Decomposition and Decoupling of Regional Carbon Emissions: A Case of the Yangtze River Delta in China

Weiwei Huang, Beijing Institute of Technology, China
Muhammad Shahbaz, Beijing Institute of Technology, Pakistan
Hui Li, Beijing Institute of Technology, China

ABSTRACT

This paper applies the logarithmic mean divisia index to explore the decomposition and decoupling of sectoral carbon emissions across four provinces in the Yangtze River Delta (YRD). The results show that (1) the YRD experienced a significant upward trend in sectoral carbon emissions, among which Anhui and Jiangsu provinces experienced the largest increase in carbon emissions. (2) Anhui and Jiangsu showed expansive coupling or weak decoupling in the “10th Five-Year Plan (FYP),” and Shanghai and Zhejiang indicated weak decoupling and strong decoupling in the “11th FYP,” “12th FYP,” and “13th FYP.” These observations showed that the YRD has been transforming its economic growth patterns and increasingly concentrating on the green economy. (3) Shanghai was the most progressive in decoupling. An inspection of decoupling indicators reveals that declining energy intensity contributed most to decoupling, whereas the population scale was less important. In addition, the industry structure and energy structure varied among the provinces.

KEYWORDS

Decoupling Evolution, Driving Factors, Regional Carbon Emissions, Yangtze River Delta

1. INTRODUCTION

In tandem with rapid economic development, urbanization, and industrialization, China is facing severe environmental problems (Gao et al. 2020). In light of these problems, China has pledged to achieve the goal of carbon peaking by 2030 and carbon neutrality by 2060 (World Bank, 2020). As a significant economic region and one of the world’s six largest city clusters, the Yangtze River Delta (YRD) has a high level of economic development and technological innovation (Liu et al. 2020). Although the YRD has less than 3% of its area in China, it produced a quarter of the country’s output in 2012, with a nominal GDP of 24.4 trillion yuan that year (CSY, 2021). However, energy consumption is rising in the YRD, together with the region’s rapid economic growth. The YRD plays a crucial role in the...
global economic and trade system as an important window for China. Energy consumption increased from 270 million tons of coal equivalent (Mtce) in 2001 to 830 Mtce in 2020, an increase of 200% and an average annual growth rate of 6.6% (CESY, 2021) (see Figure 1). Energy consumption of YRD in 2020 exceeds that of Germany and France combined. In particular, the energy consumption of Jiangsu Province is 326.72 Mtce, which exceeds United Kingdom in 2020. The study of energy consumption and carbon emissions in the YRD region has reference value for other countries and regions in the world.

The YRD region is an important region for China to participate in global competition, and it is a sample of other regional integration construction. Sectoral energy consumption accounts for more than 80% of the total energy consumption, and residential consumption accounts for less than 20% of the total energy consumption in the YRD. As the energy structure is dominated by coal consumption, carbon emissions reduction has become a priority in the sector. The ecological and environmental problems caused by carbon emissions in the YRD have become one of the main environmental challenges in China (Zhu et al. 2017a). In addition, the internal economic development and energy consumption of the YRD are also issues worthy of further study, which have important theoretical and practical significance. There are still relatively few studies on decomposition factors and the decoupling state at the regional sector level. In addition, considering the availability of data and the identification of factors relating to carbon emissions, the logarithmic mean divisia index (LMDI) method can be used to determine which factors are driving changes in carbon emissions in the YRD. Meanwhile, the paper identifies the decoupling of different provinces and sectors in the YRD to varying stages through the Tapio method. The decomposition and decoupling of sectoral carbon emissions in the YRD are of great significance for other regions.

To fill the research gap, this paper first explores the differences in CO$_2$ emissions across provinces and sectors and identifies the primary source of CO$_2$ emissions growth in the future. Then, the contributions of population, economic growth, energy structure, and energy intensity to the carbon emissions of the YRD are assessed. Finally, we explore the trends of sectoral decoupling of the YRD, including the decarbonizing progress made by each province. The results contribute to provide insights

Figure 1. 2000-2020 GDP and energy consumption in YRD
into which provinces should continue to increase energy-saving and emission-reduction efforts and strive to achieve carbon peaking. This paper contributes to three aspects: (1) It quantitatively calculates the carbon emissions of the YRD from the sectoral and regional perspectives. The research conclusions provide a reference for the YRD region to promote industrial upgrading, improve energy and carbon emission planning, and promote social and economic green development. (2) This paper extends the analysis to a longer time period to provide insight into the impact of the different drivers over time. The driving factors such as the energy structure, energy intensity, industrial structure, economic growth, and population on the carbon emissions of the YRD is assessed. (3) The decomposition analysis of carbon emissions at the temporal and spatial levels is conducted, which helps to provide evidence to explain the decoupling state and propose specific targeted carbon emission reduction measures at the regional and sectoral levels. The results of the article are conducive to clarifying the responsibilities of the government and the market and providing a reference for the YRD to achieve carbon peak and carbon neutral targets.

The rest of this paper is arranged as follows: Section 2 reviews the previous research on LMDI and Tapio. Section 3 introduces the methodology and data. Section 4 explores the carbon emissions factors and evaluates the decoupling status in the YRD from 2000 to 2018. Section 5 proposes the policy implications and then concludes the paper.

2. LITERATURE REVIEW

In recent years, carbon emissions have caused great concern. Several studies have explored the driving factors of carbon emissions. Table 1 concludes the existing literature and provides an overview of sectoral carbon emissions.

| Reference                          | Period       | Method | Level                | Main conclusion                                                                 |
|------------------------------------|--------------|--------|----------------------|---------------------------------------------------------------------------------|
| Diakoulaki and Mandaraka (2007)    | 1990-2003    | IDA    | EU manufacturing     | Most EU countries made a considerable but not sufficient decoupling effort      |
| Guan et al. (2008)                 | 1980-2013    | SDA    | China                | Capital investment household consumption and exports drive the increase in CO₂ emissions    |
| Defreitas and Kaneko (2011)        | 2004-2009    | LMDI   | Brazil               | Carbon intensity and diversification of energy are the main factors contributing to emission mitigation |
| Jorgenson and Clark (2012)         | 1960-2005    | Regression | World               | Developed countries have a better decoupling relationship than developing countries |
| Dai et al (2016)                   | 1995-2014    | LMDI   | BRICS                | Energy intensity plays a positive role in decreasing CO₂ emission in BRICS countries  |
| Liu et al. (2018)                  | 2007-2012    | IDA and PDA | 30 Provinces         | Economic development was the most significant factor in driving energy consumption growth |
| Li et al. (2019)                   | 1999-2015    | LMDI   | Shanghai             | Decoupling is mostly driven by land economic and energy intensity                  |
| Xia et al. (2020)                  | 2006-2017    | LMDI   | Zhejiang Province    | Energy intensity and technology are the predominant driving forces for the reducing air pollutants |
| Zhang et al. (2020)                | 2000-2016    | LMDI   | Yangtze River        | Energy intensity is the main driver for promoting the decoupling state in most provinces |
Since the issue of CO2 emissions came to the world’s attention, many scholars have conducted research on carbon, an important greenhouse gas. For instance, Defreitas and Kaneko (2011) studied the relationship between economic growth and CO2 emissions in Brazil from 2004 to 2009. Their results found that carbon intensity and energy structure are determinants of carbon emission reduction, while energy intensity was not the main factor behind emissions reduction, as in other countries. Cai et al. (2018) analyzed the drivers of carbon emissions for 286 cities in China. Their study pointed out that urbanization, climatic conditions, and R&D are essential factors for increasing urban CO2 emissions. Liu et al. (2018b) researched provincial carbon emissions through index decomposition analysis (IDA) and production decomposition analysis (PDA) in China. They noted that economic growth was the most significant factor in the growth of energy consumption, and technological changes have played an essential role in reducing energy consumption. In most countries (Gonzalez et al. 2015, Jiao et al. 2013) or regions (Chen et al. 2018a, Liu et al. 2012), economic development (Engo 2019, O’Mahony et al. 2012) has been the primary driver of carbon emissions. The decoupling status has varied widely between developing and developed countries (Song et al. 2019, Wei et al. 2020). At the sectoral level, the decoupling of industrial CO2 emissions and economic growth are widely discussed (Diakoulaki and Mandaraka 2007, Ma et al. 2018a). The results of the study found that most EU countries have made significant but insufficient efforts to achieve decoupling. Gu et al. (2015) measured the factors influencing CO2 emissions in China’s power industry through the LMDI model. They concluded that the share of low-carbon power generation and the efficiency of thermal power generation were important factors for reducing carbon emissions. Ouyang and Lin (2015) used the LMDI method to study the driving forces behind carbon emissions in China’s industrial sector. Their research suggested that the most significant influencing factor of industrial carbon emissions is the energy structure.

Regarding the studies on drivers of CO2 emissions in the case of the YRD, the influence of driving factors (Chen et al. 2019, Gao et al. 2016) and decoupling state (Meng et al. 2018, Yao et al. 2019) on carbon emissions has shown regional differences. Ning et al. (2017) used Tapio to calculate the energy and carbon emissions decoupling index in different regions of China. They found that structural factors in the YRD region had a positive effect from 1996 to 2013, while the efficiency of emissions reduction was less stable over the years. Zhang et al. (2020) investigated the driving factors and inequalities of carbon emissions in the transportation sector in the YRD from 2000-2016. Their results identified Gini inequality and energy intensity in various provinces as a primary source of regional differences. Several studies have analyzed the influencing factors of CO2 emissions in Jiangsu Province for the period 1995 to 2009 (Yu et al. 2019, Yuan et al. 2018, Zhang et al. 2016), while other studies have examined the influence of CO2 emissions on sectors (Wang et al. 2019, Xia et al. 2020, Wang et al. 2013). The results of such studies show that economic activity has been a critical factor influencing CO2 growth, and energy intensity has played a significant role in CO2 reduction. Li et al. (2019), using the LMDI method, studied the energy-saving and emissions-reduction effects of the construction industry in Shanghai. Their study suggested that the construction sector’s annual carbon emissions growth was 15.4 million tons between 1999 and 2015. Xia et al. (2020) constructed Tapio and LMDI models of industrial air pollutant emissions in Zhejiang Province from 2006-2017. They found that energy emissions intensity and technological progress are the main driving forces for reducing pollutant emissions.

Most of the above studies at the regional (Zheng et al. 2019, Zhou et al. 2017), country (Wang and Su 2020, Xu et al. 2014), and sectoral (Leal et al. 2019, Liang et al. 2019) levels have pointed out that economic growth is the most significant factor promoting carbon emissions. However, there are relatively few studies at the regional sector level that focus on the impact of decoupling across sectors. China has been implementing energy conservation and emissions-reduction measures for many years. In addition, it is worth exploring whether economic growth and sector carbon emissions have been decoupled, what factors were essential for sectors to achieve decoupling, and whether there were significant differences between regions.
Based on the above literature review, there still exists some research gap. First, knowledge about the nexus between economic development and carbon emissions in the case of the YRD is limited. Second, few scholars fail to explore the key driver of carbon emissions of the YRD from the perspective of the end-use sector. Third, scholars have not yet explored the decoupling of sectoral carbon emissions in the YRD. To fill these research gaps, this paper investigates the interrelationship between economic growth and CO2 emissions in the case of the YRD and further explores the major factors of the increase in CO2 emissions. The findings contribute to providing a good reference for the YRD to achieve its carbon peak and carbon neutral targets and implement an effective regional development policy.

3. METHODOLOGY AND DATA

3.1 Methodology

3.1.1 Carbon Emissions Accounting Method

According to the method provided by the 2006 IPCC guidelines for national greenhouse gas inventories, CO2 emissions from the relevant sectors are measured (IPCC, 2006). In general, the coefficients of the carbon emissions factor vary over time due to the changes in fuel grades. In this paper, we assume that the carbon emission coefficients of all energy types are constant because of the short study period (2000-2018). Specifically, the emission coefficients of nine types of fossil fuels are considered, including raw coal, cleaned coal, coke, crude oil, gasoline, kerosene, diesel oil, LPG and natural gas. The formula for CO2 emissions produced by each type of energy is given as follows:

\[ C_i = E_i * NCV_i * CC_i * COF_i \]  

where \(C_i\) indicates carbon emissions of energy \(i\), \(E_i\) denotes consumption of energy \(i\), \(NCV_i\) indicates the calorific value of the combustion coefficient of energy \(i\), and \(CC_i\) and \(COF_i\) represent the carbon content and carbon oxidation factor of energy \(i\), respectively.

3.1.2 LMDI Method

The trends in energy consumption or CO2 emissions over time can be well identified through descriptive statistics, but there has been no further analysis on the driving factors of these changes. The Kaya model is commonly used as an analytical tool to explore the key drivers of energy consumption and CO2 emissions (Shahbaz et al. 2019, Wei et al. 2020). This model was first introduced to the IPCC by Kaya (1990) in 1990, which decomposed CO2 emissions into multiple influencing factors. According to the Kaya model (see Equation 2), CO2 emissions from energy consumption were decomposed into four factors: population, GDP per capita, energy efficiency, and energy carbon emission intensity. It is clear from this model that a reduction in carbon emissions from any factor may cause a reduction in total emissions. The formula for Kaya model is as follows:

\[ \frac{CO_2}{E} = \frac{CO_2}{G} * \frac{E}{G} * \frac{G}{P} * P \]  

where \(CO_2\), \(E\), \(G\), and \(P\) denote carbon emissions, energy consumption, gross domestic product, and population, respectively. Different values show the direction and magnitude of each factor’s effect on carbon emissions. The factor with a value greater than 0 indicated a positive contribution, while
less than 0 showed a negative contribution to carbon emissions in the YRD. The larger the value is, the greater the effect of the factor.

With the development of time, the LMDI method was developed on the basis of the Kaya model and gradually became one of the main tools for solving energy and environmental problems. Ang and Choi (1997) proposed the LMDI method to solve the problem of residual and zero values in exponential decomposition analysis, which has become the mainstream method in the field of energy and environment research (Wang et al. 2017, Wang et al. 2014, Zhang et al. 2015). In this paper, the LMDI decomposition model is introduced to analyze the YRD at the sectoral level (Liu et al., 2018a). The LMDI can investigate the drivers of carbon emissions in the YRD region and reveal the relationship between carbon emissions and factors such as energy consumption, economic growth and population. Based on the existing studies, the drivers of carbon emission are selected and determined, taking into account the actual situation and data availability in the YRD. The formulas are as follows (for the variables, see Table 2):

\[
C = \sum_{i=1}^{5} \sum_{j=1}^{9} C^i_j = \sum_{i=1}^{5} \sum_{j=1}^{9} W^i_j \frac{Q^i}{E^i} \frac{E^i}{R^i} \frac{R^i}{G^i} \frac{G^i}{P^i} \\
= \sum_{i=1}^{5} \sum_{j=1}^{9} CI^i_j \times ES^i_j \times EI^i_j \times SI^i_j \times GI^i_j \times P^i \\
\]

where \( \Delta \) represents the amount of change in carbon emissions caused by a particular factor:

\[
\Delta C = \Delta CI + \Delta ES + \Delta EI + \Delta SI + \Delta GI + \Delta P
\]

where the variables are calculated using the following formulas:

\[
\Delta CI = \sum_{i=1}^{5} \sum_{j=1}^{9} W^i_j \left(t^*\right) \ln \left(\frac{CI^T^i_j}{CI^0^i_j}\right)
\]

\[
\Delta ES = \sum_{i=1}^{5} \sum_{j=1}^{9} W^i_j \left(t^*\right) \ln \left(\frac{ES^T^i_j}{ES^0^i_j}\right)
\]

\[
\Delta EI = \sum_{i=1}^{5} \sum_{j=1}^{9} W^i_j \left(t^*\right) \ln \left(\frac{EI^T^i_j}{EI^0^i_j}\right)
\]

\[
\Delta SI = \sum_{i=1}^{5} \sum_{j=1}^{9} W^i_j \left(t^*\right) \ln \left(\frac{SI^T^i_j}{SI^0^i_j}\right)
\]
\[
\Delta GI = \sum_{i=1}^{5} \sum_{j=1}^{9} W_{ij}(t^*) \ln \frac{GI_{ij}^T}{GI_{ij}^0}
\]

\[
\Delta P = \sum_{i=1}^{5} \sum_{j=1}^{9} W_{ij}(t^*) \ln \frac{P_{ij}^T}{P_{ij}^0}
\]

\(W_{ij}(t^*)\) can be calculated from the following equation:

\[
W_{ij}(t^*) = \frac{L(C_{ij}^T, C_{ij}^0)}{L(C^T, C^0)}
\]

The formula used the log-average function of the two endpoint values of the study period as the decomposition weights:

\[
L(x, y) = \begin{cases} 
\frac{x - y}{\ln x - \ln y}, & x \neq y \\
\frac{x^x}{x}, & x = y \\
0, & x = y = 0
\end{cases}
\]

3.1.3 Decoupling Method

Tapio (2005) used the relative amounts of change in pollutants and economic growth to define decoupling through a range of elasticity values. To date, the Tapio decoupling method has been widely used to examine the relationship between economic growth and energy consumption or environmental problems (Brizga et al., 2013; Shahbaz et al., 2022). The relationship between carbon emissions and economic growth for each year obtained through the decomposition process is explored by decoupling. The formula is as follows:

\[
\varepsilon = \frac{\Delta C}{\Delta G} \times \frac{C}{G}
\]

where \(\varepsilon\) denotes the decoupling elasticity coefficient of CO\textsubscript{2} and economic development, \(C\) represents carbon emissions, \(G\) indicates regional output, and \(\Delta G\) and \(\Delta C\) denote the change in GDP and carbon emissions relative to the base period, respectively.

Accordingly, decoupling indicators can be divided into eight states: strong decoupling, weak decoupling, expansive coupling, expansive negative decoupling, strong negative decoupling, weak negative decoupling, recessive coupling, and recessive decoupling (Tapio 2005). Strong decoupling shows that when the economy grows, the carbon emissions of the industry are reduced, which is a better state. The strong negative decoupling indicates that when the economy is in recession, carbon
emissions increase, which is a relatively extensive and chaotic development model. Weak negative decoupling is where both the economy and CO₂ emissions decrease, and the economic deceleration is smaller than the CO₂ deceleration. Expansive negative decoupling shows that both the economy and CO₂ emissions have grown, but the economic growth rate is less than that of CO₂. The YRD economy has been growing for a long time, so the decoupling relationship between the economy and carbon emissions is mostly on the right side (Figure 2). Table 3 provides the classification criteria for the eight decoupling states.

The decoupling efforts can be further evaluated by removing carbon emissions caused by economic growth from the total carbon emissions. The result is the effect of implementing measures such as improving energy efficiency, upgrading the sectoral structure, and optimizing the energy structure. The decoupling effort indicators for carbon emissions are:

\[
\Delta E = \Delta C - \Delta GI = \Delta ES + \Delta EI + \Delta SI + \Delta P
\]  \hspace{1cm} (14)

\[
D = -\frac{\Delta E}{\Delta G} = -\frac{\Delta ES}{\Delta G} - \frac{\Delta EI}{\Delta G} - \frac{\Delta SI}{\Delta G} - \frac{\Delta P}{\Delta G} = D_{ES} + D_{EI} + D_{SI} + D_{P}
\]  \hspace{1cm} (15)

In the formula, \(\Delta E\) is the change in carbon emissions excluding economic growth, and \(D\) is the decoupling effort indicator. When \(D \leq 0\) (no decoupling effort), the decoupling effort makes CO₂ emissions greater than or equal to 0. \(D \geq 1\) (strong decoupling effort) means that the decoupling effort makes CO₂ emission change less than 0. \(0 < D < 1\), which means a weak decoupling effort.

**Figure 2. Decoupling state division**
3.2 Data

This paper collects data on nine types of energy consumption in five sectors in the YRD from the China Energy Statistical Yearbook (CESY). The demographic and economic data were obtained from the China Statistical Yearbook (CSY) in different periods, and the population data in each region were permanent. Since the target period of our study is from 2000 to 2018, a more recent price index may be more appropriate. Thus, we used the GDP and industrial value-added data at 2010 prices. Carbon emissions factors and equivalent standard coal factors for energy were obtained from the 2006 IPCC guidelines for national greenhouse gas inventories. Carbon emissions data were calculated through various carbon emissions coefficients and sectoral energy consumption.

4. RESULTS AND DISCUSSION

4.1 Trends of Sectoral Carbon Emissions in the YRD

Carbon emissions of the YRD by sector are shown in Figure 3. Carbon emissions in all provinces in the YRD increased significantly. The differences between regions showed an expanding trend. During the “10th FYP” (2001-2005) period, the differences in carbon emissions between regions were relatively small, but then the regional differences continued to expand. In particular, the emissions and growth rates of Anhui and Jiangsu were much higher than those in other regions.

From the perspective of time, the average carbon emission of sectors in the YRD during the “10th FYP” was 320 million tons (Mt), among which the largest was 110 Mt in Jiangsu Province, 70 Mt in Zhejiang, and the least was 60 Mt in Anhui. The province with the most significant carbon emissions during the initial stage of the “13th FYP” (2016-2018) was still Jiangsu, with 290 Mt, and the smallest was Shanghai, with 90 Mt. The total carbon emissions in the YRD were 670 Mt. From the sector perspective, industry accounted for the largest share of carbon emissions in the YRD, followed by the construction and transportation sectors. The average carbon emissions of the YRD industry in the initial stage of the “13th FYP” were 610 Mt, accounting for approximately 90% of all sectors. From the growth rate perspective, the “11th FYP” (2006-2010) recorded the
highest growth rate. The average rate in the YRD was 59% in the “11th FYP”. Jiangsu had the most significant increase (77%), and Shanghai had the smallest gain (17%). During the “13th FYP”, the average carbon emissions in the YRD were 670 Mt, an increase of 3%, and the growth rate dropped significantly. For example, carbon emissions decreased by 2% to 90 Mt in Shanghai. Jiangsu had the largest carbon emissions (280 Mt). Anhui’s carbon emissions increased by 5%, reaching 160 Mt, the most significant increase in the YRD.

From the above analysis, Anhui and Jiangsu have had relatively large emissions, while Shanghai and Zhejiang have experienced a decrease in total emissions and rates in recent years. On the one hand, the GDP of the Jiangsu region was close to 9.3 trillion in 2018, which was the highest of the four regions in terms of GDP. The share of industry in Anhui’s 2018 GDP was 39%, which was relatively high among the four regions. On the other hand, Shanghai and Zhejiang have promoted the continuous reduction of carbon emissions through economic restructuring and the phasing out of backward production capacity. In addition, the government should pay attention to the rapid growth of carbon emissions from the transportation sector in the region. With the rapid development of the tertiary sector, carbon emissions in some regions have shown rapid growth. Although the proportion of commercial carbon emissions is still small, there is still significant room for growth. Therefore, the large internal gap in carbon emissions in the YRD should be worthy of attention.

4.2 Decomposition of Sectoral Carbon Emissions

As shown in Figure 4, carbon emissions in the YRD have shown noticeable temporal and regional differences. Total carbon emissions in the YRD have shown a gradually decreasing trend, with significant differences between regions. For example, Shanghai’s sectoral carbon emissions were reduced by 4 Mt in 2018, which related to Shanghai’s efforts to facilitate low energy-consuming sectors and eliminate backward production capacity in recent years.

Figure 4. Carbon emission decomposition factors in the YRD from 2000 to 2018
The role of economic growth in promoting carbon emissions has continued to decline. For example, carbon emissions caused by economic growth dropped from 24 Mt in 2010 to 17 Mt in 2018, a drop of 29% in Jiangsu. This may be related to the strict implementation of the “dual control” target in the YRD. For instance, Zhejiang Province required regional energy consumption per unit of GDP to be reduced by 18% in “12th FYP” compared to the “11th FYP”. Anhui Province has strengthened the construction of energy-saving and environmental protection systems for key departments such as construction, transportation, public institutions, commerce, and agriculture in “13th FYP”. The population has played a role in promoting carbon emissions. For example, the contribution of the population to carbon emissions in Zhejiang increased from 1 Mt in 2000 to 40 Mt in 2010 and then decreased to 20 Mt in 2018. The energy structure and industrial structure have not behaved uniformly in different regions of the YRD.

The cumulative contribution of each decomposition effect to carbon emissions of the YRD region and sectors is shown in Figure 5. Economic growth has been the main factor in the growth of carbon emissions, and energy intensity has been a critical factor in curbing carbon emissions. The energy structure and industrial structure have had a dampening effect on carbon emissions, but this effect has not been significant. The population has increased carbon emissions in some regions.

The increase in GDP contributed to the growth of carbon emissions in the YRD, which indicates that economic growth relies on energy consumption. The cumulative increase in carbon emissions caused by the economic growth of the YRD from 2000 to 2018 was 806 Mt, including 190 Mt in Anhui, 343 Mt in Jiangsu, 169 Mt in Zhejiang, and 100 Mt in Shanghai. The decrease in energy intensity was an essential factor in curbing carbon emissions. The reduction in carbon emissions caused by energy intensity in the YRD region was approximately 445 Mt, including 159 Mt in Jiangsu, 115 Mt in Anhui, 91 Mt in Zhejiang, and 81 Mt in Shanghai. This reflected greater energy conservation and emission reduction in the YRD, with significant technical efficiency and resource utilization improvements. The contribution of the population to carbon emissions has gradually

Figure 5. The cumulative decomposition of carbon emissions in the YRD from 2000-2018

Note: ES: Energy Structure, EI: Energy Intensity, IS: Industrial Structure, Eco: Economic Growth, Pop: Population, Tot: Total
become apparent. Although the population growth rate in the YRD has continued to slow down, the large population base increased carbon emissions from even a slight increase in population. The total cumulative increase in carbon emissions caused by population was 69 Mt from 2010 to 2018, of which Shanghai accounted for 33 Mt. As urbanization proceeds and the population in first-tier cities continues to expand, carbon emissions caused by population will continue to increase. From 2000 to 2018, the energy structure and industrial structure reduced cumulative carbon emissions by 6 Mt and 23 Mt in respectively, in the YRD. However, it is worth noting that there were significant differences between regions. The industrial structure in Anhui even promoted carbon emissions, which was similar to the results of some studies (Cao et al. 2017, Chen et al. 2018b). In addition to Shanghai, the proportion of secondary industry in other regions of the YRD was mainly above 40% from 2010 to 2018, and energy consumption was dominated by coal. Therefore, there is still a long way to go to adjust the industrial structure and energy structure in the future.

4.3 Decoupling of Sectoral Carbon Emissions in Different Periods

Figure 6 shows the decoupling states of the YRD from 2001 to 2018. From the decoupling states of the YRD, the decoupling elasticity index during the “10th FYP” period was 1.02, indicating an expansive coupling state. The “11th FYP” and “12th FYP” (2011-2015) decoupling elasticity indices dropped significantly, showing a weak decoupling state. The initial stage of the “13th FYP” was a strong decoupling state. The expansive coupling state indicated that both the economy and carbon emissions grew during the “10th FYP”, and at roughly the same rate. The YRD has a rough economic growth state and the energy consumption per unit of GDP is at a high level. The government stepped up energy conservation and emissions reduction efforts, and a weak decoupling of economic development and carbon emissions began after the “11th FYP”. From a temporal perspective, most regions exhibited expansive coupling or weak decoupling during the “10th FYP” and “11th FYP”. During the “12th FYP” and “13th FYP”, the decoupling states changed significantly, and most of

Figure 6. Decoupling status of the YRD in different periods

Note: III: Expansive Negative Decoupling, II: Expansive Coupling, I: Weak Decoupling, IV: Strong Decoupling
them revealed weak or strong decoupling. The above analysis shows that the YRD has been gradually adjusting its development approach and changing economic growth to reduce its dependence on energy consumption. From a regional perspective, Zhejiang, Shanghai, and Jiangsu have mostly entered a strong decoupling state, while Anhui is still in a weak decoupling state. This indicates that economically developed provinces have changed their development approach and focused on the quality of economic growth. Therefore, the YRD region should focus on the imbalance among regions and realize the complementary advantages of regional resources in the future.

Figure 7 shows that the decoupling efforts of various provinces increased after removing the economic growth effect. The decoupling efforts reached over 0.3 in all regions during the “12th FYP” period. In terms of the structure of decoupling efforts, energy intensity has made the most significant contribution. The industrial structure mostly showed negative decoupling actions in the “10th FYP”, which had an obvious positive effect after the “11th FYP”. For example, the industrial structure, among other regions in the YRD, has played an excellent decoupling role in Shanghai. This shows that industrial structure adjustments achieved specific results and will remain a meaningful way to save energy and reduce emissions in the future. The population has mostly not made efforts to decouple, especially in densely populated areas such as Shanghai and Zhejiang.

5. Conclusion and Policy Implications

5.1 Conclusion

This paper explores the development trend of sectoral carbon emissions in the YRD over different periods. More specifically, we first identify the characteristics of various provinces and sectors. Then, we explore which sectors may become primary sources of carbon emissions growth in the future and the changing trends of the decoupling status of sectors in the YRD. Finally, we examine the impacts of population, economic growth, energy structure, and energy intensity on sectoral carbon emissions. In conclusion, this paper uses the LMDI and Tapio methods to analyze the decoupling elasticity and decoupling efforts of sectoral development and CO₂ emissions in the YRD from a sector perspective during 2000-2018. The results show that carbon emissions in the YRD sectors have been increasing significantly. From 2000 to 2010, Anhui and Jiangsu experienced a higher increase in carbon emissions.
than other regions in the YRD. In addition, the increases in carbon emissions of Anhui and Jiangsu slowed down from 2010 to 2018. However, there are significant differences in carbon emissions between regions. In 2018, the YRD’s sectoral carbon emissions were 663 Mt, including 159 Mt in Anhui, 278 Mt in Jiangsu, 136 Mt in Zhejiang, and 89 Mt in Shanghai. From a sectoral perspective, industry is still the largest source of carbon emissions in the regions and has a significant impact on achieving the overall decoupling of carbon emissions and economic growth in the YRD. It is worth noting that the transportation sector has seen a substantial increase in carbon emissions in recent years. The government should strengthen the policy constraints of development planning for energy, industry and transportation in the region.

Economic growth is the most crucial factor influencing the increase in sectoral carbon emissions. Energy intensity is essential for curbing carbon emissions and contributed to a cumulative reduction of 430 Mt carbon emissions from 2010 to 2018. The energy structure and industrial structure played a restraining role in some areas, reducing carbon emissions by 6 Mt and 23 Mt, respectively, from 2000 to 2018 in YRD. The population has increased carbon emissions most of the time, but the effect has not been significant. During the “10th FYP”, the YRD experienced expansive coupling. The decoupling indicators in various regions subsequently improved significantly, mostly showing a weak decoupling state during the “11th FYP” period. In the “12th FYP” and early stage of the “13th FYP”, some regions entered a strong decoupling state, especially in Shanghai, where the work of reducing carbon emissions was remarkable.

The YRD has made much headway in decoupling. Decoupling efforts during the “12th FYP” period increased by 236% compared to the “11th FYP”. In terms of each decoupling effort indicator, energy intensity has had the most significant effect, while population decoupling efforts are not apparent. The “10th FYP” showed negative decoupling efforts in the industrial structure, and the “11th FYP” has transformed into an obvious positive effect. Industry structure is an important factor driving the decoupling trend in Jiangsu, Zhejiang, and Shanghai, while its effect has yet to be seen in Anhui. The energy structure varies significantly in different regions. The YRD integrates the region’s scientific and educational resources and the strength of environmental protection enterprises, promotes the transformation of green innovation achievements, and realizes the transformation of enterprises’ green products and the transformation and upgrading of the industry.

5.2 Policy Implications

Through the above conclusions and combined with the current economic and social development and resource endowments of the YRD, this paper proposes the following recommendations. First, the YRD should strengthen regional communication and cooperation to achieve green and coordinated development. In recent years, Anhui and Jiangsu’s emissions have been relatively large, while Shanghai and Zhejiang’s total emissions and rates have shown a decreasing trend. Anhui and Jiangsu should be used as key areas to promote emissions reduction, and Shanghai and Zhejiang should continue to play exemplary roles in the YRD. For the YRD, economic development will remain important, and active economic activities will promote a significant increase in carbon emissions. Therefore, the government should implement corresponding energy conservation and emission reduction measures to balance economic development and environmental protection and gradually develop a low-carbon economy.

Second, it enhances the energy structure and reduces the proportion of coal use. In fact, fossil fuels, such as oil and coal, are still the main sources of energy consumption in the YRD. The proportion of coal consumption in the YRD region is still above 40%, and the effect of the energy structure on carbon emissions reduction is not apparent. Therefore, the proportion of new and renewable energy should be increased as much as possible to improve the existing fossil energy consumption structure and reduce the reliance on fossil energy in the YRD. It is important to consider the impact of the energy structure and determine the subregions and subsectors that have a significant impact. Consequently, the government should continue to apply efforts to develop clean energy and technology. More efforts should be made to adjust the industrial structure instead of simply improving energy efficiency, such
as giving priority to the development of high-tech and low-energy-consuming industries and limiting the further expansion of energy-intensive industries.

In addition, there is an urgent need to adjust the energy structure to promote the development of renewable energy. The government should increase clean energy production and enhance awareness of the comprehensive utilization of clean energy. The development of clean energy is an essential strategy for the sustainable economic development of the YRD, and with the implementation of projects such as “coal to gas”, the demand for natural gas in the YRD is increasing. Therefore, the government and enterprises should increase the exploration of clean energy such as natural gas, water energy, wind energy, and solar energy.

Third, Shanghai should aim to achieve carbon peaking as soon as possible, and Anhui and others should accelerate the achievement of carbon peaking. Shanghai has already achieved a strong decoupling of economic growth and carbon emissions, so it should achieve carbon peaking soon. Anhui and other regions are still in a weak decoupling state and should continue to increase energy conservation and emission-reduction efforts to achieve carbon peaking. The YRD thus achieves overall carbon peaking. The YRD region should accelerate the development of new industries and advanced manufacturing industries. The government builds a modern industrial system with high technological content, low resource consumption and low carbon emissions. In general, there are massive differences in how each province attempts to decouple economic growth from carbon emissions in the YRD. The total carbon emissions of each province decrease over time, and the energy structure and industrial structure are not consistent in different regions of the YRD. Sectoral restructuring and improving energy efficiency will also be essential ways to save energy and reduce emissions in the future. In addition, policymakers should consider financial subsidies and tax incentives in new and renewable energy development to increase their share of energy consumption and achieve the targeted reduction of CO₂. Nonfossil energy will become the dominant energy source in the YRD in the future. The proportion of electricity in end-use energy consumption will gradually rise, pushing the YRD energy toward clean, low-carbon and intellectual development. Therefore, it is important to improve the cross-regional energy allocation and planning layout of the YRD and play an essential role in renewable energy in the energy industry. In addition, increasing the proportion of renewable energy in the overall energy industry will be necessary for decoupling. The measures in the integration process of the YRD should take into account the differences in regional economic growth levels, energy consumption, and carbon emissions and formulate “common but differentiated” responsibilities.

This paper also has some limitations that cannot be well addressed. There is a certain lack of economic data and sectoral data on energy by sector, which hinders us from exploring the decoupling effect of sectoral carbon emissions of provinces and cities in the YRD from a more macroscopic perspective. In the meantime, the paper cannot explore the internal linkages between regions and sectors in the YRD. Therefore, this study can be improved by obtaining more detailed data through extensive surveys and machine learning in the future.
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APPENDIX

Table 2. Symbols and meaning of the variables in the decomposition model

| Variables | Meaning |
|-----------|---------|
| C         | Industry Carbon Emissions |
| W<sub>ij</sub> | Carbon emissions of the energy j in the sector i |
| Q<sub>ij</sub> | Consumption of energy j in the sector i |
| E<sub>i</sub> | Energy consumption in the sector i |
| R<sub>i</sub> | Output in the sector i |
| G         | GDP |
| P         | Population |
| CI<sub>ij</sub> | Carbon emission intensity of the energy j in the sector i |
| ES<sub>ij</sub> | The share of energy j in the sector i |
| EI<sub>i</sub> | Energy consumption per unit of output in the sector i |
| SI<sub>i</sub> | The proportion of the output of the sector i in GDP |
| GI        | GDP per capita |

Table 3. The meaning of carbon emission decoupling

| Decoupling status | Meaning |
|-------------------|---------|
| Strong decoupling | Economy increase while carbon emission decrease |
| Weak decoupling   | The increase pace of carbon emission is smaller than economy |
| Expansive coupling| The increase pace of carbon emission is approximately equal to economy |
| Expansive negative decoupling | The increase pace of carbon emission is obviously bigger than economy |
| Strong negative decoupling | Economy decrease while carbon emission increase |
| Weak negative decoupling | The decrease pace of carbon emission is smaller than economy |
| Recessive coupling | The decrease pace of carbon emission is approximately equal to economy |
| Recessive decoupling | The decrease pace of carbon emission is bigger than economy |