addition, they used the LDMI model to decompose the driving factors promoting decoupling [32–34]. In

this study, the improved two-stage rolling Tapio method is used to calculate the carbon decoupling index of provinces in the Yangtze River Economic Belt to reflect the development level of the low-carbon economy in the Yangtze River Economic Belt. The construction formula is as follows:

$$e_{lon} = \frac{\Delta CE / CE_0}{\Delta GDP / GDP_0} \quad (1)$$

$$e_{sho} = \frac{\Delta CE / CE_i}{\Delta GDP / GDP_i} \quad (2)$$

In Equation (1), e_{lon} is the long-term carbon decoupling index, ΔCE is the change amount of regional carbon emissions in a certain period, CE_0 represents the carbon emissions in 2007 as the base period, ΔGDP is the change amount of regional gross domestic product in a certain period, GDP_0 is the regional gross domestic product in 2007, as the base period. In Equation (2), e_{sho} is the short-term carbon decoupling index, which reflects the short-term change in carbon decoupling level in the Yangtze River Economic Belt. CE_i is the carbon emissions with of year i as the base period, and GDP_i is the regional gross domestic product with year i as the base period. In this decoupling model, the following specific conditions were adopted: (1) in order to eliminate the price factor, the real GDP was calculated based on 2007; (2) e_{lon} adopted the fixed base period of 2007, and e_{sho} adopted the rolling base period divided into stages; (3) the decoupling state was divided into 8 categories; (4) the elastic form ensures that the index is not affected by the changes in the index dimension during the calculation process.

Drawing on the decoupling theory, Table 1 describes three types of decoupling between carbon emissions and the gross domestic product: linkage, decoupling, and negative decoupling. The linkage state reflects the synchronous changes in both. Under the concept of developing a low-carbon economy, the decoupling status is ranked and evaluated based on the changes in carbon emissions and gross domestic product, as well as the decoupling index. The most ideal state is strong decoupling, and the worst decoupling situation is strong negative decoupling. Because developing a low-carbon economy does not require a trade-off between environmental pressure and economic growth, this study temporarily puts recession decoupling and expansion negative decoupling at the same level.

Table 1. Types of decoupling between carbon emissions and GDP.

Decoupling Types	Decoupling State	ΔCE	ΔGDP	Decoupling Index (e)	Decoupling Rank
Coupling	Expanding coupling	+	+	[0.8,1.2)	3
	Declining coupling	−	−	[0.8,1.2)	5
Decoupling	Strong decoupling	−	+	(−∞,0)	1
	Weak decoupling	+	+	[0,0.8)	2
	Recessionary decoupling	−	−	[1.2,+∞)	4
Negative decoupling	Strong negative decoupling	+	−	(−∞,0)	7
	Weak negative decoupling	−	−	[0,0.8)	6
	Expanding negative decoupling	+	+	[1.2,+∞)	4

Figure 3 delineates the temporal evolution of the carbon decoupling index within the Yangtze River Economic Belt spanning the years 2008 to 2019. The empirical findings reveal an ascendant trajectory of the carbon decoupling index from 2008 to 2011, escalating from 0.348 to 0.655, with a mean annual growth rate of 7.68%. This suggests that the Yangtze River Economic Belt transitioned into a state of weak decoupling between economic advancement and carbon emissions, congruent with the flourishing phase of China's rapid economic growth during that period. Conversely, the period from 2012 to 2015 witnessed a descending trend in the carbon decoupling index, plummeting from 0.559 to 0.271, accompanied by an average annual decrement of 6.64%. During this phase, the increment in carbon emissions within the Yangtze River Economic Belt exhibited a significant downturn, thereby optimizing the overall carbon decoupling level, which was potentially attributable

to advancements in technological capabilities and the implementation of environmental regulations. The interval from 2016 to 2019 saw the carbon decoupling index maintain relative stability with a marginal decline, bottoming out at 0.242 in 2019. This implies that the comprehensive development of the Yangtze River Economic Belt is inclining towards strong decoupling, but it is still within the realm of weak decoupling, so there is still greater pressure for carbon emission reduction in the Yangtze River Economic Belt.

Carbon Decoupling

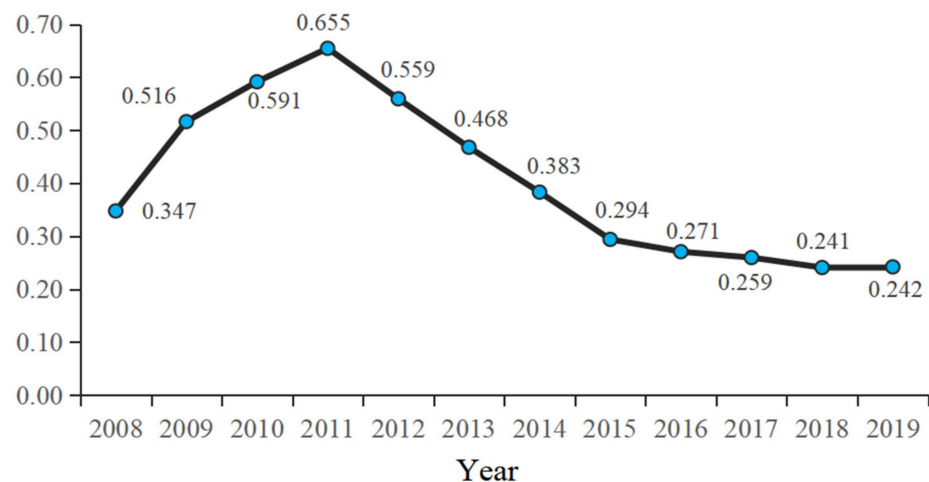


Figure 3. Long-term changes in the carbon decoupling index of the Yangtze River Economic Belt from 2008 to 2019.

According to the conventional division of the upper, middle and lower reaches of the Yangtze River, the Yangtze River Economic Belt can be divided into three regional circles: the Chengdu-Chongqing economic zone in the upper reaches, urban agglomeration in the middle reaches and the Yangtze River Delta region in the lower reaches. In order to present the regional differences within the Yangtze River Economic Belt in more detail, Equation (2) is used to calculate the short-term change in carbon decoupling among provinces. Table 2 describes the carbon decoupling levels of 11 provinces in the Yangtze River Economic Belt from 2008 to 2019. Although most provinces showed weak decoupling between economic growth and carbon emissions during the study period, there were still some regional differences in the change trend. In the Yangtze River Delta region in the lower reaches, Anhui Province had the largest change in carbon decoupling, and carbon emission reduction also achieved obvious effects, upgrading from an expansionary negative decoupling level to a weak decoupling level. Shanghai has consistently been at the forefront of achieving a strong decoupling between economic growth and carbon emissions within the Yangtze River Delta region. As to the midstream urban agglomeration with Wuhan as the core, Jiangxi Province's carbon decoupling level is the most stable, fluctuating around 0.4 as a whole. This stability is closely related to the local metallurgy, coal, construction and other high-consumption industrial structures. With regard to the upstream Chengdu–Chongqing economic zone across the source of the Yangtze River, the carbon decoupling indexes of Chongqing, Sichuan and Yunnan have been declining continuously in recent years, reaching the lowest level of 0.091, becoming the ideal state closest to strong decoupling in the Yangtze River Economic Belt, which may be related to the limited local industrial transfer and the good ecological environment of carbon sinks, such as rich forests, lakes and other carbon sink resources. In summary, from the perspective of the economic development level and carbon emission reduction effectiveness, the lower Yangtze River Delta region is more efficient in its low-carbon economy than other regions, and Jiangxi Province in the middle reaches urgently needs to find a carbon emission reduction path by optimizing its own industrial structure.

Table 2. Short-term changes in the carbon decoupling index of provinces in the Yangtze River Economic Belt from 2008 to 2019.

Year Province	ΔCE	ΔGDP	2008–2011 e	Decoupling	ΔCE	ΔGDP	2012–2015 e	Decoupling
Shanghai	+	+	0.422	Weak decoupling	+	+	−0.055	Strong decoupling
Jiangsu	+	+	0.456	Weak decoupling	+	+	0.246	Weak decoupling
Zhejiang	+	+	0.349	Weak decoupling	+	+	−0.111	Strong decoupling
Anhui	+	+	1.187	Expanding negative	+	+	0.655	Weak decoupling
Jiangxi	+	+	0.507	Weak decoupling	+	+	0.361	Weak decoupling
Hubei	+	+	0.384	Weak decoupling	+	+	−0.437	Strong decoupling
Hunan	+	+	0.228	Weak decoupling	+	+	−0.237	Strong decoupling
Chongqing	+	+	0.693	Weak decoupling	+	+	0.378	Weak decoupling
Sichuan	+	+	0.647	Weak decoupling	+	+	0.390	Weak decoupling
Guizhou	+	+	0.453	Weak decoupling	+	+	0.527	Weak decoupling
Yunnan	+	+	0.477	Weak decoupling	+	+	0.250	Strong decoupling

Year Province	ΔCE	ΔGDP	2015–2019 e	Decoupling
Shanghai	+	+	0.040	Weak decoupling
Jiangsu	+	+	0.266	Weak decoupling
Zhejiang	+	+	0.010	Weak decoupling
Anhui	+	+	0.203	Weak decoupling
Jiangxi	+	+	0.291	Weak decoupling
Hubei	+	+	0.184	Weak decoupling
Hunan	+	+	0.248	Weak decoupling
Chongqing	+	+	0.160	Weak decoupling
Sichuan	+	+	0.106	Weak decoupling
Guizhou	+	+	0.314	Weak decoupling
Yunnan	+	+	0.091	Weak decoupling

3.2. Evaluation Method of Energy Equity

Traditional energy difficulty research focuses on the supply side of energy, and measures the degree of energy difficulty in a region through the evaluation of energy availability, affordability and cleanliness [35]. The energy difficulty evaluation can reflect the energy shortage problem of a region well, but there are, inevitably, two defects: First, the evaluation focuses on the energy supply side, but in reality, energy supply often relies on the external transfer of energy, so energy difficulty evaluation based on the local supply side is prone to producing large errors. Second, energy difficulties hardly reflect regional differences in equal access to energy opportunities and rights. In fact, under the premise of controlling energy carbon emissions, the problem of energy difficulties may be alleviated to a certain extent because whether through developing clean energy or restricting the exploitation of fossil energy, local energy reserves will be more abundant. However, neglecting this aspect brings threats to the equal access to energy rights for different groups or regions, that is, energy equity. Therefore, research on energy equity should be paid more and more attention to, and it is no longer limited to the energy supply side as the core, but focuses on narrowing the differences in equal access to energy opportunities between different groups or regions.

Quantitative research on energy equity is a complex system, whether viewed from the perspective of different income groups or regions. Although there are few measurement studies on energy equity at present, there are many research results on medical equity issues, such as measurement models of spatial accessibility and affordability of medical resources [36,37]. Nevertheless, compared with the medical equity problem, energy equity has a more complex resource allocation problem, which is caused by more frequent energy mobility and more diversified consumer entities. Therefore, when considering the energy supply side, energy equity often involves more than local energy resources. To sum up, in order to more accurately estimate the energy equity in the Yangtze River Economic Belt and to deal with the particularity of energy resources, this study adopts the two-stage Theil index method to construct an evaluation model. First of all, based on the energy consumption demand, this study designs three sub-systems of input, process and outcome to estimate the basic value of energy fairness, so as to comprehensively evaluate the opportunity and cost of energy acquisition for residents and enterprises. Second, using the Theil index method to measure the energy equity Theil value, this study explores the

regional differences in energy equity within the Yangtze River Economic Belt and identifies the main sources affecting energy equity.

Table 3 lists all the evaluation indicators of the basic value of energy equity, and Table 4 elaborates on the necessary explanations for each indicator. As shown in Table 3, energy input mainly revolves around the availability of the energy supply side, specifically utilizing the actual reserves of raw coal, crude oil, natural gas and primary electricity available for local consumption. It is worth noting that the actual energy reserves here include the external input of energy and exclude the external output of energy, aiming to fully consider the high fluidity of energy in the calculation process. In the energy consumption process, there are differences between energy-using objects and energy-consuming carriers. This study mainly considers the energy consumption of residents' living needs and the production energy consumption of enterprises. Due to the availability of data, this study selects cars, air conditioners, water heaters and microwave ovens as representative residential energy-consuming devices. It also selects the output value of the secondary industry and environmental pollution control to measure the energy consumption process of industrial enterprises, mainly focusing on the production energy consumption of industry and the pollution control generated by the energy consumption process. The energy results mainly revolve around the affordability and sustainability of the energy demand, respectively, measured by the energy consumption of residents and per-capita electricity expenditure, as well as the clean energy and carbon emission intensity of the region. In order to reduce the interference of price factors, some indicators in Table 4 use the actual GDP calculated based on the 2007 base period, using a more stable basic electricity price to calculate the living electricity expenditure.

Table 3. Evaluation index system of the basic value of energy equity.

Primary Indicators	Secondary Indicators	Tertiary Indicators	Index Attribute	
Input	Availability	Raw coal	+	
		Crude oil	+	
		Natural gas	+	
		Primary electricity	+	
Process	Energy-consuming equipment	The number of household cars per hundred households	+	
		The number of air conditioners per hundred households	+	
		The number of water heaters per hundred households	+	
		The number of microwave ovens per hundred households	+	
	Pollution control	The output value of the secondary industry	+	
		The proportion of environmental pollution control to GDP	+	
		The comprehensive utilization rate of industrial solid waste	+	
	Result	Affordability	The proportion of urban per-capita living electricity expenditure to income	—
			Per-capita energy consumption	+
Sustainability		Per-capita electricity consumption	+	
		Energy structure cleanliness	+	
		Energy consumption intensity of GDP	—	
		Carbon emission intensity	—	

Table 4. Description of evaluation indicators.

Tertiary Indicators	Description of Indicators
Raw coal	Actual coal reserves available for local consumption (in ten thousand tons)
Crude oil	Actual oil reserves available for local consumption (in ten thousand tons)
Natural gas	Actual natural gas reserves available for local consumption (in 100 million cubic meters)
Primary electricity	Actual primary electricity reserves available for local consumption (in 100 million kilowatt-hours)
The number of household cars per hundred households	The annual number of cars in urban households
The number of air conditioners per hundred households	The annual number of air conditioners in urban households
The number of water heaters per hundred households	The annual number of water heaters in urban households
The number of microwave ovens per hundred households	The annual number of microwave ovens in urban households
The output value of the secondary industry	(100 million yuan)
The proportion of environmental pollution control to GDP	The total investment in environmental pollution control divided by the actual GDP (%)
The comprehensive utilization rate of industrial solid waste	(%)
The proportion of urban per-capita living electricity expenditure to income	The ratio of per-capita living electricity expenditure of urban residents to per-capita income (%)
Per-capita energy consumption	Energy consumption divided by population (%)
Per-capita electricity consumption	Electricity consumption divided by population (%)
Energy structure cleanliness	Proportion of coal consumption (%)
Energy consumption intensity of GDP	Energy consumption divided by real GDP (%)
Carbon emission intensity	Carbon emissions divided by real GDP (%)

In order to calculate the base value of energy equity, it is necessary to determine the weight of each indicator. This study uses the entropy method of the objective weighting method to measure the weight of the index. Specifically, the entropy method and linear weighting function method are used to measure the basic value of energy fairness, and the corresponding weight level is determined objectively according to the information contained in the index, which provides the basis for the multi-index evaluation system. The specific calculation formula is as follows:

$$X'_{ij} = \frac{X_{ij} - X_{\min}}{X_{\max} - X_{\min}} \quad (3)$$

$$X''_{ij} = \frac{X_{\max} - X_{ij}}{X_{\max} - X_{\min}} \quad (4)$$

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^n \frac{X_{ij}}{\sum_{i=1}^n X_{ij}} \ln \frac{X_{ij}}{\sum_{i=1}^n X_{ij}} \quad (5)$$

$$w_j = \frac{1 - e_j}{\sum_{i=1}^n (1 - e_j)} \quad (6)$$

$$enf_{it} = \sum_{j=1}^n w_j \times \frac{X_{ij}}{\sum_{i=1}^n X_{ij}} \quad (7)$$

Among them, X'_{ij} is the dimensionless index matrix, e_j refers to the entropy value of the j -th index, w_j is the index weight determined by information entropy, and enf_{it} is the basic value of energy equity in the t year of region i . Equations (3) and (4) normalize the initial index values in positive and negative directions, respectively.

The basic value of energy equity calculated by the entropy method can better reflect the right of equal access to energy in a certain region, but it is difficult to show the regional differences in energy equity and the reasons affecting inter-regional energy equity in detail,

so it is necessary to further calculate the Theil value of energy equity. With the discovery and improvement of calculation methods, economic research on equity has expanded from the qualitative to the quantitative level and achieved rich results, such as the application of the Gini coefficient and the Theil index in the fields of medical equity and resource allocation, among which the Theil index has been favored by many scholars in reflecting regional differences in the equity of resource allocation. This study constructs the Theil value of energy equity based on the Theil index principle, aiming to reflect the development differences in energy equity between regions. Specific practices: 11 provinces in the Yangtze River Economic Belt are divided into three regional groups: upstream, middle and downstream. The Theil value is used to analyze the changes in the overall gap of energy equity level in the Yangtze River Economic Belt, as well as the gaps between and within the upper, middle and lower three regions. This further describes the unfairness of energy rights among regions. The relevant calculation formula is as follows:

$$T_{enf} = T_{br} + T_{wr} \quad (8)$$

$$T_{br} = \sum_{k=1}^K y_k \ln \frac{y_k * n}{n_k} \quad (9)$$

$$T_{wr} = \sum_{k=1}^K y_k \left(\sum_{j \in g_k} \frac{y_j}{y_k} \ln \frac{y_j * n_k}{y_k} \right) \quad (10)$$

Among these, T_{enf} is the Theil value of energy equity, T_{br} and T_{wr} are inter-group differences and intra-group differences, respectively. y_k represents the proportion of the energy equity level of group k in the total energy equity level of the Yangtze River Economic Belt, n_k is the number of Group k provinces. g_k is the group, y_j is the proportion of the energy equity level of province j in the total energy equity level of the Yangtze River Economic Belt. Through calculating T_{br} and T_{wr} , the internal and inter-regional disparities of energy equity in each region of the Yangtze River Economic Belt can be estimated, which helps to further reflect the unfairness of energy access rights.

3.3. Coordination Model Design

Low-carbon energy is an important booster for the development of a low-carbon economy, but the blind and disorderly expansion of low-carbon energy transition makes it easy to undermine energy equity, especially in low- and middle-income countries, where such low-carbon traps are more likely to occur. Therefore, for the coordinated development of a low-carbon economy and energy equity, this study will focus on analyzing the coordination of carbon decoupling and energy equity. After sorting out and analyzing the research results of the coordination degree evaluation, it was found that there are various methods for the measurement of coordination degree, such as correlation analysis, decoupling analysis, coupling coordination degree model, etc. After repeatedly comparing the advantages and disadvantages of each method and combining the characteristics of this study, it was decided to adopt the coupling coordination degree evaluation model [38,39].

To calculate the coupling coordination degree of carbon decoupling and energy equity in the Yangtze River Economic Belt, three steps are required. First, the direct coupling degree C value of each system should be computed. Second, the comprehensive coordination index T value of each system should be calculated. Finally, the coupling coordination degree D value could be evaluated according to the C and T values. The specific calculation formula is as follows:

$$C = \left\{ \frac{E(x) \times W(y)}{\left(\frac{E(x) + W(y)}{2} \right)^2} \right\}^{\frac{1}{2}} \quad (11)$$

$$T = a'E(x) + b'W(y) \quad (12)$$

$$D = \sqrt{C \times T} \quad (13)$$

Among these, $E(x)$ is the carbon decoupling level of negative normalization treatment, $W(y)$ is the Theil value of energy fairness, a' and b' are weights. According to the coupling coordination degree value obtained, the coordination degree level of the low-carbon economy and energy equity can be assessed. At present, there is a relatively mature basis for this assessment, and the coordination level is divided into ten categories, as shown in Table 5. In this research, the coordination degree of carbon decoupling and energy equity is divided into three coordination stages, namely, the stage of imbalance decline, transition and coordinated development. The coordination degree is also subdivided into 10 coordination types according to the coordination level. Among them, near coordination and barely coordination are at the medium coordination level, which belongs to the transitional stage.

Table 5. Evaluation criteria for the coordination degree of carbon decoupling and energy equity.

Coordination Stage	Recessionary Imbalance Stage				Transition Stage	
Coordination type	Extreme imbalance	Severe imbalance	Moderate imbalance	Mild imbalance	Near coordination	Reluctant coordination
Coordination level	[0, 0.1)	[0.1, 0.2)	[0.2, 0.3)	[0.3, 0.4)	[0.4, 0.5)	[0.5, 0.6)
Coordination stage	Coordinated development stage					
Coordination type	Primary coordination		Intermediate coordination		Good coordination	Excellent coordination
Coordination level	[0.6, 0.7)		[0.7, 0.8)		[0.8, 0.9)	[0.9, 1]

3.4. Bivariate Local Moran Index

The bivariate local Moran index can measure the direction and strength of the correlation between two variables in the spatial distribution. As for carbon decoupling and energy equity, the bivariate local Moreland index can reveal the agglomeration and differentiation of the two within provincial spaces. This is helpful for analyzing the provincial synergy of carbon decoupling and energy equity, as well as verifying the accuracy of the results of the coordination degree model. The specific calculation formula is as follows:

$$I_{ce} = \frac{Z_c^i - \bar{Z}_c}{S_c^2} \sum_{j=1, j \neq i}^n W_{ij} \frac{Z_e^i - \bar{Z}_e}{S_e^2} \quad (14)$$

In Equation (14), I_{ce} is the bivariate local Moran index, Z_c^i and Z_e^i are the observed values of carbon decoupling and energy equity in provinces, respectively, $\bar{Z}_c$ and $\bar{Z}_e$ are the mean values of carbon decoupling and energy equity, respectively, W_{ij} is the spatial weight matrix, S_c^2 and S_e^2 are the variance of carbon decoupling and energy equity, respectively.

In summary, this study reveals the threats to the sustainability of the 3E system in the Yangtze River Economic Belt from the perspective of energy equity. First, it employs the decoupling model, the entropy method, and the Theil index to comprehensively evaluate development changes in carbon decoupling and energy fairness. Subsequently, it analyzes the limitations of coordinating carbon decoupling and energy equity using a coupled coordination model and bivariate local Moran index. Figure 4 provides a detailed presentation of the purpose and application process of this study's methodology.

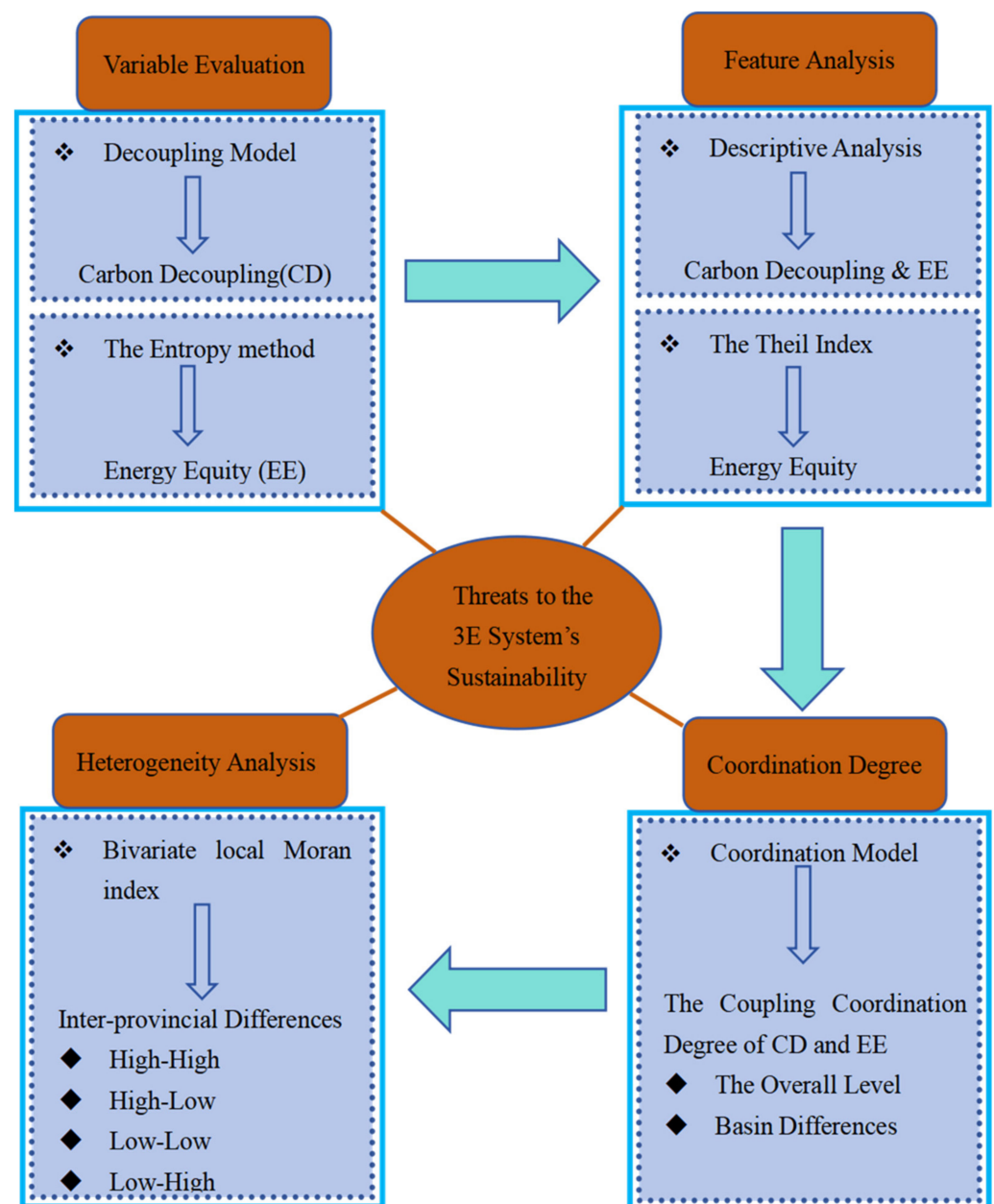


Figure 4. The methods' roadmap.

3.5. Data Sources

To avoid the interference of the novel coronavirus epidemic on the data of socio-economic activities, panel data from 11 provinces in China from 2008 to 2019 were selected for this study. The data come from provincial and municipal statistical yearbooks, the China Environmental Statistical Yearbook, the China Energy Statistical Yearbook, the China Urban Statistical Yearbook, and the Ecological Environment Statistical Annual Report, which are official statistical data sources. The raw data can be downloaded from <https://data.cnki.net/> (accessed on 1 January 2024). As for missing data on individual index years, the interpolation method commonly utilized in academia is used to supplement the original data.

4. Empirical Analysis Results

4.1. Energy Equity Evaluation

After the positive and negative normalization processes, the index data eliminated the dimension influence, and Equation (6) of the entropy method was used to determine the objective weight of the energy equity evaluation index, and then the comprehensive score of the basic value of energy equity was calculated. Table 6 shows the specific weights for each indicator of energy equity.

Table 6. Weight of evaluation index of energy equity basic value.

Primary Indicators	Tertiary Indicators	Indicator Symbol	Weight
Input	Raw coal	X1	0.09
	Crude oil	X2	0.07
	Natural gas	X3	0.05
	Primary electricity	X4	0.03
Process	The number of household cars per hundred households	Y1	0.07
	The number of air conditioners per hundred households	Y2	0.11
	The number of water heaters per hundred households	Y3	0.02
	The number of microwave ovens per hundred households	Y4	0.07
	The output value of the secondary industry	Y5	0.11
	The proportion of environmental pollution control to GDP	Y6	0.08
	The comprehensive utilization rate of industrial solid waste	Y7	0.04
Result	The proportion of urban per-capita living electricity expenditure to income	Z1	0.02
	Per-capita energy consumption	Z2	0.07
	Per-capita electricity consumption	Z3	0.08
	Energy structure cleanliness	Z4	0.04
	Energy consumption intensity of GDP	Z5	0.02
	Carbon emission intensity	Z6	0.01

Based on the measurement of index weights, the evaluation scores of three subsystems of energy equity in 11 provinces along the Yangtze River Economic Belt were calculated according to Equation (7). The development level of each subsystem is directly related to the level of coordinated development of carbon decoupling and energy equity. Figure 5 reflects the temporal changes in the overall level of energy equity in the Yangtze River Economic Belt from 2008 to 2019. As can be seen from Figure 5, the overall level of energy equity in the Yangtze River Economic Belt shows a steady upward trend, rising from 0.277 to 0.426, with a growth rate of 53.9%. It indicates that the equity of regional energy consumption in the Yangtze River Economic Belt has been greatly improved in recent years, which has enhanced the energy consumption standards for residents and enterprises. In terms of growth rate, the growth rate of the early period (2008–2011) and the later period (2016–2019) was relatively fast. According to the characteristics of the data structure, with the increase in energy consumption at the industrial end and the development of clean energy, the level of energy equity in these periods jumped significantly. Despite the remarkable achievements in the past, the energy equity index levels of the Yangtze River Economic Belt are all lower than 0.5, and the overall level still has great room for improvement, which is mainly related to the regional industrial structure and energy structure.

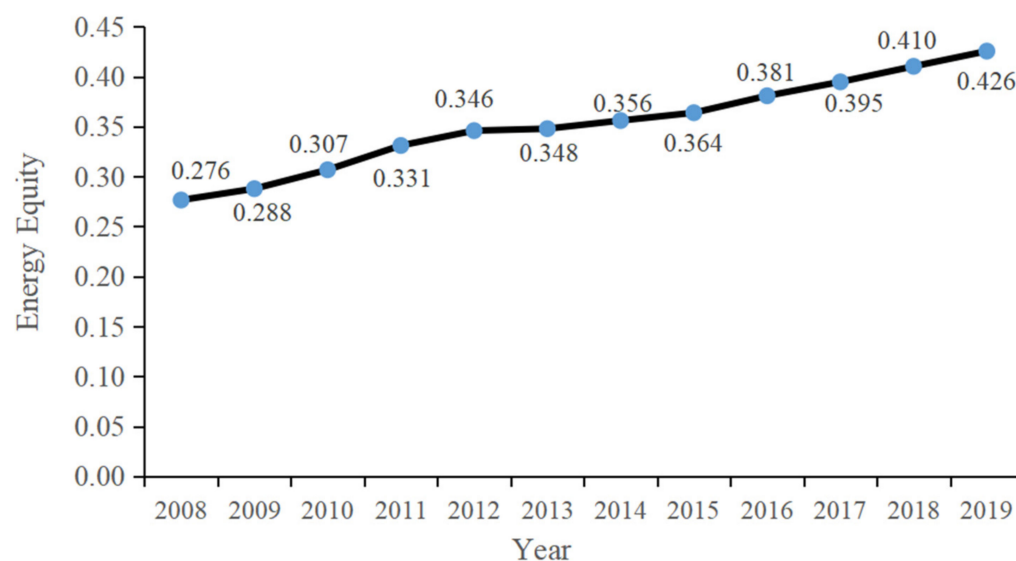


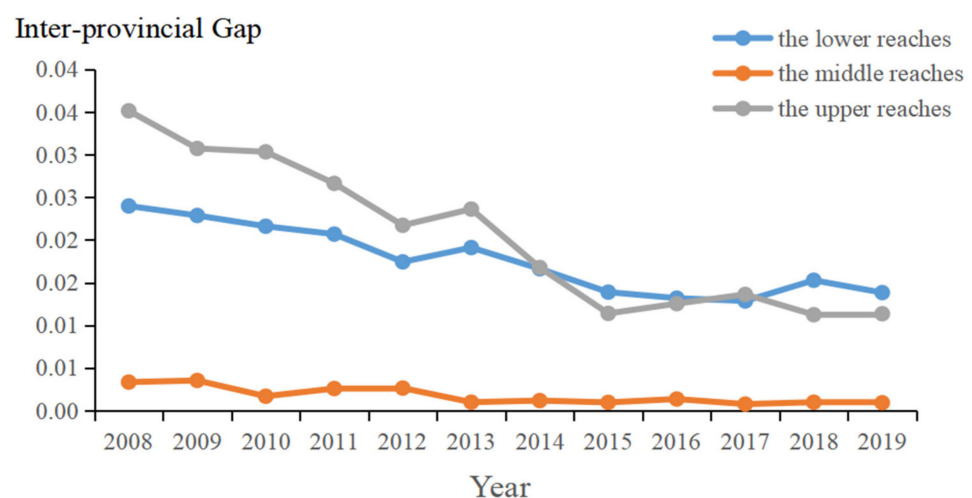
Figure 5. Temporal changes of energy equity in the Yangtze River Economic Belt from 2008 to 2019.

In order to further analyze the regional differences in energy equity in the Yangtze River Economic Belt, this study uses the Theil index to analyze the overall gap in the energy equity index in the Yangtze River Economic Belt and the gap between the upper, middle and lower reaches, as well as within the basin. Table 7 shows the calculation results of the energy equity Theil value and the intra-group and inter-group Theil index of the Yangtze River Economic Belt from 2008 to 2019. Due to space limitations in the table and the statistical custom, the numerical results were rounded to three decimal places, without affecting the comparisons. The calculations involved used actual values (Table 8 follows the same practice). As shown in Table 6, the overall gap in energy equity shows a fluctuating downward trend, from 0.057 to 0.029, a decrease of 48.59%. Specifically, from 2008 to 2011, the energy equity Theil value decreased significantly, indicating that the regional gap in energy equity in the Yangtze River Economic Belt was narrowing during this period. From 2012 to 2014, the energy equity Theil value fluctuated downward, and the gap widened further in 2013, indicating that there were factors that threatened the stability of energy equity in the Yangtze River Economic Belt during this period. From 2015 to 2019, the energy equity Theil value showed a slight downward trend, indicating that the overall gap in energy equity in the Yangtze River Economic Belt tended to be stable. From the perspective of regional difference evolution trends, both the inter-group and intra-group Theil indices show a similar downward trend to the overall level, indicating that there were long-term energy equity gaps both between and within the upper, middle and lower reaches, and these gaps were gradually narrowing. In addition, the intra-group difference decreased from 0.023 to 0.010, a decrease of 55.11%, which exceeded the change in the inter-group difference. From the perspective of the difference contribution rate, the inter-group difference in the energy equity Theil value was significantly larger than the intra-group difference, and the inter-group difference was the main source of the overall difference, with an average contribution rate of 64.44%. This indicates that narrowing the inter-group difference and coordinating the overall management were the keys to promoting the regional spatial balance of energy consumption in the Yangtze River Economic Belt.

Table 7. Analysis of regional differences in energy equity in the Yangtze River Economic Belt from 2008 to 2019.

Year	Theil Value	Inter-Group Difference	Contribution Rate	Intra-Group Difference	Contribution Rate
2008	0.057	0.034	60.50%	0.023	39.50%
2009	0.051	0.031	59.65%	0.021	40.35%
2010	0.049	0.029	59.84%	0.020	40.16%
2011	0.045	0.027	59.47%	0.018	40.53%
2012	0.041	0.026	63.27%	0.015	36.73%
2013	0.044	0.028	63.52%	0.016	36.48%
2014	0.042	0.029	68.57%	0.013	31.43%
2015	0.036	0.027	72.44%	0.010	27.56%
2016	0.036	0.026	71.74%	0.010	28.26%
2017	0.036	0.025	71.19%	0.010	28.81%
2018	0.032	0.021	66.52%	0.011	33.48%
2019	0.029	0.019	65.91%	0.010	34.09%

According to the above analysis, the energy equity gap between the basins in the Yangtze River Economic Belt is an important source of the energy equity, so it is necessary to analyze the regional difference in energy equity in each basin. Figure 6 describes the changes in the energy equity gap between the provinces in the upper, middle and lower reaches of the Yangtze River Economic Belt from 2008 to 2019. As can be seen from Figure 6, the inter-provincial energy equity gap in the upper and lower reaches showed a significant downward trend from 2008 to 2019, while the gap level in the middle reaches tended to be more stable and remained the lowest among the three major basins. This indicates that the energy equity gap in the upper and lower reaches had the greatest impact on the Yangtze River Economic Belt, and the energy equity gap in the middle reaches was relatively small. In comparison, the energy equity gap in the upstream region exceeded that in the economically developed downstream region before 2015, with a maximum value of 0.035, but since 2015, the energy equity gap in the downstream region showed a slight upward trend and exceeded that in the upstream region. This could be attributed to the energy economy in the Yangtze River Delta region widening the imbalance in the downstream region. The strong economic capacity and convenient energy conditions of the former can provide more solid support for energy consumption in comparison with other regions. Therefore, from the perspective of basin heterogeneity, the energy equity gap in the upper and lower reaches of the Yangtze River Economic Belt should be particularly concerning to policy-makers and scholars.

**Figure 6.** Change in the inter-provincial gap in the upper, middle and lower reaches of the Yangtze River Economic Belt from 2008 to 2019.

4.2. Estimation of Coordination Degree

In order to guard against the threat of low-carbon economic development to energy fairness, the further examination of the coordination level of carbon decoupling and energy fairness is essential. Based on the calculation of carbon decoupling and energy equity in the Yangtze River Economic Belt, combined with Equations (10)–(12), the coupling coordination degree of carbon decoupling and energy equity was estimated. Table 8 reflects the coordinated development degree of carbon decoupling and energy fairness in the Yangtze River Economic Belt from 2008 to 2019, and Figure 4 describes the trend in the coordinated development of carbon decoupling and energy fairness.

Table 8. Level of coordination between carbon decoupling and energy fairness in the Yangtze River Economic Belt from 2008 to 2019.

Year	Degree of Coordination (D Value)	Coordination Type
2008	0.707	Intermediate coordination
2009	0.577	Reluctant coordination
2010	0.483	Near coordination
2011	0.331	Mild imbalance
2012	0.545	Reluctant coordination
2013	0.649	Primary coordination
2014	0.721	Intermediate coordination
2015	0.782	Intermediate coordination
2016	0.803	Good coordination
2017	0.816	Good coordination
2018	0.833	Good coordination
2019	0.839	Good coordination

Combining the results of Table 8 and Figure 7, the coordinated development of carbon decoupling and energy equity in the Yangtze River Economic Belt can be roughly divided into three stages:

- (1) From 2008 to 2011, the Yangtze River Economic Belt as a whole experienced a phase of recession and imbalance, declining from intermediate coordination to mild discordance. The main reason for this change was the rapid prosperity of China's economy during this period, when increasing carbon emissions deviated from the development track of the low-carbon economy, resulting in the discordant development of carbon decoupling and energy equity.
- (2) From 2012 to 2015, the Yangtze River Economic Belt as a whole experienced a phase of coordinated improvement, rising from near coordination to a level of coordinated development. This stage shows that the Yangtze River Economic Belt quickly departed from the previous mode of economic development, which came at the expense of the environment and energy. Instead, it paid more attention to curbing the high carbon emissions of traditional industries. It actively developed clean energy, such as hydroelectricity and solar energy, while maintaining a high regional economic growth rate.
- (3) From 2016 to 2019, the Yangtze River Economic Belt as a whole experienced a stable phase of coordinated development and reached the highest level of good coordination in history. This stage suggests that the Yangtze River Economic Belt as a whole maintained a balance between the low-carbon economy and energy fairness and gradually improved the coordination between the two. Although the entire Yangtze River basin did not fall into the high-consumption traditional economic development mode during this period, it revealed to some extent the challenges in promoting the coordinated development of the low-carbon economy and energy fairness.

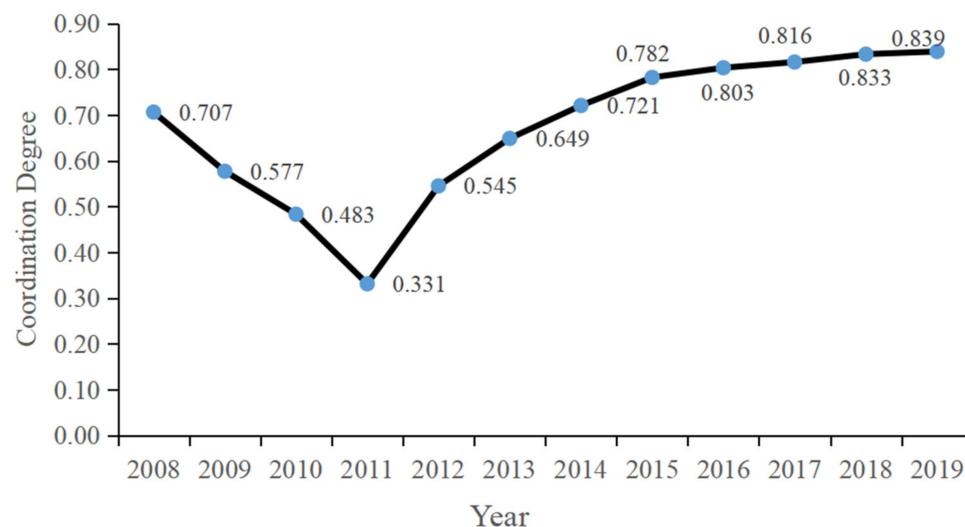


Figure 7. Trend of coupled coordinated development of carbon decoupling and energy fairness from 2008 to 2019.

In summary, the trend of coordinated development of carbon decoupling and energy equity in the Yangtze River Economic Belt from 2008 to 2019 presents a nearly “V” shape. Past efforts strove to establish a good pattern of coordinated development in the 3E system, but currently face the era problem of how to explore and guide the new power of coordinated development in the low-carbon economy and energy fairness.

As can be seen from Figure 6, there is a significant inter-provincial gap in energy fairness in the Yangtze River Economic Belt, so it is necessary to further analyze the heterogeneity of the coupling coordination of carbon decoupling and energy fairness. Figure 8 describes the trend of changes in the coordination of carbon decoupling and energy equity in the upper, middle and lower reaches of the Yangtze River Economic Belt from 2008 to 2019. As shown in Figure 8, the coordination of each river basin in the Yangtze River Economic Belt from 2008 to 2019 generally experienced a process of first declining and then rising. A reliable guess is that the Yangtze River Economic Belt and its various basins have experienced rapid development in low-carbon economies and energy fairness over the past decade, thanks to the advancements in industrial technology and the implementation of carbon trading policies. Specifically, from 2008 to 2011, the coordination of carbon decoupling and energy fairness in the upper, middle and lower reaches showed a downward trend, all below 0.6, basically at the level of near coordination. From 2012 to 2019, the coordination of carbon decoupling and energy equity in the upper, middle and lower reaches showed a slow upward trend. The coordination of the middle reaches was higher than that of the upper and lower reaches, reaching the highest value of 0.896 in 2019, indicating a good coordination state, while the coordination of the upper and lower reaches was less than 0.8, mainly in an intermediate coordination state. In summary, although the coordination of carbon decoupling and energy fairness in each river basin of the Yangtze River Economic Belt has experienced the same process of first declining and then rising in the past decade, and all have a large space for future improvement, the upper and lower reaches have more obviously encountered the obstacles of coordinated development, which indicates that the driving mechanism to promote the coordinated development of carbon decoupling and energy equity in the Yangtze River Economic Belt may vary within the river basin.

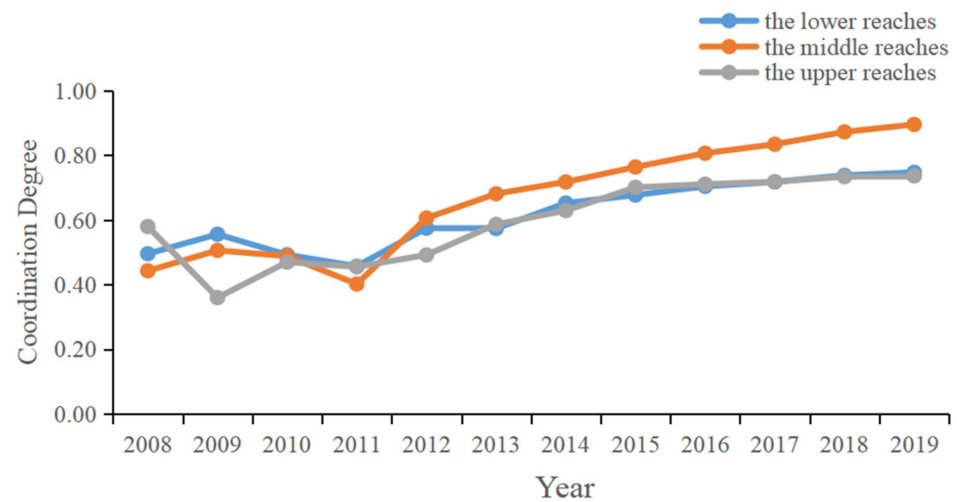


Figure 8. Changes in the level of coordination in the upper, middle and lower reaches of the Yangtze River Economic Belt from 2008 to 2019.

4.3. Heterogeneity Analysis

In order to further analyze the provincial differences in coordinated development between carbon decoupling and energy equity in the Yangtze River Economic Belt, Geoda software (v1.14) was used to calculate the bivariate local Moran index of carbon decoupling and energy equity. Figure 9 shows the spatial distribution cluster of carbon decoupling and energy equity in the Yangtze River Economic Belt from 2008 to 2019.

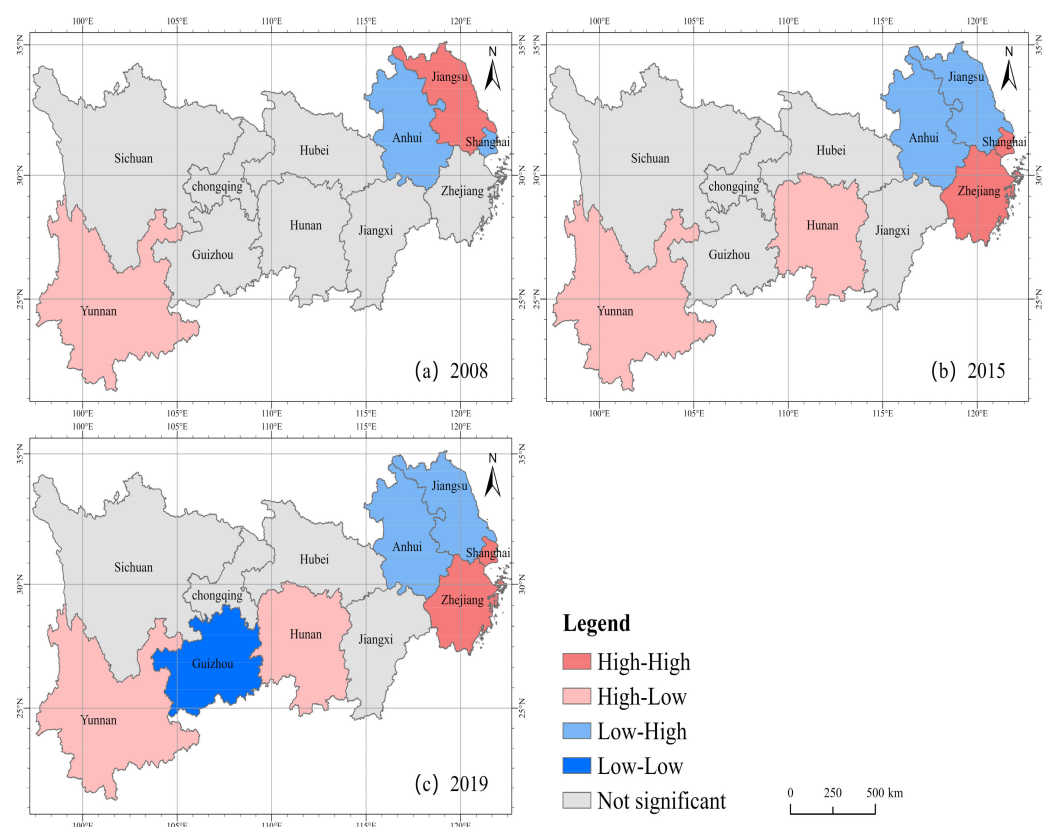


Figure 9. Lisa cluster map of carbon decoupling and energy fairness in the Yangtze River Economic Belt from 2008 to 2019.

As shown in Figure 9, from the perspective of the change trend, the synergy of carbon decoupling and energy equity in the Yangtze River Economic Belt continuously improved during the research period, and the significance of spatial agglomeration also strengthened, which is consistent with the coordinated development trend described in Figure 5. From the perspective of spatial differences, there are more agglomerations of low carbon decoupling and high energy equity compared to other types, indicating that many regions still faced the problem of coordinated development of carbon decoupling and energy equity. The provinces with strong carbon decoupling and high energy fairness (high-high), such as Zhejiang and Shanghai, are concentrated in the downstream of the Yangtze River Economic Belt, indicating that the downstream provinces have a strong synergy between energy fairness and carbon decoupling, and the threat of carbon emission reduction to energy equity is minimal. The provinces with weak carbon decoupling and low energy equity (low-low) appeared in Guizhou in 2019. The provinces with strong carbon decoupling and low energy fairness (high-low) are concentrated in Yunnan in the upper reaches and Hunan in the middle reaches, indicating that although these areas had good carbon emission reduction results, the relationship between carbon decoupling and energy equity was unbalanced, and carbon emission reduction may have hindered the development of energy equity. The provinces with weak carbon decoupling and high energy equity (low-high) are concentrated in Anhui and Jiangsu in the downstream area, indicating that these areas relied more on the development model of high energy consumption and carbon emissions, and industrial structure upgrading became the key path for them to promote coordinated development. In summary, Zhejiang and Shanghai preceded other regions in terms of the harmonious development of carbon reduction and energy fairness. These areas maintained a beneficial balance within the 3E system, which may be attributable to their local initiatives in developing a circular economy and harnessing clean energy.

5. Discussion

5.1. This Study's Limitations

This study reflects threats to the 3E system's sustainability in the Yangtze River Economic Belt, stemming from the inter-basin gap of energy equity and the coordination limitations of energy equity and carbon decoupling. However, the research process in this study still has the following limitations:

(1) Limitations of the data. This study takes the Yangtze River Economic Belt as the research object and has more reference significance for exploring the sustainable issues of the 3E system in developing countries, which may affect this study's universality to a certain extent.

(2) Limitations of the evaluation methods. First, there are certain limitations in the evaluation of energy equity by the entropy value method, such as ignoring the significance of the index itself. Second, restricted by the difficulty of data acquisition, the research on urban–rural differences in energy equity assessment is insufficient.

(3) Limitations of theoretical analysis. The theoretical analysis only considers the two scenarios of fairness and efficiency. It does not add other boundary conditions, such as the degree of development, energy resources, etc. These conditions may improve the theoretical model's complexity.

5.2. The Future Research Prospect and Its Main Difficulties

This study utilizes the coupling coordination model and bivariate local Moran index to investigate the coordination of carbon decoupling and energy equity in the Yangtze River Economic Belt, indirectly reflecting the threat of low-carbon transition to energy equity in the Yangtze River Economic Belt. However, this study does not empirically estimate the impact path of carbon decoupling on energy equity, nor does it clearly reveal the impact level of carbon decoupling on energy equity in the Yangtze River Economic Belt. Consequently, it is necessary for future research to further investigate the impact mechanism of carbon decoupling on energy equity and to analyze the action path of carbon

emission reduction on energy equity, which will also help to explore the realistic path of achieving the coordinated development of low-carbon economy and energy equity. At present, many studies have shown that technological innovation, such as digital technology and renewable energy technology, is conducive to achieving a balance between carbon emission reduction and energy justice [40,41].

However, conducting research on the impact of low-carbon transition on energy equity presents a rather evident endogeneity issue, which constitutes a significant challenge for future studies. Drawing on econometric theory, a possible solution is to use instrumental variables. Identifying an appropriate instrumental variable not only becomes a key point for future research, but also necessitates rigorous empirical testing. Therefore, it is necessary to strengthen literature research and data collection work in the future.

6. Conclusions and Policy Implication

6.1. Conclusions

In order to prevent the sacrifice of social energy welfare in the low-carbon transition, this study estimates the coupling degree of carbon decoupling and energy fairness in the Yangtze River Economic Belt. First, this study uses the improved two-stage rolling Tapio method to calculate the carbon decoupling index to reflect the level of regional low-carbon economic development. Then, the entropy method and the Theil index are employed to calculate the basic value and gap value of energy equity in the Yangtze River Economic Belt, and the internal and external differences of energy fairness are analyzed. Finally, the coupling coordination degree model and the bivariate local Moran index are used to explore the change trend of the coupling coordination degree of carbon decoupling and energy fairness in the Yangtze River Economic Belt. The research results are summarized as follows:

First, although the overall carbon decoupling in the Yangtze River Economic Belt presents a weak decoupling level, it can be divided into three periods, according to different change characteristics: 2008–2011 is the recession period; 2012–2015 is the strengthening period; and 2016–2019 is the stable period. The recession period reveals that the Yangtze River Economic Belt experienced an extensive economic development process with high emissions and high growth. The strengthening period indicates that the growth rate of carbon emissions was under relatively strong control. The stable period indicates that the Yangtze River Economic Belt faced a large emission reduction bottleneck when carbon emissions tended to be strongly decoupled. In addition, the analysis of carbon decoupling heterogeneity shows that the low-carbon economic efficiency of the downstream Yangtze River Delta region is better compared to other regions.

Second, from 2008 to 2019, the energy equity value of the Yangtze River Economic Belt as a whole showed a steady upward trend, but there was still a large room for improvement in the overall level. In terms of growth rate, the early (2008–2011) and late (2016–2019) growth rates were faster, indicating that with the increase in energy consumption at the industrial end and the development of clean energy, energy fairness made a significant leap during these periods. In addition, the calculation results of the energy fairness Theil value showed that the contribution rate of inter-basin differences to the total difference is 64.44%. The heterogeneity analysis of energy fairness showed that the internal gap in the upper and lower reaches was more obvious.

Third, from 2008 to 2019, the trend of coordinated development of carbon decoupling and energy equity in the Yangtze River Economic Belt presented a nearly “V” shape. It could be divided into three periods, according to different change characteristics: 2008–2011 was the phase of recessionary imbalance, 2012–2015 was the phase of coordination improvement, and 2016–2019 was the stable phase of coordinated development. Among them, the stable phase of coordinated development indicates that the Yangtze River Economic Belt is facing the challenge of how to explore and guide the new driving force for the coordinated development of the low-carbon economy and energy fairness. Especially in the upper and lower reaches, the obstacles to coordinated development are more obvious. In addition,

the heterogeneity analysis shows that the degree of coordinated development of carbon reduction and energy fairness in Zhejiang and Shanghai is better compared to other regions, maintaining a benign balance within the 3E ecosystem.

The empirical results clearly show that there is significant room for improvement in the coordination between carbon decoupling and energy equity. This remains an urgent issue, menacing the sustainability of the 3E system in the Yangtze River Economic Belt. Therefore, preventing the sacrifice of energy equity has become an important path for future sustainable construction.

6.2. Policy Implication

6.2.1. Eliminating Inter-Basin Differences Is an Important Way for the Yangtze River Economic Belt to Achieve Coordinated Development of Carbon Decoupling and Energy Equity

According to the empirical analysis results, the upstream region of the Yangtze River Economic Belt shows more obvious shortcomings in both carbon decoupling and energy equity. In balancing the development of a low-carbon economy and energy fairness, the upper and lower reaches of the Yangtze River Economic Belt both show obstacles to maintaining balance. However, the way for the less developed upstream region to break the current coordination dilemma is different from that of the downstream region, and the main problem to be solved is the lag in carbon efficiency and energy infrastructure development. Hence, eliminating inter-basin differences is an important way for the Yangtze River Economic Belt to promote the coordinated development of a low-carbon economy and energy fairness. Meanwhile, policy-makers should formulate appropriate regional strategies to promote the coordinated development of the 3E system, according to the specific situation of the river basin, such as whether the contradiction comes from the energy structure or the industrial structure.

6.2.2. Accelerating the Construction of a Guaranteed Mechanism for Energy Equity

The energy trilemma index and the coordination degree analysis of this study reveal a trend: energy equity gradually replaces energy difficulties, as an important factor threatening the sustainability of the 3E system in the Yangtze River Economic Belt. When promoting low-carbon production and lifestyles, governments should not only consider the accessibility of clean energy but also prioritize affordability for middle- and low-income groups, as well as community environmental risks. To ensure that a broader population benefits from a modern energy system, energy transition policies should accelerate the establishment of mechanisms that guarantee energy equity. Specifically, this involves the following: first, encouraging public participation and establishing inclusive and transparent decision-making mechanisms for energy; second, implementing a gradual and orderly energy transition process to avoid one-size-fits-all approaches for fossil fuels, such as orderly facilitating the transition from coal to natural gas in some areas; third, feeding the carbon market. Carbon trading revenues should be more directed toward supporting the low-carbon transition to reduce carbon costs for enterprises and residents.

Author Contributions: C.F.: supervision, resources, project administration. C.L.: writing—review and editing, writing—original draft. Y.L.: software, data curation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflicts of interest.

References

- World Energy Council. *World Energy Trilemma Index 2022*; World Energy Council: London, UK, 2022.
- Wang, R.; Ren, L. Logic and Its Unexpected Consequences of Local Environmental Policy Excessive Implementation—Case Study from the “Coal to Gas” Policy in 2017. *J. Public Adm.* **2021**, *18*, 33–44+168.
- Shakya, S.R.; Nakarmi, A.M.; Prajapati, A.; Pradhan, B.B.; Rajbhandari, U.S.; Rupakheti, M.; Lawrence, M.G. Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country: A case study of Nepal. *Energy Rep.* **2023**, *9*, 2359–2371. [\[CrossRef\]](#)
- Fan, Y.; Yan, X.; Cui, L.; Zhang, L.; Wang, J. Carbon pricing, carbon equity, and the RCEP framework. *China Econ. Rev.* **2023**, *80*, 102017. [\[CrossRef\]](#)
- Sovacool, B.K. Contestation, contingency, and justice in the Nordic low-carbon energy transition. *Energy Policy* **2017**, *102*, 569–582. [\[CrossRef\]](#)
- Canelas, J.; Carvalho, A. The dark side of the energy transition: Extractivist violence, energy (in) justice and lithium mining in Portugal. *Energy Res. Soc. Sci.* **2023**, *100*, 103096. [\[CrossRef\]](#)
- Monyei, C.G.; Sovacool, B.K.; Brown, M.A.; Jenkins, K.E.; Viriri, S.; Li, Y. Justice, poverty, and electricity decarbonization. *Electr. J.* **2019**, *32*, 47–51. [\[CrossRef\]](#)
- Johnson, O.W.; Han, J.Y.-C.; Knight, A.-L.; Mortensen, S.; Aung, M.T.; Boyland, M.; Resurrección, B.P. Intersectionality and energy transitions: A review of gender, social equity and low-carbon energy. *Energy Res. Soc. Sci.* **2020**, *70*, 101774. [\[CrossRef\]](#)
- Ravigné, E.; Ghersi, F.; Nadaud, F. Is a fair energy transition possible? Evidence from the French low-carbon strategy. *Ecol. Econ.* **2022**, *196*, 107397. [\[CrossRef\]](#)
- World Energy Council. *World Energy Trilemma Index*; World Energy Council: London, UK, 2023.
- Fu, F.Y.; Alharthi, M.; Bhatti, Z.; Sun, L.; Rasul, F.; Hanif, I.; Iqbal, W. The dynamic role of energy security, energy equity and environmental sustainability in the dilemma of emission reduction and economic growth. *J. Environ. Manag.* **2021**, *280*, 111828. [\[CrossRef\]](#)
- Šprajc, P.; Bjegović, M.; Vasić, B. Energy security in decision making and governance-Methodological analysis of energy trilemma index. *Renew. Sustain. Energy Rev.* **2019**, *114*, 109341. [\[CrossRef\]](#)
- Setyowati, A.B. Mitigating inequality with emissions? Exploring energy justice and financing transitions to low carbon energy in Indonesia. *Energy Res. Soc. Sci.* **2021**, *71*, 101817. [\[CrossRef\]](#)
- Ayllón, L.M.S.; Jenkins, K.E. Energy justice, Just Transitions and Scottish energy policy: A re-grounding of theory in policy practice. *Energy Res. Soc. Sci.* **2023**, *96*, 102922. [\[CrossRef\]](#)
- Dai, J.; Li, S.; Bi, J.; Ma, Z. The health risk-benefit feasibility of nuclear power development. *J. Clean. Prod.* **2019**, *224*, 198–206. [\[CrossRef\]](#)
- Droubi, S.; Heffron, R.J.; McCauley, D. A critical review of energy democracy: A failure to deliver justice? *Energy Res. Soc. Sci.* **2022**, *86*, 102444. [\[CrossRef\]](#)
- Peng, C.; Chen, H.; Lin, C.; Guo, S.; Yang, Z.; Chen, K. A framework for evaluating energy security in China: Empirical analysis of forecasting and assessment based on energy consumption. *Energy* **2021**, *234*, 121314. [\[CrossRef\]](#)
- Wang, F.; Zhuang, L.; Cheng, S.; Zhang, Y.; Cheng, S. Spatiotemporal variation and convergence analysis of China’s regional energy security. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113923. [\[CrossRef\]](#)
- Yang, M.; Liang, X.; Ma, Y.; Lu, W.; Zhao, R. Exploring the carbon inequality embodied in China’s interregional trade based on a human well-being equity perspective. *J. Clean. Prod.* **2023**, *420*, 138367. [\[CrossRef\]](#)
- Zhang, Z.; Xiong, X. Legal implementation of energy justice in rural China. *Chin. J. Popul. Resour. Environ.* **2016**, *26*, 125–132.
- Shi, J.; Tian, J.; Xue, J. Analysis of the fairness issue in the development of new energy vehicles. *J. Nanjing Tech Univ. (Soc. Sci. Ed.)* **2017**, *16*, 5–12.
- Ning, L.; Yang, X. Legal regulation path of energy transformation in China from the perspective of energy justice. *J. Shandong Univ. (Philos. Soc. Sci.)* **2022**, *26*, 175–184.
- Yu, Y.; Gong, X. Study on the coupling problem of coordinated development of economy–energy–environment–technology system in Northeast China. *Energy Rep.* **2022**, *8*, 305–312. [\[CrossRef\]](#)
- Wang, X.; Li, J. Heterogeneous effect of digital economy on carbon emission reduction. *J. Clean. Prod.* **2023**, *429*, 139560. [\[CrossRef\]](#)
- Edziah, B.K.; Sun, H.; Adom, P.K.; Wang, F.; Agyemang, A.O. The role of exogenous technological factors and renewable energy in carbon dioxide emission reduction in Sub-Saharan Africa. *Renew. Energy* **2022**, *196*, 1418–1428. [\[CrossRef\]](#)
- Zhong, Y. Scenario analysis and path selection of China regional carbon emission based on low carbon development. *Ecol. Econ.* **2016**, *32*, 71–74.
- Liu, Q.; Gao, J.; Cai, W.; Huo, T.; Li, R. A novel allocation method of regional carbon allowance in building sector: Perspective from coupling equity and efficiency. *Environ. Impact Assess. Rev.* **2023**, *102*, 107192. [\[CrossRef\]](#)
- Putranto, L.M.; Budi, R.F.S.; Novitasari, D. Role of the energy-carbon-economy nexus and CO₂ abatement cost in supporting energy policy analysis: A multi-scenario analysis of the Java-Bali system. *Renew. Sustain. Energy Rev.* **2023**, *187*, 113708.
- Jara, E.C.; Bruns, A. Contested notions of energy justice and energy futures in struggles over tar sands development in British Columbia, Canada. *Futures* **2022**, *138*, 102921. [\[CrossRef\]](#)
- Esso, L.J.; Keho, Y. Energy consumption, economic growth and carbon emissions: Cointegration and causality evidence from selected African countries. *Energy* **2016**, *114*, 492–497. [\[CrossRef\]](#)

31. Alaganthiran, J.R.; Anaba, M.I. The effects of economic growth on carbon dioxide emissions in selected Sub-Saharan African (SSA) countries. *Heliyon* **2022**, *8*, e11193. [\[CrossRef\]](#)
32. Song, Y.; Sun, J.; Zhang, M.; Su, B. Using the Tapio-Z decoupling model to evaluate the decoupling status of China's CO₂ emissions at provincial level and its dynamic trend. *Struct. Chang. Econ. Dyn.* **2020**, *52*, 120–129. [\[CrossRef\]](#)
33. Dong, J.; Li, C.; Wang, Q. Decomposition of carbon emission and its decoupling analysis and prediction with economic development: A case study of industrial sectors in Henan Province. *J. Clean. Prod.* **2021**, *321*, 129019. [\[CrossRef\]](#)
34. Fu, C.; Min, W.; Liu, H. Decomposition and decoupling analysis of carbon emissions from cultivated land use in China's main agricultural producing areas. *Sustainability* **2022**, *14*, 5145. [\[CrossRef\]](#)
35. Khanna, R.A.; Li, Y.; Mhaisalkar, S.; Kumar, M.; Liang, L.J. Comprehensive energy poverty index: Measuring energy poverty and identifying micro-level solutions in South and Southeast Asia. *Energy Policy* **2019**, *132*, 379–391. [\[CrossRef\]](#)
36. Zhang, Y.; Dong, D.; Xu, L.; Miao, Z.; Mao, W.; Tang, S. Equity in health care after 10 years of the new rural co-operative medical insurance scheme in China: An analysis of national survey data. *Lancet* **2018**, *392*, S35. [\[CrossRef\]](#)
37. Mudrick, N.R.; Breslin, M.L.; Blackwell, J.; Wang, X.; Nielsen, K.A. Accessible medical diagnostic equipment in primary care: Assessing its geographic distribution for disability equity. *Disabil. Health J.* **2023**, *16*, 101425. [\[CrossRef\]](#)
38. Bianco, V.; Cascetta, F.; Nardini, S. Analysis of the carbon emissions trend in European Union. A decomposition and decoupling approach. *Sci. Total Environ.* **2024**, *909*, 168528. [\[CrossRef\]](#)
39. Zhu, J.; Zhu, Z. The space-time evolution and driving mechanism of coordinated development of modern logistics industry and tourism industry. *J. Clean. Prod.* **2023**, *423*, 138620. [\[CrossRef\]](#)
40. Yang, S.; Wang, J.; Dong, K.; Jiang, Q. A path towards China's energy justice: How does digital technology innovation bring about a just revolution? *Energy Econ.* **2023**, *127*, 107056. [\[CrossRef\]](#)
41. Dong, K.; Yang, S.; Wang, J.; Dong, X. Revisiting energy justice: Is renewable energy technology innovation a tool for realizing a just energy system? *Energy Policy* **2023**, *183*, 113820. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.