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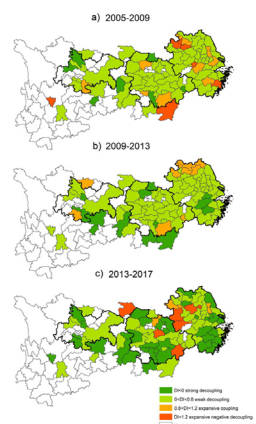
HIGHLIGHTS

- CO_2 emission inventories of 85 cities in Yangtze River Economic Belt were compiled.
- 41% of cities achieved strong decoupling of GDP from CO_2 emission.
- 45% of the cities achieved week decoupling.
- Resource cities changed from decoupling to negative decoupling or coupling.

GRAPHICAL ABSTRACT



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ABSTRACT

Cities play significant roles in mitigating global climate change and formulating low carbon roadmaps. As the first regional strategy that prioritizes green development, the Yangtze River Economic Belt (YREB) is an economic circle along the Yangtze River, stringing up 11 provinces and municipalities from west to east of China. The huge regional heterogeneity in terms of economic development, size, and structure in YREB cities need differentiated emission reduction strategies and low-carbon development pathways. This study compiled the CO_2 emission inventories of 85 cities in the YREB for the first time and explored the decoupling of economic growth from CO_2 emissions at the city level. The results show that CO_2 emissions of YREB cities increased at an annual average rate of 5.1% from 2005 to 2017, and 85 YREB cities emitted 44% of national total CO_2 emissions and contributed 41% of national GDP in 2017. 61% of cities dominated by high-tech and service industry achieved decoupling between economic development and emissions before 2009 and are moving forward to a stronger decoupling state. 25% of cities achieved decoupling after 2009 and these post-decoupling cities took the heavy industry and light industry as their leading industries. Resource-based cities with slow economic development and high CO_2 emissions changed from decoupling to negative decoupling or coupling. The proposed differentiated low-carbon development pathways for YREB cities could provide references for cities at different stages to achieve decoupling of GDP from CO_2 emissions and emission reduction goals.

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1. Introduction

Fossil fuel combustion and industrial processes are the main drivers of climate change, generating CO_2 emissions that contributed 78% of total greenhouse gas emissions increments from 1970 to 2020 (IPCC, 2014). As the world's top energy consumer and CO_2 emitter (Guan et al., 2012; BP, 2019), China has pledged that CO_2 emissions will peak around 2030 under the Paris Agreement and the CO_2 emissions intensity (emissions per unit of gross domestic product (GDP)) will decrease by 60% to 65% compared to 2005 (SC, 2015a). Cities are the major contributors to energy consumption and CO_2 emissions, covering 2% of the global area, and emitting 80% of greenhouse gases (UNHSP, 2011). Therefore, it is crucial to promoting cities' low-carbon development for global climate change mitigation.

The concept of decoupling was proposed by the Organization for Economic Cooperation and Development (OECD) to express the relationship between environmental pressure and economic growth (OECD, 2001, 2002). The CO_2 emission inventory provides a quantitative basis for CO_2 emission mitigation policies formulation and effectiveness evaluation of relevant policies (Ramaswami et al., 2008; Kennedy et al., 2010; Guan et al., 2018; Shan et al., 2018b; Chen et al., 2020; Murakami et al., 2020). Many studies have conducted decoupling analysis of CO_2 emissions from economic growth at the national and provincial levels, discussed the decoupling degrees, its drivers, and low-carbon development pathways (Muller, 2014; Ponce de Leon Barido and Marshall, 2014; Chen et al., 2018; Engo, 2019; Lu et al., 2019; Shuai et al., 2019; Li and Jiang, 2020; Raza and Lin, 2020). For example, based on the Kaya identity, Deutch (2017) analyzed the decoupling between CO_2 emissions and economic growth of the USA, China, and the World, and found that the degree of decoupling depended entirely on the reduction of energy and carbon intensity. Based on the Tapio decoupling model, Zhang et al. (2020) analyzed the elasticity of decoupling between CO_2 emissions, GDP, and energy consumption in China and Southeast Asian Nations countries from 1990 to 2014. Country case studies based on emission inventories of International Energy Agency and Carbon Dioxide Information Analysis Center found that relative decoupling has been identified for countries with intermediate economic growth (e.g. USA, European) or economic restructuring (e.g. China, India) (Mikayilov et al., 2018; Haberl et al., 2020). The dominance of coal in the primary energy mix remains a big obstacle in achieving absolute decoupling (Das and Roy, 2020). At the provincial level, Wu et al. (2019) applied the OECD decoupling model to analyze the Chinese provinces' decoupling effects during 2001–2015 and found that the main decoupling type of Chinese 30 provinces turned into strong decoupling from weak decoupling. However, few studies explored the decoupling of CO_2 emissions and economic growth at the city level (Li et al., 2019; Shan et al., 2021). By compiling emission inventories of global and Chinese cities, Kennedy et al. (2014) and Tong et al. (2018) demonstrated the differences in urban characteristics lead to huge differences in emission reduction strategies. The huge regional heterogeneity in terms of economic development, size and structure in Chinese cities leads to different decoupling patterns (Shan et al., 2021). As the major innovators and enforcers of policy measures to mitigate climate change, cities play significant roles in CO_2 emission reduction actions. Therefore, it is necessary to discuss the decoupling of CO_2 emissions and GDP at the city level to put forward more accurate and appropriate suggestions for low-carbon development.

The Yangtze River Economic Belt (YREB) is one of the major national development strategies in China. The Outline of the Development Plan of the YREB was officially issued in 2016 (NDRC, 2016), which is China's first regional development strategy that takes ecological civilization and green development as the primary principles. An inland river economic belt, the YREB has been given important roles to foster coordinated development of the upper, middle, and lower reaches of the Yangtze River. The YREB consists of 9 provinces (Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Sichuan, Yunnan, and Guizhou) and 2 municipalities (Shanghai and Chongqing), and covers 21% of the national land area (2.05 million km^2), contributing 45% of national GDP in 2017 with 43% of the total population. As one of the most important industrial agglomeration in China, YREB has gathered a group of high-energy-consuming and high-tech industries such as steel, petrochemical, energy, automotive machinery, electronics, and building materials. The output of the steel, automobile, and petrochemical industries of YREB accounts for more than 36%, 47%, and 50% of the national total output, respectively (MIIT, 2016). From 2011 to 2017, the industrial added value of YREB increased by 69.6%, and its proportion in the country increased to 43% (Wu et al., 2018). The strong economic growth of YREB drives high energy consumption and increasing CO_2 emissions. The total CO_2 emissions in the YREB from 2005 to 2013 were 28.46 billion tons, accounting for 42.9% of the national CO_2 emissions (66.4 billion tons) (Huang et al., 2016). YREB plays a significant role in achieving national carbon emission reduction targets. There are three urban agglomerations in YREB, including Yangtze River Delta (YRD), Middle Reaches of Yangtze River Urban Agglomeration (MRYRUA), and Chengdu-Chongqing Urban Agglomeration (CCUA), which including 126 cities with different geographic locations, resource endowments, development stages, industrialization stages, and urbanization levels. Some studies analyzed the peak of CO_2 emissions and the decoupling of CO_2 emissions from economic growth in the YREB at the provincial level, which is difficult to identify the decoupling status of cities and formulate tailored emission reduction strategies (Ding et al., 2019; Tang et al., 2019, 2020).

To fill the gap, this study compiled the CO_2 emission inventory of 85 YREB's prefecture-level cities from 2005 to 2017 based on the IPCC emission accounting approach and the revised emission factors by the China Emission Accounts Datasets (CEADs), which are consistent and comparable with the national/provincial inventories. We then conducted the decoupling of CO_2 emissions and GDP and divided the cities into three categories based on the decoupling trend, namely, pre-decoupling, post-decoupling, and unstable decoupling. Differentiated low-carbon development pathways of YREB cities were discussed. The results could provide references for cities at different stages to achieve decoupling of GDP and CO_2 emissions and carbon emission reduction goals.

2. Methodology

2.1. Construction of CO_2 emissions inventory

We applied the sectoral approach of the IPCC (IPCC, 2006) method to calculate the territorial-based CO_2 emission inventories of YREB cities. According to Shan, Guan (Shan et al., 2017), the CO_2 emissions are calculated by 17 fossils, 47 socioeconomic sectors, and 9 industrial processes (see Tables S2–S4). This study is concerned with emissions from fossil fuel consumption and industrial processes within the city boundary, while emissions from imported electricity, heat consumption from outside the city boundary, and the inter-city transportation energy consumption are excluded. The energy consumed by chemical raw materials and lost during the transportation is eliminated from the total energy consumption to avoid double counting. Emissions of electricity and heat generated within city boundaries are calculated based on the use of primary energy sources, such as raw coal (Peters et al., 2006).

2.1.1. Energy consumption

According to the IPCC, CO_2 emitted from energy consumption can be calculated as energy consumption of different socioeconomic sectors multiplied by the corresponding emission factors, as in Eq. (1).

$$CE_{energy} = \sum_{i=1}^{17}\sum_{j=1}^{47} CE_{ij} = \sum_{i=1}^{17}\sum_{j=1}^{47} AD_{ij} \cdot NCV_i \cdot CC_i \cdot O_{ij} \quad (1)$$

where subscript i and j refer to fossil fuel types and socioeconomic sectors respectively. CE_{ij} presents CO_2 emissions by energy type i and socioeconomic sector *j*. AD_{ij} indicates the amount of fossil fuel consumption. NCV_i, CC_i, and O_{ij} are known as emission factors, which respectively denote net caloric value (the heat value produced per physical unit of fossil fuel combusted), carbon content (the CO_2 emissions per net caloric value produced for different fossil fuel types), and the oxygenation efficiency (the oxidation ratio when burning fossil fuels). In this study, we adopt the emission factors recommended by Liu, Guan (Liu et al., 2015a), which are now widely used by other scholars (Shan et al., 2018b; Li et al., 2019).

2.1.2. Industrial process

Carbon emissions from industrial processes mainly refer to carbon emissions from chemical and physical conversion of materials during industrial production, such as cement production and limestone consumption (Wang et al., 2012; Shan et al., 2016). Eq. (2) is used to estimate CO_2 emissions related to industrial processes.

$$CE_{process} = \sum_{t=1}^{9} CE_t = \sum_{t=1}^{9} AD_t \cdot EF_t \quad (2)$$

where *t* presents the industrial process, CE_t and EF_t respectively denote the process-related CO_2 emissions and emission factors, AD_t presents industrial products. Most of the emission factors for industrial processes were sourced from the IPCC (IPCC, 2006), while the emission factor for cement production was collected from Liu, Guan (Liu et al., 2015a).

2.2. Decoupling analysis

Decoupling methods proposed by the OECD and Tapio are used to analyze the link between environment and economy (Tapio, 2005). The OECD decoupling index is defined by the growth rate of emissions intensity and depends on base period selection. The OECD decoupling method is only related to the decline of emission intensity and cannot measure the decoupling stats in expanding and recessive economies (Conte Grand, 2016). Measured by an emission-to-economic activity elasticity, the Tapio decoupling index can identify non-synchronous changes between carbon emissions and economic growth with several types of decoupling scenarios (Huo et al., 2021) and can be regarded as an effective tool for decoupling analysis (Karakaya et al., 2019; Ma et al., 2019). This study applied Tapio decoupling index to measure the decoupling degrees of CO_2 emission from economic growth at the city level, as follows:

$$\mathrm{DI} = \frac{\Delta CO_2 / CO_2}{\Delta \mathrm{GDP} / \mathrm{GDP}} \quad (3)$$

where *DI* presents decoupling index, CO_2 and *GDP* respectively indicate the baseline period values of CO_2 emissions and GDP, ΔCO_2 and ΔGDP denote the changes in CO_2 emissions and GDP in a period from the base year to the target year, respectively. Based on the decoupling elasticity value, eight decoupling types are defined and shown in Fig. 1. The types

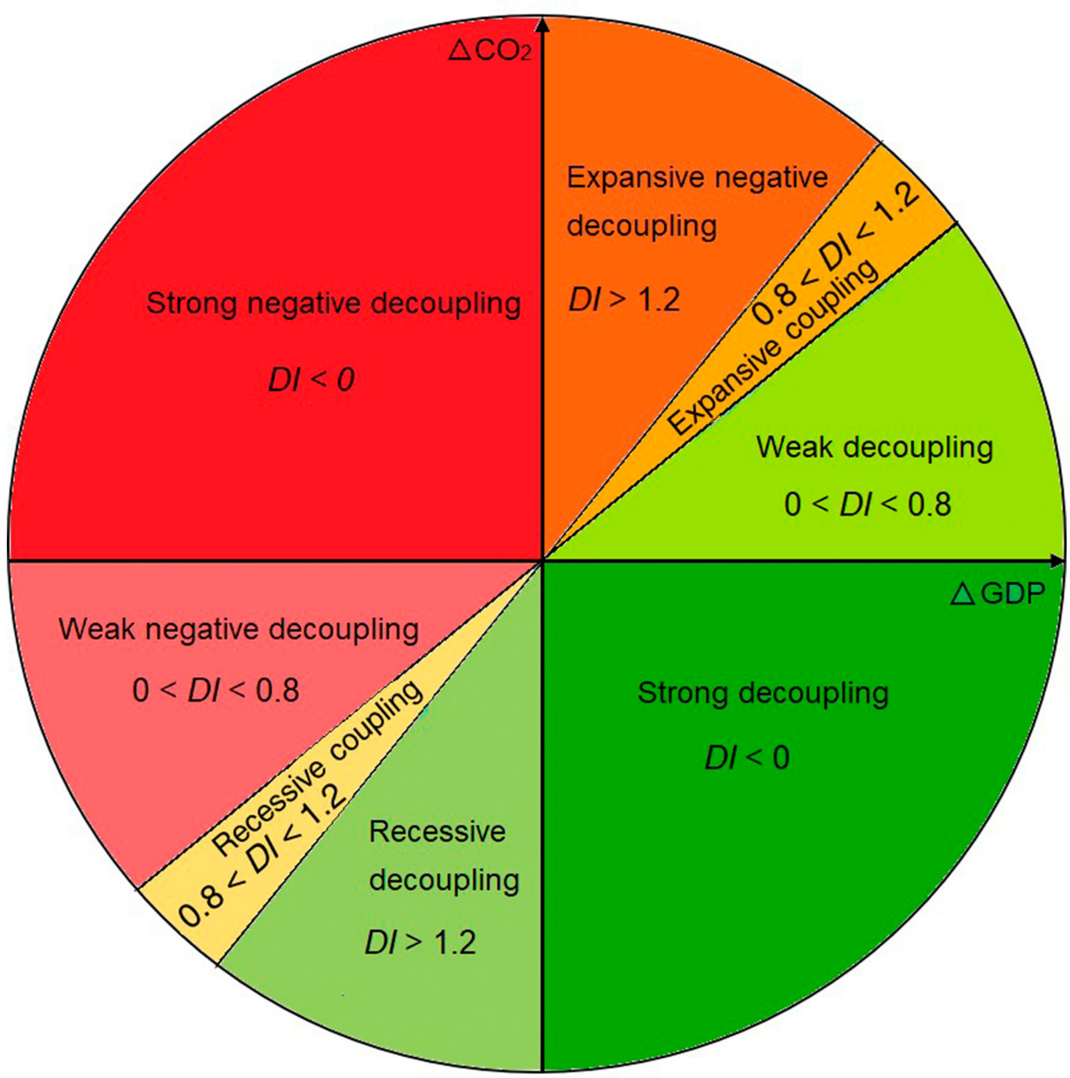

Fig. 1. Decoupling indices and decoupling types.

of decoupling are divided into decoupling (i.e. strong decoupling, weak decoupling, and recessive decoupling), coupling (i.e. expansive coupling and recessive coupling), and negative decoupling (i.e. strong negative decoupling, weak negative decoupling, and expansive negative decoupling).

2.3. Date sources

The GDP, population, and energy consumption data from 2005 to 2017 are based on statistical yearbooks of each city. Due to the lack of statistical yearbooks or data for some cities in YREB from 2005 to 2017 (1 city in YRD, 7 cities in MRYRUA, and 8 cities in CCUA), we selected 85 cities with basically complete data to compile CO_2 emission inventories. The 47 sectoral fossil fuel consumption is based on the energy balance table and industrial sectoral energy consumption table from each city's statistical yearbook. For cities that do not have energy balance tables, we follow our previous research to scale down the corresponding provincial tables to obtain the city-level energy balance tables (Shan et al., 2017). Some cities do not have energy consumption data in their statistical yearbooks for certain years, we converted the previous year's energy consumption data by type into the target year's energy consumption data in proportion.

2.4. Uncertainty of emission inventories

Estimates of urban CO_2 emissions are affected by many factors. Since CO_2 emissions are the product of activity data and emission factors, the uncertainty of activity data and emission factors is considered. This study uses the Monte Carlo method recommended by the IPCC (IPCC, 2006) and widely used in previous studies to assess the uncertainty of CO_2 emissions. Uncertainty analysis provides intervals around the center estimate with upper and lower limits of a certain confidence interval (CI). Based on the input parameters and emission factors of activity data, the Monte Carlo analysis method was established. Activity data and emission factors are assumed to be normally distributed (Liu et al., 2015a). The coefficient of variation (CV, standard deviation divided by the average value) of different emission factors and fossil fuel consumption is selected from previous literature. The CV of emission factor is 3% (coal), 1% (oil) and 2% (natural gas) respectively (IPCC, 2006; Liu et al., 2015b). The CV of activity data ranges from 5% to 30%, depending on the industry (Zhang et al., 2007; Karvosenoja et al., 2008; Wang and Zhang, 2008; Zhao et al., 2008). In the Monte Carlo analysis, we repeated the simulation process 20,000 times. The results show that the range of uncertainty analysis for 85 cities in YREB is [−5.90%, 7.34%], the highest uncertainty appeared in Huainan, Anhui in 2010 [−5.88%, 5.77%], while the lowest appeared in Suining, Sichuan in 2016 [−1.30%, 1.26%].

3. Results and discussions

3.1. CO_2 emissions of the Yangtze River Economic Belt

CO_2 emission inventories of 85 cities in YREB from 2005 to 2017 have been constructed in this study. The result revealed that the total CO_2 emissions of YREB increased from 2251.7 million tonnes (Mt) in 2005 to 4067.3 Mt. in 2017, with an annual average growth rate of 5.1%. YREB cities emitted 43.6% of national total CO_2 emissions and contributed 40.8% of national GDP in 2017. YRD cities produced the largest CO_2 emissions (2566 Mt. in 2017, 63% of total emissions of YREB), followed by MRYRUA (818 Mt., 20.2%), and CCUA (298 Mt., 7.4%). Ningbo (266Mt), Suzhou (225 Mt), Xuzhou (207Mt), Shanghai (198Mt), and Nanjing (190Mt) from YRD are the top five cities, equal to a quarter of total emissions of YREB.

The emission intensity represents the amount of CO_2 emissions emitted per unit of GDP. Fig. 2 presents the emission intensities of

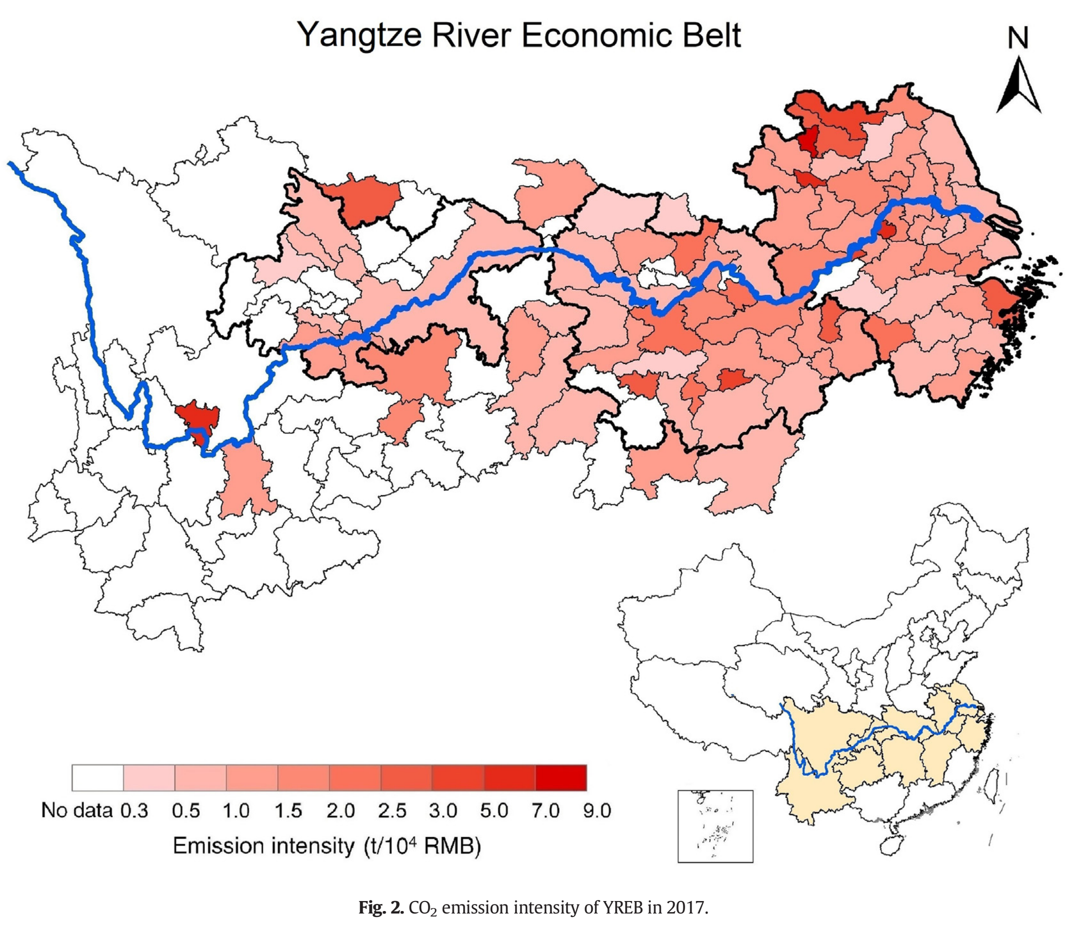

Fig. 2. CO_2 emission intensity of YREB in 2017.

YREB in 2017, and Huaibei in Anhui, a resource-exhausted city province, has the highest emission intensity (8.6 t/10^4 RMB), 27 times higher than Changsha in Hunan, a high-technology-based city, with the lowest emission intensity (0.3 t/10^4 RMB). Fig. 3(a) presents the emission intensities of YREB and three major urban agglomerations from 2005 to 2017. The CO_2 emission intensity of YREB continued to decline, and the emission intensity in 2017 is 61.9% lower than that in 2005, indicating YREB has reached the reducing carbon emission intensity target by 40–45% by 2020 compared with 2005. The emission intensity of MRYRUA experienced the largest decline, and CCUA has the lowest emission intensity. The emission intensity of Zhoushan in Zhejiang Province and Fuzhou in Jiangxi Province rose slightly from 2005 to 2017, while other cities experienced varying degrees of decline. The three cities with the largest reductions in emissions intensity were Pingxiang in Jiangxi (75.8%), Panzhihua in Sichuan (75.3%), Xiangtan in Hunan (72.6%).

As seen from the per capita CO_2 emissions (Fig. 3(b)), the per capita CO_2 emissions of YREB's cities increased steadily from 2005 to 2011 and gradually stabilized after 2011. The per capita CO_2 emissions of YRD are significantly higher than those of the MRYRUA and CCUA. Panzhihua (64 t) in Sichuan province, Ma'anshan in Anhui province (46 t), and Xinyu in Jiangxi province (41 t) are the top three cities with the highest per capita CO_2 emissions in YREB, and those are resource-based cities, relying on mining and processing of natural resources (i.e. minerals). The per capita CO_2 emissions of YREB reached 8.7 tonnes (t) in 2016, which is 1.2 times higher than the national average (7.5 t), and 1.8 times higher than that of the Guangdong-Hong Kong-Macao Greater Bay Area (4.9 t) (Zhou et al., 2018). There are huge room and potential for emission reduction in YREB.

We merged 17 fossil fuels into 3 categories (coal, oil, gas) and divided the total CO_2 emissions into coal-related, gas-related, oil-related, and process-related emissions to analyze the energy consumption structure of YREB. Fig. 3(c) displayed that the emissions of YREB by coal experienced significant growth since 2005 and peaked in 2013. In the past 13 years, the occupation of coal-related emissions decreased by 6% and contributed 66.4% of total emissions in 2017. Oil, gas, and process-related emissions accounting for 19.1%, 4.2%, and 10.3% of total emissions in 2017, respectively. The fossil fuels in YREB are mainly from the West-East Gas Pipeline Project and import from Central Asia and Russia. The coal resources of YRD are from two major coal bases of Huainan-Huaibei and Shanxi-Inner Mongolia (Shan et al., 2018a). In the YRD, 54% of the natural gas resources come from the West-East Gas Pipeline Project, and 43% depend on imports (Pan et al., 2019). To adjust the energy structure to achieve the goal of reducing emissions, Nantong (Jiangsu) eliminated and reformed coal-fired boilers below 4 tons in the urban area, and the Yicheng (Hubei) government-issued the Implementation Plan for Special Remediation of Coal-to-Gas Reformation of Yicheng Coal-fired Boilers. Although Zhejiang, Hunan, Jiangxi formulated coal-to-gas and coal-to-electricity policies to adjust the energy consumption structure, coal consumption still accounts for more than 60% of the total energy consumption in YREB. Therefore, it is necessary to vigorously develop coal purification technology, improve energy utilization, optimize energy consumption structure, and actively develop and utilize clean energy.

47 socioeconomic sectors were classified into 8 categories to better discuss the industrial CO_2 emissions (Fig. 3(d)). Except for the light manufacturing sector, emissions in the other seven sectors have increased in past 13 years. The energy production sector was the largest

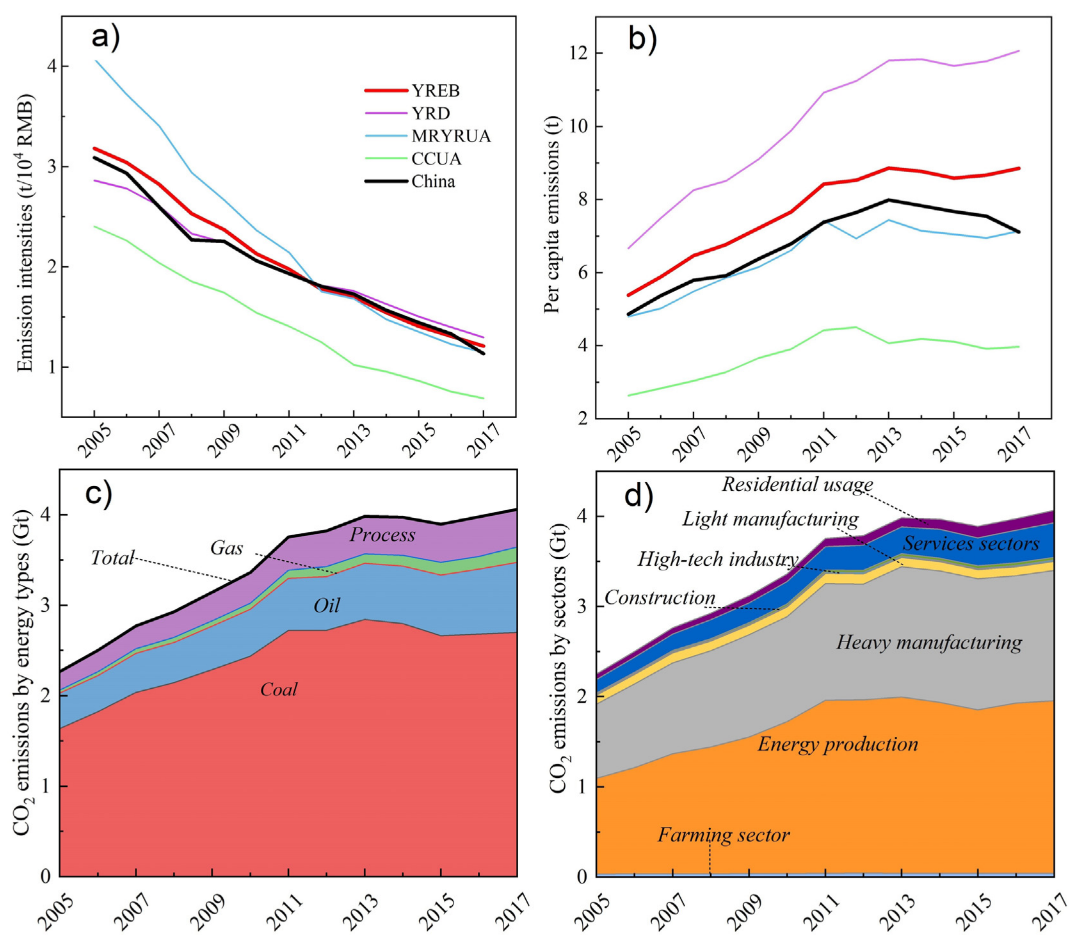

Fig. 3. Time series of CO_2 emissions and related indicators in YREB cities from 2005 to 2017. Carbon emission intensity (a) and per capita carbon emissions (b) of China, the YREB, and its three urban agglomerations. CO_2 emissions by energy types (c) and sectors (d) in YREB.

contributor to total emissions (occupying 47.1% of YREB in 2017), followed by the heavy manufacturing sector (35.5%) and service sectors (9.4%). Emissions by energy production and heavy manufacturing sectors peaked in 2011 and 2013, respectively, while service sectors remain rapid growth. YREB mainly depends on the heavy chemical industry, electromechanical industry, and high-tech industry. The heavy chemical industry includes large enterprises of iron and steel, petrochemical, energy, building materials, and other industries gather in YREB. High-technology industrial clusters are mainly concentrated in provincial capital cities such as Shanghai, Nanjing, Wuhan, Chongqing, and Changsha. The electronic information industry in Shanghai, the biomedical industry in Wuhan, and the automobile manufacturing industry in Chongqing have strong competitiveness nationwide. The Guide to the Industrial Transfer of the YREB (MIIT, 2017) states that it is necessary to vigorously cultivate five world-class industrial clusters of electronic information, high-end equipment, automobiles, home appliances, and textiles and clothing. Therefore, it is necessary to accelerate the low-carbon transformation of key energy utilization industries such as steel, building materials, nonferrous metals, petrochemicals, and chemicals, and build low-carbon enterprises and accelerate the transformation and upgrading of manufacturing. Also, we should pay attention to the contribution of the transport sector. Measures such as vigorously developing urban public transportation, encouraging the development and utilization of new energy vehicles, and low-carbon travel can achieve emission reduction effects.

3.2. Decoupling analysis of the Yangtze River Economic Belt cities

Based on the Tapio decoupling index, we conducted a decoupling analysis between CO_2 emissions and GDP of the YREB cities from 2005 to 2017 (see decoupling index in Table S5, Figs. 4, and S1). During 2005–2009, 69 cities (or 81.1%) in the YREB achieved decoupling of GDP from CO_2 emissions (7 strong decoupling cities, and 62 weak decoupling cities), 9 cities (10.6%) had expansively coupled, and 7 cities (8.2%) appeared to be expansive negative decoupling. During 2009–2013, the number of strong decoupling cities increased to 14 (16.5%), 61 cities (72.9%) maintained weak decoupling, and 10 cities (11.8%) appeared to be expansive coupling. During 2013–2017, strong decoupling cities increased significantly and came to 35 (41.2%), and weak decoupling cities fell to 38 (44.7%); 7 cities (5.9%) appeared to be expansive negative decoupling. Based on the differences in the decoupling stage, cities are into three categories: pre-decoupling cities that achieved decoupling in 2005–2009, post-decoupling cities that achieved decoupling after 2009, and unstable decoupling cities that changed from decoupling to negative decoupling or coupling during 2005–2017 (as shown in Fig. 5). We analyzed the decoupling degrees and characteristics of these three types of cities to explore the differentiated low-carbon development paths of cities in the YREB and discussed the low-carbon development paths of typical case cities.

3.2.1. Pre-decoupling cities

The pre-decoupling city, the optimal city type, indicates a city is driving away from the lock-in effect between economic growth and CO_2 emissions, whose decoupling index is less than 0.8 and is experiencing a decreasing trend. There are 52 cities (61% of the YREB cities) in this group. Among them, 25 cities are strong decoupling cities during 2013–2017, while 27 cities are weak decoupling cities. The CO_2 emissions of pre-decoupling cities increase slowly or even see a decreasing trend, which brings about the results that the change rate of CO_2 emissions becomes smaller than that of GDP. Pre-decoupling cities are mainly dominated by high-tech industries or service industries, such as Shanghai (DI of −0.11), Chongqing (DI of 0.17) and many cities in Jiangsu Province (DI of 0.19), Zhejiang Province (DI of −0.04), Hunan Province (DI of −0.23), Jiangxi Province (DI of 0.08) and Sichuan Province (DI of −0.12).

Shanghai, the center of the international economy, finance, trade, shipping, science, and technology innovation, has made great achievements in the energy transition. In 2010, the offshore wind farm of East China Sea Bridge (100 MW), the first offshore wind power project in China, was connected to the grid and citywide installed wind power capacity reached 210 MW. The installed capacity of photovoltaic power plants came to 20 MW and solar water heaters reached 3.5 million square meters of the heat collection area. The share of non-fossil energy in Shanghai reached 6% (SHADR, 2012). Benefited from West-East Gas Transmission Project, 43.9 billion cubic meters of natural gas was supplied to Shanghai from 2004 to 2019, which replaced 56 million tons of standard coal (Chen, 2019). The share of gas-related emissions in total CO_2 emissions rose to 7.9% in 2017, while the share of coal-related emissions fell to 48%. The service sectors contributed the second-largest amount of CO_2 emissions of Shanghai (33%) after the energy production sectors (38%). The transport sector was the main emitter within the service sectors, and oil-related emissions increased from 34.4% in 2005 to 43.3% in 2017. Shanghai introduced policies to control the number of private cars, increase investment in public transportation facilities, and promote new energy vehicles to reduce CO_2 emissions of the transport sector. The citywide total emissions peaked in 2013 (207.6 Mt). During 2005–2017, GDP grew by 235% while CO_2 emissions increased by only 24%. Shanghai achieved weak decoupling during 2005–2009 (DI of 0.2) and shifted to strong decoupling during 2013–2017 (DI of −0.1). Coal and oil still accounted for a large proportion of the fossil fuel in Shanghai, at 74% in 2016 (SG, 2019). It is significant to further accelerate the development of low-carbon technologies (i.e., large-scale renewable energy power, stored energy, hydrogen energy, and distributed power generation) and adjust energy consumption structure to promote low-carbon development.

Changsha, the capital of Hunan Province and an important central city in the MRYRUA, whose low-carbon development is mainly due to its rational industrial structure. In 2006, Changsha formed three pillar industries of construction machinery, automobiles and parts, and household appliances, and three emerging industries including electronic information, biomedicine, and new materials. A citywide development plan for new energy and energy conservation and environmental protection industries was formulated in 2010 (CEC 2010). As the pilot demonstration city of the 'Made in China 2015 Initiative', Changsha took the lead in intelligent manufacturing of the country. With the high value-added and high-tech industries as the leading industries, the emission intensity of Changsha was only 0.3 t/10^4 RMB in 2017, which was the lowest emission intensity in the YREB. The coal-related and oil-related emissions accounted for 49.9% and 32.2% of total emissions in 2017, respectively. The construction of a 300 MW natural gas distributed energy project will be completed by 2025, and the gasification rate of natural gas in the main urban area will reach 95% (CSBEE, 2020). CO_2 emissions of Changsha peaked in 2011 (41.1 Mt), and there was a strong decoupling of CO_2 emissions from GDP between 2013 and 2017 (DI of 0.5). To realize the target of non-fossil energy share (18% of primary energy consumption) of Changsha in 2025, more efforts should be made to promote the development of clean energy and renewable energy, with a focus on the development and utilization of solar, wind, biomass, and geothermal energy.

3.2.2. Post-decoupling cities

The post-decoupling city suggest a city achieved decoupling after 2009, and its decoupling index fell from 1.1 during 2005–2009 to −0.1 during 2013–2017. Post-decoupling cities are primarily dominated by the heavy and light manufacturing industry, and there are 21 cities (25% of the YREB cities) in this group. Some cities combined their resources and geographical advantages to form unique pillar industries (i.e., the steel industry in Panzhihua), and some cities have accelerated the decoupling by eliminating high-emission industries, extending industrial chains, and nurturing new pillar industries (i.e., the coal chemical industry in Huaibei). Therefore, Panzhihua and Huaibei are selected as the case cities to discuss the differentiated low-carbon development pathways.

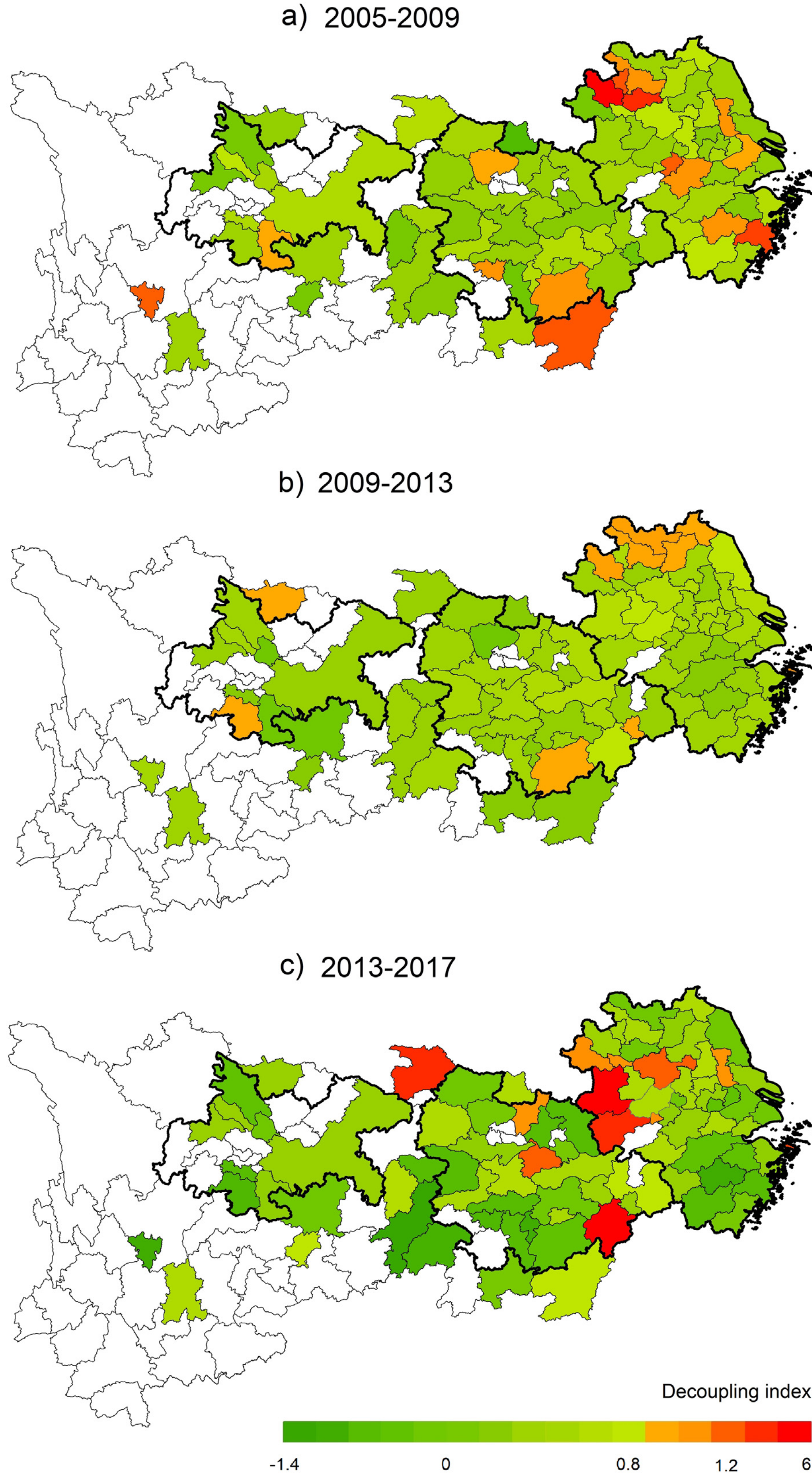

Fig. 4. Decoupling index of the YREB cities in the period of 2015–2017. A lower DI indicates a higher degree of decoupling. DI < 0 means strong decoupling (dark green); 0 < DI < 0.8 stands for weak decoupling (light green); 0.8 < DI < 1.2 denotes for expansive coupling (orange); DI > 1.2 shows expansive negative decoupling (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Panzhihua (Sichuan) is a typical mineral resource-based city in western China. As one of the four largest iron mining areas, it is also the largest production base of vanadium and titanium products in China. Panzhihua relies on its resource endowments to form the industry development model with the steel industry and mining industry as the pillars. The CO_2 emissions of the energy production and heavy

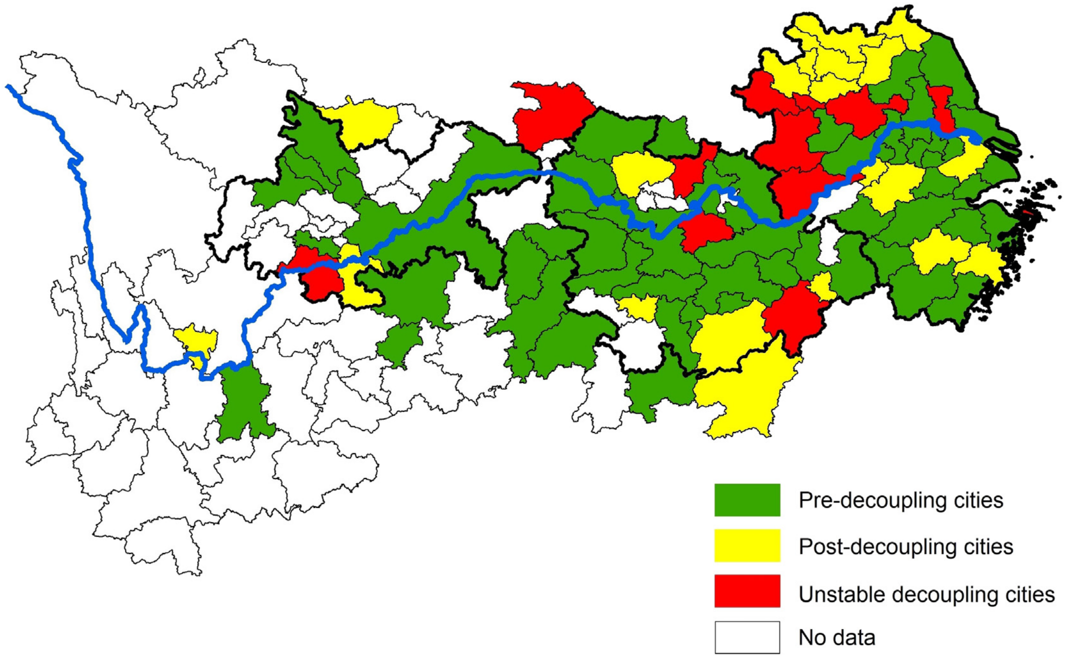

Fig. 5. City category based on the differences in the decoupling stage of YREB.

industry sector in Panzhihua accounted for 98% of total emissions, while the share of the coal-related emissions was 81%. To change the high energy consumption and low value-added development model, Panzhihua explored a new transformation and development pathway. 'Three industrial clusters', the Rehabilitation Equipment Industrial Park, the Vanadium and Titanium Final Products Industrial Park, and the Vanadium and Titanium Steel Recycling and Casting Industrial Park were established to eliminate emission-intensive industries. In 2019, the output value of the circular economy contributed more than 80% of the park's total industrial output, making it the only provincial-level circular economy demonstration zone in Panzhihua (Net, 2019). Transformation efforts brought about a significant change in CO_2 emissions. The citywide total emissions peaked in 2013 (134.1 Mt) and dropped to 89.7 Mt. in 2017. Panzhihua has transformed from expansive negative decoupling (DI of 1.3) to weak decoupling (DI of 0.3), and to strong decoupling (DI of −1.1) during 2005–2017, which can provide a reference of the industrial transformation and sustainable development for other resource-based cities.

Huaibei is an important coal resource-based city and a resource-exhausted city in China. The economic development of Huaibei is based on the mining and processing of coal resources, forming an industrial structure dominated by coal and electricity. The energy industry is in a dominant position in the city's economy. The proportion of emissions by coal accounted for 96.5% in 2005, and continued to grow, reaching a peak in 2011 (97.1%). After 2012, Huaibei faced multiple pressures such as a downturn in the macroeconomy and a sharp decline in coal prices (Hao and Chai, 2013). Economic and social development was in distress, and the urban transformation was imminent. Huaibei launched the 'Special Study on Strengthening the Development of a Low-Carbon Economy during the Twelfth Five-Year Plan', issued the 'Huaibei Low-Carbon Economy Pilot Implementation Plan (Draft)' (HBPGO, 2017), and was selected as the third batch of the pilot the national low-carbon cities in 2017 (NDRC, 2017). Huaibei actively implements the transformation strategy of 'based on coal, extending coal, and surpassing coal'. While extending the coal chemical industry chain, it promotes aluminum-based, carbon-based, silicon-based, biotechnology, and big data industries as its leading industries. Huaibei has built a new coal chemical synthetic material base and formed a coal-coke-electricity-chemical-material circular economy industrial chain. Huaibei achieved weak decoupling of CO_2 emissions from GDP between 2009 and 2017 (DI of 0.3). In 2018, the share of value-added of the non-coal industry in Huaibei has reached 71.7%. In November 2018, the State Council issued a document to affirm and praise the typical experience of Huaibei's transformation (SC, 2018). Huaibei's experience in industrial transformation and building a circular economy industrial chain can provide a reference for the transformation and development of resource-exhausted cities.

3.2.3. Unstable decoupling cities

The unstable decoupling city means the degree of decoupling is changing unsteadily from weak decoupling to negative decoupling or even expansive coupling during 2013–2017. There are 12 cities in this group, including Huainan, Tongling, Anqing, Chuzhou, Fuyang, Lu'an in Anhui Province, Taizhou in Jiangsu Province, Zhoushan in Zhejiang Province, Fuzhou in Jiangxi Province, Shiyan, Xiaogan, and Xianning in Hubei Province. These cities are in a critical period of industrialization, with high-emission and low-value-added industries as their pillar industries. Their CO_2 emissions are in a stage of rapid growth. Around half of the unstable decoupling cities are concentrated in Anhui Province, which should be the focus of low-carbon development in the YREB. The decoupling index of Anhui Province during 2013–2017 was 1.0, while the decoupling index for unstable decoupling cities within Anhui Province reached 2.3. The emission intensity of Huaibei in Anhui was 8.6 t/10^4 RMB in 2017, which is 11 times higher than that of Bengbu in Anhui (0.6 t/10^4 RMB). Cities in Anhui that are lagging in low-carbon development should gain more financial and policy support to narrow the low-carbon development gap within the province. To accelerate the realization of low-carbon development, Anhui should choose to undertake the industrial transfer of low-carbon emission and high added value in Shanghai, Jiangsu, and Zhejiang, such as electronic and telecommunications equipment manufacturing.

These unstable decoupling cities are mainly resource-based cities and cities with slow economic development. The development of resource-based cities relies heavily on high energy consumption and low value-added industries, resulting in CO_2 emissions growing faster than GDP. However, economically depressed cities suffer from negative decoupling mainly due to the lagging urban development and slow GDP growth. Take Lu'an as an example, Lu'an, located in the west of Anhui Province, is a city with underdeveloped industries and a low level of socio-economic development. Lu'an is an expansive negative decoupling city, with a decoupling index of 6.6 from 2013 to 2017. The CO_2 emissions increased by 102% from 2013 to 2017, while GDP growth is the slowest in the YREB with a mere 20.6%. Therefore, to decouple CO_2 emissions from GDP, reducing energy consumption per GDP and emission intensity are the primary objectives. Making the agricultural advantages of Lu'an to develop special tourism and boost economic growth can be a solution. Improving energy efficiency as well as developing renewable projects should also be strategically put on the agenda. Lu'an needs to make more efforts in low carbon development to achieve the peak of 19.73 million tons of carbon dioxide equivalent by 2028, as issued by the Department of Ecology and Environment of Anhui Province.

4. Conclusions and policy recommendations

As a pioneering demonstration zone for green development and ecological protection, the low-carbon development of the YREB is of great significance to the nation in reaching the peak of carbon emissions by 2030. To discuss the low-carbon and sustainable pathways of the YREB, this study compiled the CO_2 emissions inventory of 85 cities in YREB from 2005 to 2017, and analyzed the CO_2 emission characteristics, explored the decoupling relationship between CO_2 emission and economic growth. The main results are as follows:

The CO_2 emissions of the YREB increased from 2251.7 million tonnes (Mt) in 2005 to 4067.3 Mt. in 2017, accounting for 43.6% of the national CO_2 emissions in 2017. The CO_2 emission intensity of the YREB in 2017 decreased by 61.9% compared to 2005, indicating the YREB has reached the reducing carbon emission intensity target by 40–45% by 2020 compared with 2005. The per capita CO_2 emissions of the YREB need to be lowered, which is 1.2 times higher than the national average and 1.8 times higher than that of the Guangdong-Hong Kong-Macao Greater Bay Area. Coal is the main fossil fuel in producing CO_2 emissions, accounting for 66.4% of energy-related emissions in 2017, followed by oil (19.1%), and natural gas (4.2%). The energy production sector was the largest contributor to total emissions, at 47.1%, followed by the heavy manufacturing sector (35.5%) and service sectors (9.4%). The industrial structure and energy structure of the YREB need to be further optimized.

Mitigating CO_2 emissions while maintaining current economic growth is crucial for the sustainable development of the YREB cities, especially after the outbreak of COVID-19. The decoupling analysis shows that 35 cities (41% of YREB cities) have achieved strong decoupling, with decreasing CO_2 emissions and a growing economy. 38 cities (45% of YREB cities) have achieved weak decoupling, with GDP growth greater than the growth of CO_2 emissions. These 73 cities (86% of the YREB cities) show a positive sign in escaping from the lock-in effects between economic growth and CO_2 emissions. The YREB cities show distinct evolution characteristics regarding the decoupling between economic growth and CO_2 emissions. 52 cities can be categorized as pre-decoupling cities, which have achieved decoupling between economic development and emissions before 2009 and are moving forward to a stronger decoupling state. These cities are mainly dominated by service-based and high-tech industries, take the lead in low-carbon development, such as Shanghai and Changsha. In comparison, post-decoupling cities are primarily dominated by the heavy and light manufacturing industry. For the unstable decoupling cities, they changed from decoupling to negative decoupling or coupling from 2005 to 2017 and are characterized by resource-dependence and slow economic growth. The leading industries of unstable decoupling cities are primarily high-emission and low value-added energy production industry.

Differentiated low-carbon development strategies are proposed to realize the low-carbon development of the YREB based on the characteristics of each city type. For the pre-decoupling cities, it is necessary to build a renewable energy-based system by accelerating the energy structure adjustment and increasing the proportion of renewable energy and nuclear energy. The cases of Shanghai and Changsha show that the decoupling of economic growth and emissions can be achieved for cities with different economic structures. Thus, it is not necessary for every city to reorganize its industry structure to be a service-based economy. Promoting technological innovation in low-carbon technologies can be an effective solution to improve energy use efficiency and apply carbon capture, use, and storage industry across the energy system.

CO_2 emissions of post-decoupling cities are mainly contributed by energy production and heavy manufacturing sector. These cities should conscientiously implement the strategic plan of 'Made in China 2025' and seize the opportunity to integrate into the world-class manufacturing clusters of electronic information, high-end equipment, automobiles, home appliances, textiles, and clothing that the YREB intends to build (SC, 2015b; MIIT, 2017). The successful experience of Huaibei and Panzhihua can be borrowed by other cities with similar development patterns, such as developing high-tech and intellectual industries, extending industrial chains, and nurturing new pillar industries. At the same time, the manufacturing clusters should be developed with a focus on circular economy and decarbonization of electric power production.

The unstable decoupling cities are characterized by slow economic development and resource-dependence, whose main challenge is to maintain the current decoupling state or even move towards strong decoupling. The characteristic of heavy resource dependence for unstable decoupling cities inevitably brings about a large demand for fossil fuel and a vast quantity of CO_2 emissions. Their fluctuating decoupling situations are mainly caused by the diverse development paths of resource-based cities. Some cities have moved away from the institutional lock-in and path-dependence and actively promoting industry transformation and upgrading to a low-carbon economy. Some cities are faced with a series of socio-economic problems, such as resource depletion problem, single industrial structure, and sluggish economic development. For the cities with sluggish economic development and resource-dependent characteristics, they should promote the development of clean energy and renewable energy, explore new economic growth points, and accelerate industry transformation and upgrading.

CRediT authorship contribution statement

Kejun Li compiled the emission inventories, conducted the decoupling analysis, and draft the manuscript.

Ya Zhou designed the study, led the analysis and revised the manuscript.

Huijuan Xiao compiled emission inventories.

Zeng Li drew the figure.

Yuli Shan revised the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplemental information

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