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The Dynamics of Energy-Related Carbon Emissions and Their Influencing Factors in the Yangtze River Delta, China

Xiang'er Li ¹, Jiajun Gong ¹, Xuan Ni ¹, Zhiyi Zheng ¹, Qingshan Zhao ¹ and Yi'na Hu ^{1,2,*} ¹ School of Environmental and Geographical Sciences, Shanghai Normal University, Shanghai 200234, China² Yangtze River Delta Urban Wetland Ecosystem National Field Scientific Observation and Research Station, Shanghai 201722, China

* Correspondence: huyina@shnu.edu.cn; Tel.: +86-13641016694

Abstract: Chinese cities are pursuing an energy transition to decouple energy-related carbon emissions (ERCEs) from economic growth. Despite numerous studies focusing on the factors influencing carbon emissions, few have quantitatively analyzed their respective contribution rates, thus leaving a gap in effectively guiding policies. This study took 16 cities in the Yangtze River Delta (YRD) as the study area. The decoupling between ERCEs and economic growth was analyzed during 2000–2020, and the contribution rates of different factors were explored. The results showed that the total ERCEs increased from 413.40 million to 1265.86 million tons during 2000–2020, increasing by over three times. Coal and oil were the dominant energy sources in most cities, but natural gas consumption increased from 0.15% to 5.96%. Moreover, 14 cities showed a decoupling status, indicating a certain win–win situation between economic growth and ERCE reduction. Economic growth greatly increased ERCEs, with its contribution rate ranging from 114.65% to 493.27% during 2000–2020. On the contrary, energy structure and energy intensity both contributed to reducing ERCEs in most cities, and their maximum contribution rates reached −32.29% and −449.13%, respectively, which were the main forces for the win–win situation. Finally, carbon reduction proposals are put forward, which provide theoretical support for achieving the “Double Carbon” goal in the YRD.

Keywords: carbon emission; decoupling; energy structure and intensity; influencing factors; Yangtze River Delta



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1. Introduction

Carbon emissions from fossil fuels and unsustainable energy burning are reported as the primary drivers of global warming, causing the current global average temperature to rise 1.1 °C above pre-industrial levels [1]. Consequently, there has been a growing consensus among the international community to reduce carbon emissions [2–4]. Over the past few decades, China has witnessed an astonishing pace of industrialization and urbanization, with its GDP growing at an annual rate of 9% [5,6]. However, this rapid economic growth has been accompanied by a significant surge in energy consumption, resulting in massive energy-related carbon emissions (ERCEs) [7,8]. In 2021, China contributed a substantial 33% share of the world's total carbon emissions [9], making it the highest carbon emitter. To address this, the Chinese government has set forth the ambitious “Double Carbon” goal, aiming to achieve a carbon emission peak by 2030 and carbon neutrality by 2060. Chinese cities are thus facing the dual pressure of maintaining rapid economic growth while reducing carbon emissions. Understanding the relationship between these two objectives is essential and can provide crucial insights for promoting sustainable development in China.

Scholars have pointed out that economic growth exhibits varying relationships with carbon emissions, depending on the specific region and time period [10,11]. For instance, Mireille et al. found that economic growth in resource-rich countries was more carbon-intensive than that in resource-poor countries [12]. Due to the availability of energy consumption data, previous research has primarily focused on the national level [13] and

provincial levels [14,15]. For instance, Magazzino [16] and Lenzen et al. [17] conducted studies on carbon emissions in Israel and Brazil, respectively. Previous studies have significantly influenced the formulation of economic policies [18], carbon reduction strategies [19], and environmental planning [20,21] in different countries and provinces. In 2018, China surpassed its 2020 national carbon intensity reduction target through collective societal efforts [22]. The next phase of carbon reduction will be more challenging and necessitates targeted policies for smaller-scale regions. Studies on a national and provincial scale can no longer meet demand. Shan et al. pointed out that cities are the key zones for implementing the “Dual Carbon” strategy, given that cities have become the spatial carriers for socio-economic development in China [23]. Therefore, the city-level relationship between economic growth and ERCs should be emphasized, thereby helping set strategies for a win-win situation in Chinese cities.

Chinese cities are striving to reduce ERCs while maintaining robust economic growth [24]. Energy transition is a multi-faceted approach encompassing optimizing energy intensity, altering energy structure, and developing sustainable clean energy. It has been a widely pursued strategy in many cities [25,26]. Scholars have also extensively examined the influence of energy transition, economic growth, and other variables on ERCs [27–29]. For instance, Zeng et al. pointed out that carbon emission efficiency was positively correlated with factors like industrial structure and external development while being negatively related to energy intensity [30]. However, previous research has mainly focused on identifying influencing factors, overlooking the quantitative analysis of their respective contribution rates. This gap makes it challenging to formulate effective policy guidance. There is a need to further clarify the contribution rates of different factors, thus identifying the main cause of carbon emissions [31,32]. This clarification would enable the formulation of targeted recommendations for cities with diverse carbon emission characteristics.

The Yangtze River Delta (YRD) has witnessed remarkable economic growth in the past few decades, which also makes it a hot spot for carbon emissions [33,34]. Given that fossil fuels remain the primary energy source in the YRD, cities in this region have actively pursued measures to reduce energy-related carbon emissions (ERCs), including reducing energy intensity and optimizing energy structures. Against this background, assessing the coupling between ERCs and economic growth and exploring their underlying mechanisms is crucial for formulating effective carbon reduction policies. In this study, involving 16 cities in the core area of the YRD as the study area, the spatio-temporal dynamics of ERCs and their decoupling relationship with economic growth at the city level were evaluated. According to the characteristics of the YRD, the driving forces of ERCs were decomposed into economic growth, population size, energy structure, and energy intensity. After that, the contribution rates of them were identified, and the proposals for carbon reduction were put forward. The main objectives were: (1) to examine whether economic growth has decoupled with ERCs and (2) to determine the contribution rate of different carbon emission drivers and provide strategies for carbon reduction for the core area of the YRD.

2. Materials and Methods

2.1. Study Area

This study took 16 cities in the YRD as the study area, including Shanghai, seven cities in Zhejiang, and eight cities in Jiangsu (Figure 1). According to the Regional Planning of the Yangtze River Delta issued by the State Council in 2010, these 16 cities serve as the core areas of the YRD, with them aiming to drive and coordinate the development of cities in the YRD. As a rapidly urbanized region, the YRD is home to 7.5% of China's total population and contributes 15.9% of its GDP, despite occupying only 1.1% of the country's land area [34]. However, this rapid economic growth has been paralleled by a substantial surge in energy consumption, making the YRD one of the top carbon emitters in China. In pursuit of balancing economic growth with carbon reduction, cities in the YRD are actively pursuing energy transitions [35]. Thus, it is essential to explore the decoupling between

economic growth and ERCs, along with their influencing factors, which may help to promote a low-carbon economy in the YRD.

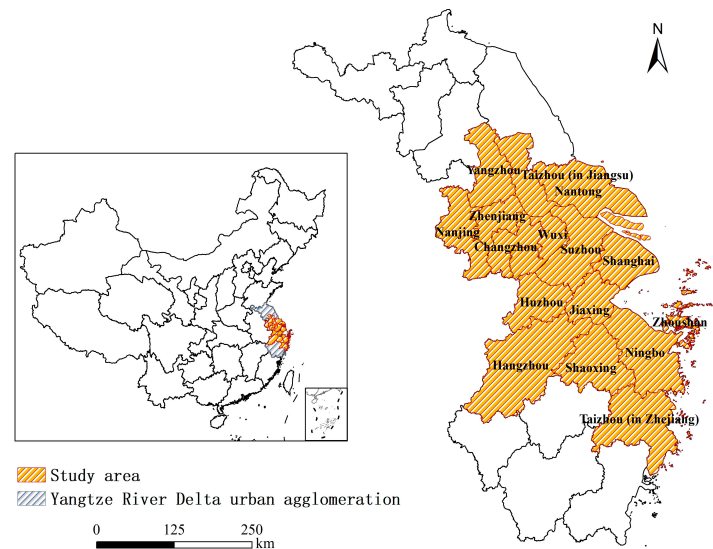


Figure 1. Study area.

2.2. Data Sources

The following data were utilized in our paper: (1) energy consumption and socio-economic data were obtained from the Statistical Yearbook of Zhejiang, Jiangsu, and Shanghai, China Energy Statistical Yearbook; (2) population data and GDP data were obtained from the Resource and Environment Science and Data Center [36]; and (3) administrative boundary data were obtained from the National Geographic Information Public Service Platform [37].

2.3. Evaluation of Energy-Related Carbon Emission

Based on the statistical yearbook, the main energy sources in the YRD are coke, coal, gasoline, crude oil, kerosene, fuel oil, diesel, and natural gas. The IPCC has proposed a standard formula for the carbon dioxide emission calculation formula [1,38]. Referring to the IPCC, this study divided them into three categories, i.e., coal (including coke and coal), oil (including gasoline, crude oil, kerosene, fuel oil, and diesel), and natural gas. The ERCs were calculated as Equation (1) [1,38].

$$TC = \sum_{k=1}^8 E_k \times CF_k \times CC_k \times \frac{44}{12} \quad (1)$$

where TC is the total amount of ERCs; E_k represents the consumption amount of energy type k ; CF_k is the conversion factor for standard coal of energy type k ; CC_k is the carbon emission coefficient of energy type k ; $44/12$ is the molecular weight of carbon dioxide. The conversion factors for standard coal and carbon emission coefficients for each energy source were set according to the IPCC [1,38].

2.4. Tapio Decoupling Analysis

Decoupling is commonly applied to represent variables that are no longer related to each other [39]. If economic growth is decoupled with ERCs, this indicates economic growth is achieved without an accompanying increase in ERCs, and ERCE reduction can be achieved along with economic growth [40]. The Tapio model, as a widely used method in decoupling measurement [41–43], can calculate the decoupling elastic coefficient by utilizing the ratio of the change rate in carbon emissions to that in GDP [44].

$$e = (\Delta C/C)/(\Delta GDP/GDP) \quad (2)$$

where e is the decoupling elastic coefficient; C represents the carbon emissions; ΔC is the carbon emission changes; ΔGDP indicates the GDP change. According to the elastic coefficient, ΔGDP and ΔC , the decoupling status can be divided into eight types (Table 1). In the 16 cities in the YRD, ΔGDP is always greater than 0; thus, only four types appeared, that is, expansive negative decoupling, expansive coupling, strong decoupling, and weak decoupling.

Table 1. Classification of decoupling status based on carbon emission change, economic growth, and elastic coefficient [44].

Classification	Status of Decoupling	Carbon Emission Change (ΔC)	Economic Growth (ΔGDP)	Elastic Coefficient
Negative decoupling	Expansive negative decoupling	>0	>0	$e > 1.2$
	Strong negative decoupling	>0	<0	$e < 0$
	Weak negative decoupling	<0	<0	$0 < e < 0.8$
Decoupling	Weak decoupling	>0	>0	$0 < e < 0.8$
	Strong decoupling	<0	>0	$e < 0$
	Recessive decoupling	<0	<0	$e > 1.2$
Coupling	Expansive coupling	>0	>0	$0.8 < e < 1.2$
	Recessive coupling	<0	<0	$0.8 < e < 1.2$

2.5. LMDI Factor Decomposition Model

The logarithmic mean divisor index method (LMDI), as an effective approach to identifying influencing factors, enables the breakdown of total change into several comprehensible factors for ease of interpretation [45]. The LMDI model offers a straightforward calculation process and is aptly suited for conducting time series analysis involving multiple influencing factors [46], with it being a widely used method in driver decomposition [32,47]. Due to the fact that the YRD has the most rapid economic growth and the most densely populated population in China, economic growth and population size were considered to be the typical factors of ERCs in the YRD. Meanwhile, according to the characteristics of energy consumption in the YRD and previous studies [48,49], energy structure and energy intensity were taken into account. Finally, LMDI was applied in this study, and four factors were considered as the driving forces behind ERCs: economic growth, population size, energy intensity, and energy structure. The specific formula can be expressed as [46]:

$$C = \sum_i C_i = \sum_i \frac{C_i}{E_i} \times \frac{E_i}{E} \times \frac{E}{G} \times \frac{G}{P} \times P \quad (3)$$

$$U_i = \frac{C_i}{E_i}, I_i = \frac{E_i}{G}, M_i = \frac{E_i}{E}, Y = \frac{G}{P} \quad (4)$$

where C is energy-related carbon emissions; C_i is the carbon emissions of energy i ; E_i represents the consumption of the energy i ; G represents GDP; P is population; U_i is carbon emission intensity; I_i is energy intensity; M_i is energy structure; Y is per capita GDP, indicating economic growth; P is population size.

This study assumed that C^0 represents the carbon emissions for the base year, C^t represents the carbon emissions for year t , and ΔC represents the carbon emission change from the base year to year t . In the LMDI model, the total effect can be decomposed into energy structure effect (ΔC_M), energy intensity effect (ΔC_I), economic growth effect (ΔC_Y) and population size effect (ΔC_P). The decomposition effect of each driver was calculated as follows:

$$\Delta C_M = \sum_{i=1} \left(\frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \right) \times \ln \frac{M_i^t}{M_i^0} \quad (5)$$

$$\Delta C_I = \sum_{i=1} \left(\frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \right) \times \ln \frac{I_i^t}{I_i^0} \quad (6)$$

$$\Delta C_Y = \sum_{i=1} \left(\frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \right) \times \ln \frac{Y_i^t}{Y_i^0} \quad (7)$$

$$\Delta C_P = \sum_{i=1} \left(\frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \right) \times \ln \frac{P_i^t}{P_i^0} \quad (8)$$

Finally, the comprehensive effect of carbon emission changes is shown as Equation (9). The contribution rate of energy structure (φ_M), energy intensity (φ_I), economic growth (φ_Y), and population size (φ_P) can be expressed as Equation (10), respectively.

$$\Delta C = C_0 - C_t = \Delta C_M + \Delta C_I + \Delta C_Y + C_P \quad (9)$$

$$\varphi_M = \frac{\Delta C_M}{\Delta C}, \varphi_I = \frac{\Delta C_I}{\Delta C}, \varphi_Y = \frac{\Delta C_Y}{\Delta C}, \varphi_P = \frac{\Delta C_P}{\Delta C} \quad (10)$$

3. Results

3.1. Spatio-Temporal Dynamics of ERCES

During 2000–2020, the total amount of ERCES rose significantly from 413.40 million tons to 1265.86 million tons in 16 cities in the YRD. In 2000, Zhoushan generated 2.20 million tons of ERCES, ranking the least among all of the cities, while Shanghai ranked the top, with 104.21 million tons. In 2020, Yangzhou became the city producing the least ERCES, with a total amount of 28.40 million tons, while Shanghai remained the largest emitter, generating 187.35 million tons of ERCES. During 2000–2020, ERCES increased in all of the cities (Figure 2). In detail, Zhoushan was the city with the largest growth rate in ERCES, and it rose by 44 times from 2000 to 2020. Shanghai was the city with the slowest growth rate, but its ERCES still increased by 80% from 2000 to 2020. Among the 16 cities, the ERCES of Hangzhou, Ningbo, and Yangzhou showed a trend of increasing first and then stabilizing during the study period; that of Shanghai, Nantong, and Zhenjiang also increased first but then decreased; and in the remaining 10 cities, the ERCES showed a continuous increase, with different growth rates. In the early period, Jiaxing, Taizhou (in Zhejiang), Changzhou, and Suzhou experienced rapid growth of ERCES while in the later period, Zhoushan underwent a faster growth rate.

As shown in Figure 2, the 16 cities were divided into four types based on their ERCES: low level (0–30 million tons), relatively low level (30–60 million tons), relatively high level (60–90 million tons), and high level (>90 million tons). Economically developed coastal cities had relatively higher ERCES than those internal cities in the study period (Figure 2). Shanghai, Suzhou, Nanjing, and Ningbo had higher levels of economic growth, and they also generated a larger amount of ERCES. On the contrary, Taizhou (in Zhejiang), Huzhou, and Taizhou (in Jiangsu), with relatively low levels of economic growth, had relatively low ERCES. Shanghai always had high levels of ERCES from 2000 to 2020, while Huzhou always had low levels (Figure 2). It is worth mentioning that Hangzhou, as the capital of Zhejiang Province, was never listed as a city with high-level ERCES during the study period.

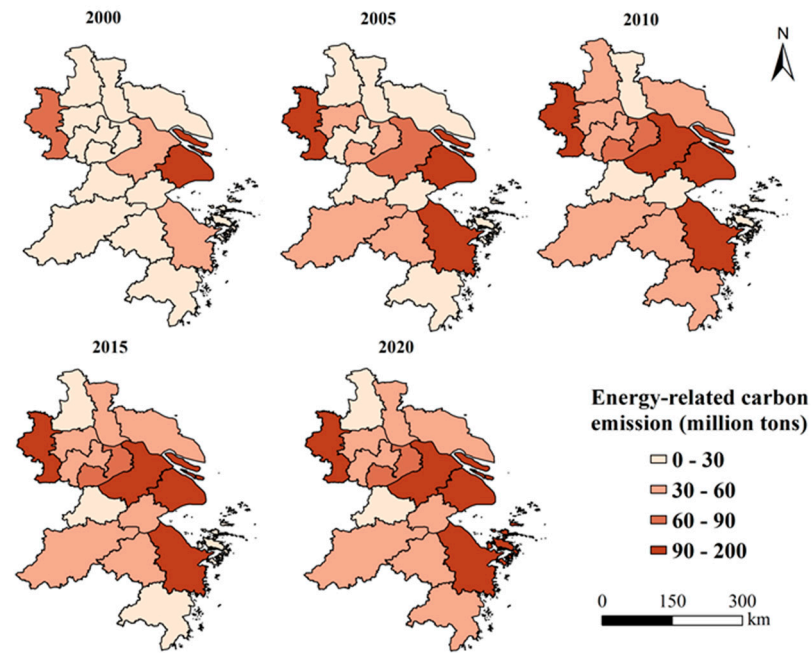


Figure 2. Spatial pattern of ERCEs in the 16 cities from 2000 to 2020.

3.2. Dynamics of Energy Structure in Different Cities

In 2000, 16 cities in the YRD consumed a total of 238.46 billion kg of coal, 174.31 billion kg of oil, and 0.62 billion kg of natural gas (Figure 3). From 2000 to 2020, with economic development, the consumption of all three energy types continued to increase. In 2020, the consumption of coal increased to 674.15 billion kg, oil increased to 516.27 billion kg, and natural gas increased to 74.44 billion kg. In terms of proportion, from 2000 to 2020, coal's share decreased from 57.68% to 53.26%, oil's share declined from 42.17% to 40.78%, while natural gas's proportion increased significantly, from 0.15% to 5.96%. Among the 16 cities, Shanghai, Suzhou, and Nanjing consumed the most coal in 2000, while in 2020, the top three cities of coal consumption changed to Suzhou, Nanjing, and Ningbo. As for oil consumption, Shanghai, Nanjing, and Ningbo were always the top three cities. Shanghai consumed the highest amount of natural gas in the YRD, with its consumption being 15.88 times higher than the second-ranked city in 2000 and 1.60 times higher in 2020.

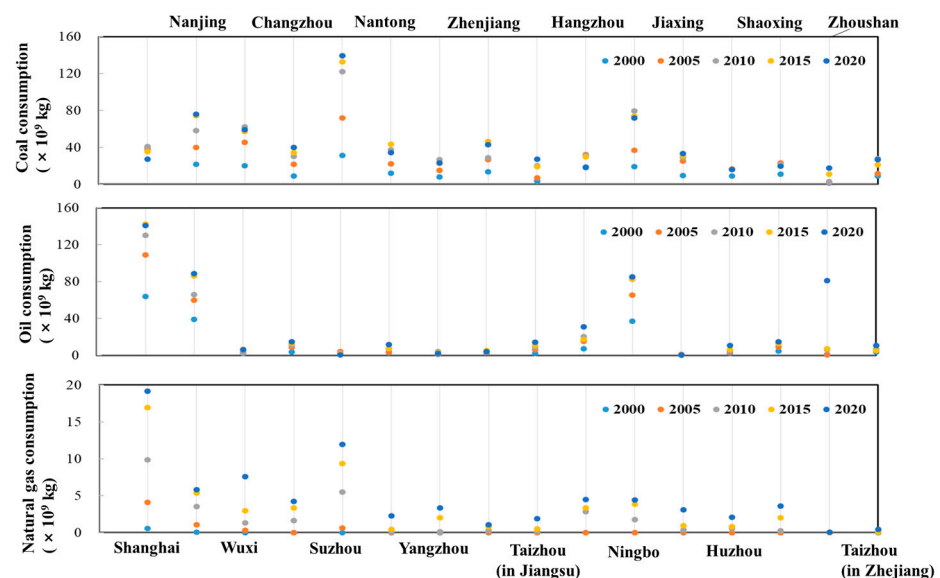


Figure 3. Dynamics of energy intensity in 16 cities from 2000 to 2020.

Figure 4 shows the dynamics of energy structure in different cities in the YRD. From 2000 to 2020, coal was the dominant carbon source in 11 of the 16 cities. Specifically, coal consumption resulted in over 80% of the carbon emissions in Suzhou, Jiaxing, Wuxi, Yangzhou, and Zhenjiang. In Huzhou and Shaoxing, the carbon emissions caused by coal occupied a proportion of over 70% during 2000–2005 and then decreased to about 50% in 2020, while the carbon emissions caused by oil and natural gas increased during 2000–2020. The carbon emissions from coal in four cities, including Changzhou, Nantong, Taizhou (in Zhejiang), and Taizhou (in Jiangsu), have always accounted for over 50% of their total ERCs, with a small change from 2000 to 2020.

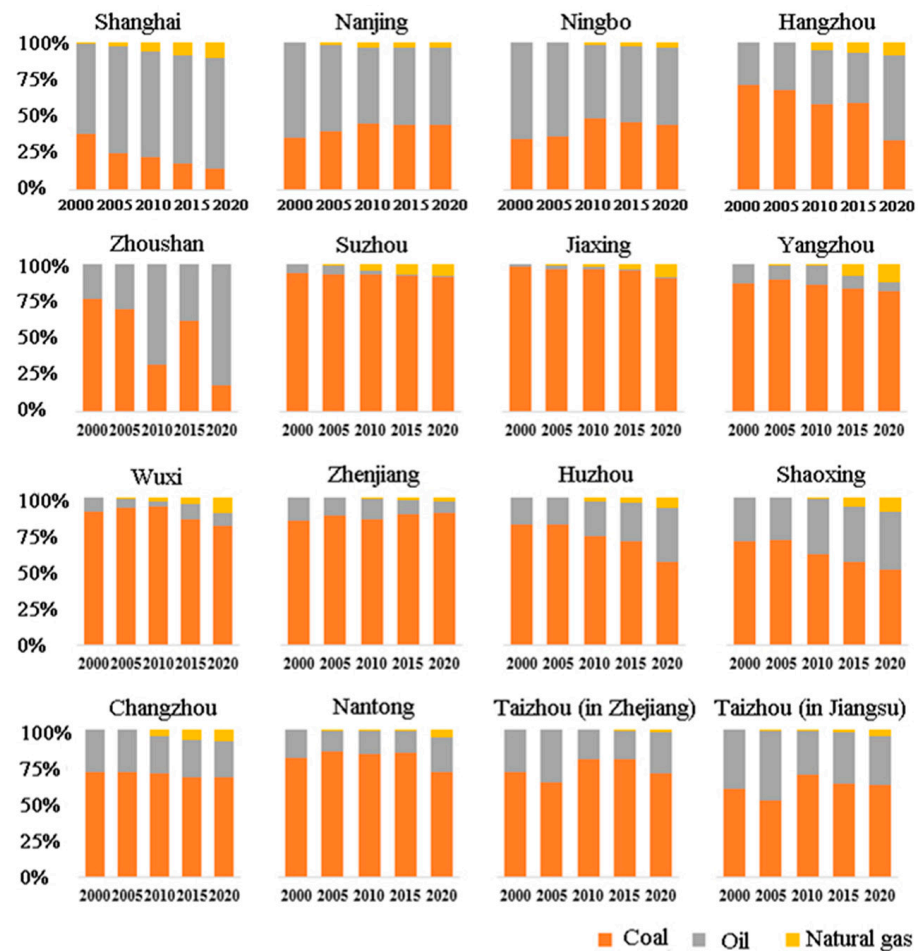


Figure 4. Dynamics of energy structure in 16 cities from 2000 to 2020.

From 2000 to 2020, oil was the leading source of carbon emissions in Shanghai, Nanjing, and Ningbo (Figure 4). Specifically, in Shanghai, the proportion of carbon emissions from oil gradually increased from 61.20% to 75.08%, while that from coal gradually decreased from 38.27% to 14.70% and that from natural gas increased from 0.53% to 10.22%. In Nanjing, the carbon emissions from oil decreased from 64.18% to 52.02% during 2000–2020, while the carbon emissions from coal and natural gas gradually increased. Ningbo's carbon emissions from oil consumption decreased from 65.55% to 52.82% from 2000 to 2020, with those from coal and natural gas slightly increasing from 34.45% to 44.43% and from 0% to 2.75%, respectively. In Hangzhou, the main carbon source from 2000 to 2015 was coal, while in 2020, oil became the dominant carbon source. As for Zhoushan, the main carbon source constantly changed in coal and oil products from 2000 to 2020. Overall, during 2000–2020, coal and oil remained the primary energy sources in most cities, though there was a gradual increase in the use of natural gas.

3.3. Decoupling between Economic Growth and ERCEs

The status of economic growth decoupling from ERCEs in 16 cities is shown in Figure 5. From 2000 to 2020, only the economic growth in Zhoushan showed an expansive negative decoupling with ERCEs, while that in the other 15 cities showed a weak decoupling trend. During 2000–2005, the economic growth of cities was closely linked to ERCEs. Six cities including Suzhou, Wuxi, Changzhou, Taizhou (in Jiangsu), Huzhou, and Shaoxing showed expansive coupling, Jiaying presented a state of expansive negative decoupling, while the other nine cities showed weak decoupling. From 2005 to 2010, the coupling was gradually weakened between ERCEs and economic growth. Only Taizhou (in Jiangsu) remained in a state of expansive coupling, while 14 cities showed a state of weak decoupling. During 2010–2015, the economic growth in Yangzhou, Hangzhou, Ningbo, and Taizhou (in Zhejiang) showed a strong decoupling relationship with ERCEs, but the four cities showed weak decoupling during 2015–2020, which indicated that the impact of economic growth on ERCEs gradually reduced. Shanghai, Nantong and Zhenjiang achieved strong decoupling from 2005 to 2020, indicating that they struck a balance, achieving a win–win scenario where economic growth was accompanied by a reduction in ERCEs. However, since 2005, the state between ERCEs and economic growth has turned from weak decoupling to expansive negative decoupling in Zhoushan.

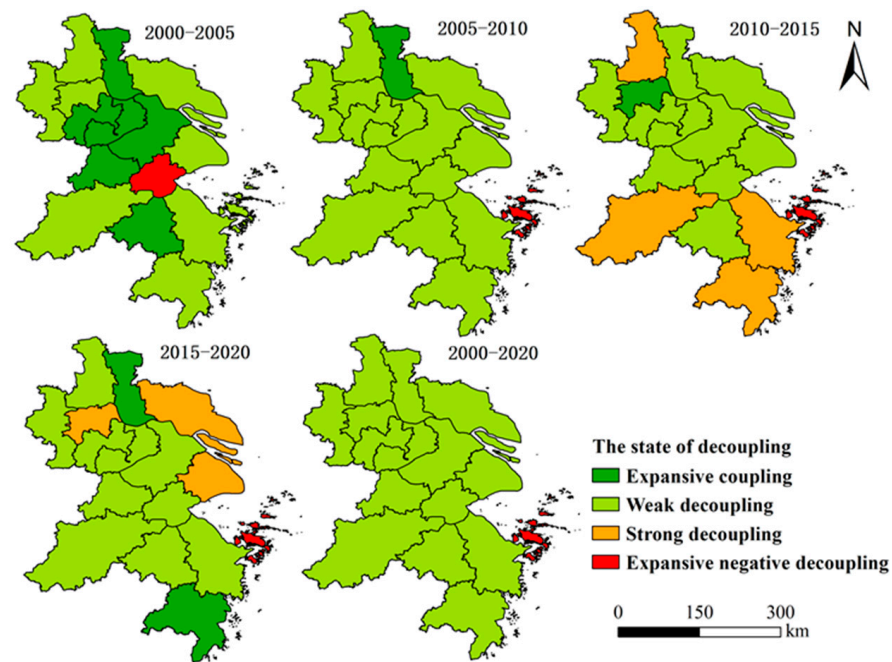


Figure 5. Spatial pattern of the decoupling elasticity index during 2000–2020.

In terms of the changes in the decoupling elastic coefficient, it decreased obviously from 2000 to 2020 in all of the cities, except Zhoushan and Taizhou (in Jiangsu), showing that the link between economic growth and ERCEs weakened. Among them, the decoupling elastic coefficients of Shanghai, Nanjing, Suzhou, and Nantong continued to decline during 2000–2020, and the coupling between economic growth and ERCEs gradually weakened. The decoupling elastic coefficients of nine cities, including Wuxi, Changzhou, Yangzhou, Taizhou (in Jiangsu), Hangzhou, Ningbo, Jiaying, Huzhou, and Shaoxing, showed a trend of declining first and then increasing. The decoupling elastic coefficients of Zhenjiang and Taizhou (in Zhejiang) continued to fluctuate, while the decoupling elastic coefficient of Zhoushan continued to rise, showing that economic growth gradually coupled with ERCEs in Zhoushan.

3.4. Influencing Factors of ERCES

Figure 6 shows that economic growth was the leading positive driver of ERCES for the entire study area from 2000 to 2020. Its contribution rate showed an upward trend, peaking at 493.27% between 2010 and 2015. Population size also contributed positively to the rise in ERCES, but its contribution rate was only 10–20% of that of economic growth. As for energy intensity, it was a negative driver of ERCES. Its negative impact gradually increased from 2000 to 2015, and its maximum contribution rate appeared during 2010–2015 at −449.13%. Comparatively speaking, energy structure had the weakest effect on ERCES. It mainly played a negative driving role from 2000 to 2020, but from 2005 to 2020, the energy structure showed a positive contribution of 2.03%.

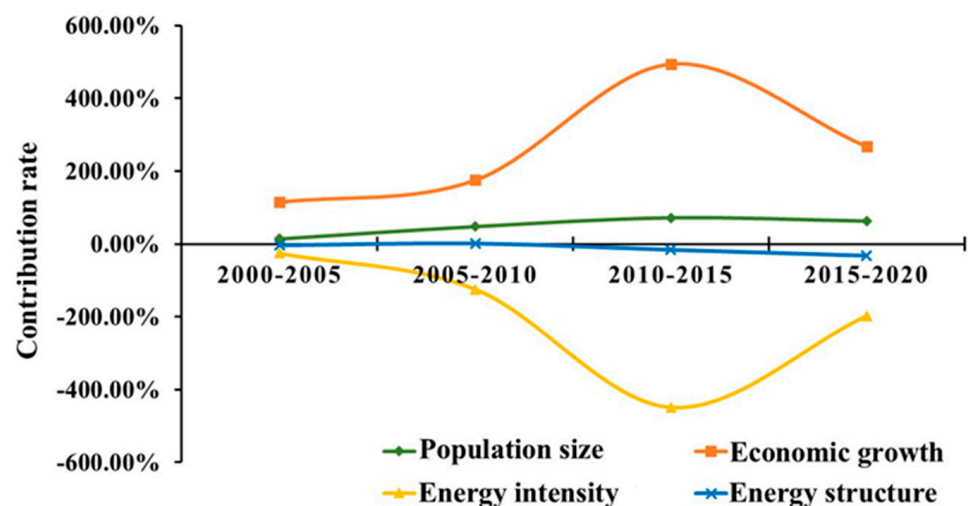


Figure 6. Dynamics of the contribution rates of ERCE drivers from 2000 to 2020.

Comparing the driving factors of ERCES in each city, economic growth was a leading one (Figure 7). The ERCES in Nanjing and Shanghai were most severely affected by economic growth, with increases of over 200 million tons of ERCES. And its impact in Huzhou, Jiaxing, Yangzhou, Taizhou (in Zhejiang), Shaoxing, and Taizhou (in Jiangsu) was relatively weak, resulting in an increase in ERCES of less than 40%. Population size played weak negative roles in Taizhou (in Jiangsu) and Yangzhou, reducing ERCES by 1.07 million tons and 0.10 million tons, respectively, but it had a positive impact in the other 14 cities. The largest contribution rates of population size were in Shanghai and Suzhou, increasing ERCES by 61.83 million tons and 49.15 million tons, respectively. Energy intensity resulted in 42.41 million tons of ERCES in Zhoushan, with a contribution rate of 43.90%; however, it had a negative effect on the other 15 cities. Shanghai and Nanjing were mostly influenced by energy intensity, which helped reduce 198.33 million tons and 173.56 million tons of ERCES, respectively. As for energy structure, it was a positive driver in Nantong, Taizhou (in Jiangsu), Nanjing, and Ningbo, while it had a negative effect on the other 12 cities. Among them, the energy structure of Shanghai had the largest negative impact on ERCES, reducing carbon emissions by 15.22 million tons. The positive effect on Ningbo was the greatest, with ERCES increasing by 5.74 million tons. Overall, economic growth and population size mainly played a positive role, whereas energy intensity and structure mainly helped to reduce the ERCES in the YRD.

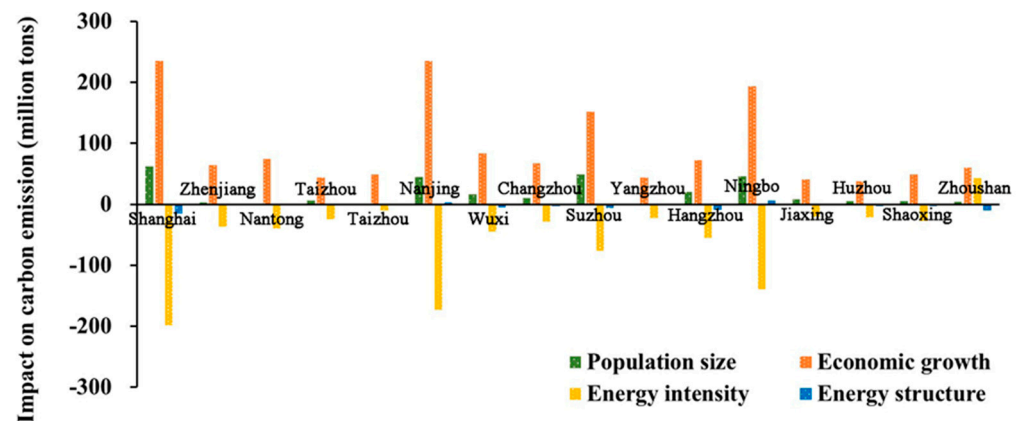


Figure 7. Decomposition of drivers of ERCEs from 2000 to 2020.

4. Discussion

4.1. A Win–Win Situation between ERCE Reduction and Economic Growth

Cities in the YRD have achieved remarkable economic growth, which has also positioned the region as a major carbon emission hotspot in China. The decoupling analysis conducted in this study reveals that economic growth has decoupled from ERCEs in most cities, except Zhoushan and Taizhou (in Jiangsu). Notably, Shanghai, Nantong, and Zhenjiang achieved strong decoupling in 2020, suggesting that their ERCEs are no longer directly tied to economic growth. It is worth mentioning that during the time period, COVID-19 impacted the entire world in 2019 and lasted a few years, which may have influenced our results in 2020. On the one hand, COVID-19 may have reduced the amount of energy-related carbon emissions in 2020, as it influenced transportation for residents and production in factories [50]. On the other hand, COVID-19 may have affected economic growth, thus influencing the decoupling status between ERCEs and economic growth. However, during 2000–2020, a status from coupling to decoupling occurred in many cities; thus, a win–win scenario has been achieved between economic growth and ERCE reduction in the YRD.

The proportion changes of different energy sources also proved this win–win situation. Cities in the YRD are pursuing a low-carbon economy through energy transition [31]. This paper emphasizes that during the period from 2000 to 2020, coal and oil were the primary energy sources utilized in the study area, exhibiting a trend of gradual decline in their proportions, while most cities saw increasing consumption of natural gas. Notably, natural gas reduces greenhouse gas emissions by approximately one-third compared to oil and more than half compared to coal; thus, its increasing consumption aids in reducing ERCEs. The analysis of influencing factors further revealed that both energy intensity and structure help reduce ERCEs in the YRD, and their contribution rates increased during 2000–2020. In particular, the contribution rate of energy intensity reached -449.13% during 2010–2015, nearly matching the contribution rate of economic growth (493.27%). While the consumption of sustainable clean energy was not included due to data limitations, the energy transition process, encompassing reductions in energy intensity and optimizations in energy structure, contributed to the achievement of a win–win situation in the YRD.

4.2. Policy Implications for Carbon Reduction

Mitigating global warming necessitates an urgent reduction in carbon emissions. The cities in the YRD have exhibited notable disparities in their decoupling status and drivers of their ERCEs across various time periods. In light of this comprehensive analysis, tailored proposals have been formulated to facilitate carbon emission reduction efforts in diverse cities across the YRD.

Regarding economic growth in the YRD, while it has gradually decoupled from ERCEs, it remains a dominant driver in the region. To further promote a low-carbon economy in YRD cities, especially Zhoushan and Taizhou (Jiangsu), industrial upgrading and structural

optimization are crucial. On the one hand, there should be a focus on fostering high-tech industries and service sectors, such as the IT industry and ecotourism. On the other hand, local governments must expedite industrial innovation and optimize the geographical layout of regional pillar industries and strategic sectors to foster a greener and more sustainable economic development model.

As for energy intensity and structure, they functioned as negative factors in the majority of cities in the YRD. Despite the fact that coal remained the primary carbon source in most YRD cities, there was a gradual increase in the rate of natural gas utilization in some areas. Shanghai's government, for instance, has introduced measures to control energy consumption in terms of both quantity and intensity, with a focus on enhancing energy structure and emission reductions in key sectors like electricity, steel, and chemicals [51]. Other cities have also formulated strategies to promote energy structural improvements and reduce consumption [52]. Moving forward, Zhoushan specifically should address the reduction of energy intensity, as it is the only city where energy intensity currently has a positive effect. Conversely, cities like Nantong, Taizhou (Jiangsu), Nanjing, and Ningbo, where energy structure currently contributes positively, should continue to formulate policies aimed at optimizing their energy mix. Across the board, all cities in the YRD should prioritize policies that encourage the adoption of clean energy sources, thereby strengthening their energy transition efforts.

Population size was found to contribute to an increase in ERCEs in most cities, except Yangzhou and Taizhou (in Jiangsu). The YRD, boasting a high-level economy and numerous job opportunities, has attracted a significant influx of migrants in recent years. Shanghai, for instance, has set a long-term target of maintaining its permanent population below 25 million to control population growth. However, in other YRD cities, policies aimed at accelerating economic growth have often entailed attracting outsiders, particularly high-quality talent [53]. This approach could potentially exacerbate carbon emissions and lead to various environmental issues. Therefore, it is crucial for YRD cities to scientifically manage population size and migration flows to ensure sustainable development.

Moreover, since the implementation of the national strategy of integrated development of the YRD, local governments have indeed put forth significant efforts to promote integration across various aspects, including transportation and trade [54,55]. The recent implementation of the Implementation Plan for Carbon Peaking in the YRD Eco-Green Integrated Development Demonstration Zone further underscores the importance of cooperation and collaboration between cities in the region. This plan aims to achieve carbon-peaking goals through the joint efforts of all cities in the YRD. In this context, cities need to work closely with each other, formulate targeted carbon emission reduction policies, and develop an integrated approach to achieving the "Double Carbon" goal through win-win cooperation.

4.3. Limitations and Prospects

Due to limitations in data availability, earlier investigations predominantly concentrated on analyzing ERCEs at the national level [13] and provincial levels [14,15], thereby lacking guidance for policymaking in smaller-scale regions. In our study, we delved into the spatio-temporal dynamics of ERCEs and their decoupling from economic growth across 16 cities in the YRD. Our result was consistent with that of Shan et al. [23], which can help in shaping strategies for a win-win situation at the city level. Nonetheless, while Shan et al. [23] merely focused on ERCE evaluation, our study extended further to explore its underlying drivers. Moreover, in previous explorations of influencing factors, most studies overlook the quantitative analysis of their respective contribution rates. This oversight poses challenges in developing effective policy recommendations. Our study addresses this gap, and our insights provide scientific support for carbon reduction initiatives in the YRD.

However, several limitations need to be acknowledged. Firstly, owing to data availability constraints, only a select few commonly used energy sources were considered for ERCE estimation, potentially leading to an underestimation of the overall emissions. Future studies should consider a wider range of energy types to provide a more comprehensive

reflection of ERCE dynamics. Secondly, the factors influencing ERCEs were broadly categorized into four aspects, and their contribution rates were calculated accordingly. However, the underlying mechanisms driving ERCEs are intricate and require a more systematic examination, especially from the perspectives of specific industries like manufacturing and transportation [52,56]. Econometric methods can be further applied to reveal the influencing mechanism of carbon emissions quantitatively. Meanwhile, we solely explored the influencing factors of ERCEs, neglecting the potential reasons for the different levels of relationships between the dynamics of ERCEs and the rates of economic growth. In future studies, they should be explored to help low-carbon economy development. Lastly, apart from carbon emissions, exploring carbon sinks is also crucial to achieving the “Dual Carbon” goal through a balanced carbon budget perspective. This area represents a promising direction for future research.

5. Conclusions

Carbon emission reduction along with economic growth has become a great challenge for Chinese cities against the background of China’s “Double Carbon” goal. Exploring their decoupling status and influencing factors is of great significance in guiding policies for carbon reduction. In this study, including 16 cities in the YRD as the study area, we evaluated ERCEs and their decoupling with economic growth using the Tapio method and explored the contribution rate of four drivers by using the LMDI method.

Our result showed that during 2000–2020, the total ERCEs increased more than three times, from 413.40 million tons to 1265.86 million tons in the YRD. Spatially, coastal economically developed cities owned significantly higher carbon emissions than those internal cities. The energy structure was continuously improved in the YRD, with the consumption of natural gas gradually increasing from 0.15% to 5.96% from 2000 to 2020. Except for Zhoushan and Taizhou (in Jiangsu), the other 14 cities showed a decoupling relationship between ERCEs and economic growth from 2000 to 2020. The change in energy consumption and decoupling status in most cities both indicated a win–win situation between economic growth and ERCE reduction. As for influencing factors, economic growth was always the key positive factor for ERCEs, while energy structure and intensity played negative roles. Finally, we put forward carbon reduction proposals for achieving the “Double Carbon” goal in the YRD.

Our city-level study addresses a crucial gap, examining ERCE dynamics in 16 YRD cities and quantifying the contribution rate of drivers. This nuanced understanding reveals specific emission drivers and regional differences, informing tailored carbon reduction strategies. Our research bridges the gap between large-scale analyses and policy implementation, contributing to global climate change mitigation efforts.

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