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Effect of carbon reduction policies on economic growth from a dual carbon perspective

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Abstract

The study focuses on the energy consumption (EC) and environmental pollution caused by carbon consumption in China's development. The Yangtze River Delta (YRD) region is selected as the primary focus of investigation. To gain insight into the relationship between China's economic growth (EG) and carbon reduction (CR), two major research elements, the impact of each on the other is examined. The study mainly uses decoupling models and influence models to analyze the decoupling relationship and effectiveness between CR and EG. The research results showed that there was a difference between long-term and short-term effects. The short-term effect in the YRD region was manifested as a continuously improving decoupling state, while the long-term effect was manifested as the significant impact of population and per capita Gross Domestic Product on CR. The effect value of EC factor was 0.43, while the effect value of CR factor was 0.07. In functional comparison, the role of EC factors was more significant.

Keywords Double carbon goal, Carbon reduction, Economic growth, Environmental kuznets curve, Decoupling model, Stochastic regression impact model

The abbreviations used in the article was shown in Table 1.

Introduction

As the speedy growth of the national economy, energy consumption (EC) has increased significantly. Although the energy industry can promote rapid social economic growth (EG), excessive EC and consequent environmental pollution can also pose a threat to the sustainability of human development. In the context of mounting global concern about carbon reduction (CR), the establishment of a double carbon goal (DCG) represents a binding development strategy goal that is achievable under a sustainable EG path (Shen 2022; Qin et al. 2009; Cao et al. 2019). Firstly, the DCG is the inevitable direction of human economic and social growth, and the double carbon constraint is essential as long as human society needs the energy industry. Double carbon constraint is an effective inhibitor of sustainable development (Li and Peng 2020; Li 2021; Chuai et al. 2012). Secondly, the strategic DCG can be an effective means for China to seek a path to

Table 1 Abbreviation table

Full name	Abbreviation
Energy consumption	EC
Yangtze river delta	YRD
Economic growth	EG
Carbon reduction	CR
Gross domestic product	GDP
Double carbon goal	DCG
Foreign Direct Investment	FDI

sustainable development and phased development in the context of international ecological public opinion. With the assistance of the DCG, China can successfully achieve EG while fulfilling its obligations as a great power to protect the environment. This approach provides an effective means to domesticate EG and internationalize ecological development (Liu et al. 2019a, b; Liu and Niu 2021).

China's traditional EG model is mainly driven by high-intensity EC, and this growth model will lead to a sustained increase in carbon emissions. In recent years, as the international community has become increasingly aware of the necessity for environmental responsibility, countries have placed greater emphasis on the development of green, low-carbon, and renewable technologies. The economic expansion model has gradually shifted towards a growth model that places more emphasis on green growth and sustainable development, attempting to decouple EG from carbon emissions and achieve green economic development.

Under the dual carbon target, the impact of corporate social responsibility policies on China's environmental benefits is explored by analyzing the long-term and short-term relationship between carbon emissions and economic benefits. In addition, by supplementing research on corporate social responsibility and policy impact under DCG, theoretical support is provided for formulating more scientific green development policies and promoting China's economic transformation towards green, low-carbon, and sustainable development.

Theoretical analysis

The Strategic significance of the double carbon goal

The DCG has a guiding and targeting role in China's green low-carbon economy, charting a path for the adjustment and the development of China's energy industry. The DCG is concerned with the reduction of CR, which has the dual benefit of facilitating the transformation of energy and socio-economic structures, as well as the formation of green industries and green production methods (Sovacool et al. 2020; Bai et al. 2018; Li et al. 2018). Conversely, it is conducive to the adjustment of environmental management and industrial transformation, thereby facilitating the overall social adjustment around CR. This is achieved through the generation of synergy effects in energy, pollution, industry and infrastructure, which are employed to achieve simultaneous promotion (Mossberg et al. 2021; Aoki et al. 2019; Yang 2020). At the same time, the introduction of the DCG also helps the community to develop a concrete concept of CR, which is more conducive to the promotion of sustainable green lifestyles and the concept of social responsibility for environmental protection. From an international point, the introduction of the DCG reflects China's sense of global responsibility as a large economy and its active participation and leadership in the development of a global low carbon economy (Li and Gong 2020; Yuan et al. 2019; Li and Wang 2021).

The need for CR policies under the double carbon goal constraint

Under the constraint of DCG, CR policy is an important measure to implement the exact path of DCG. CR policy can make CR laws and regulations more sound based on the existing industrial market, and gradually establish a healthy CR trading market through policy planning. Through a scientific management system to coordinate the relation between the government and enterprises, the basic system of energy and environmental management is formed, and the active role of the industrial market under the policy regulation is given full play (Shen et al. 2020; Dong et al. 2018; Jiang et al. 2019). Only the correct regulation of industrial markets can form an autonomous development path toward the DCG. CR policy is conducive to the growth of innovative technologies related to CR, promoting the formation of an industrial market with technological advantages through policy preferences. By fully leveraging the fundamental role of technological innovation in corporate responsibility policies, absorbing and flexibly applying corporate responsibility policies and relevant preferential regulations, it can promote the innovative development of enterprises. In addition, it is also conducive to the formation of innovative talents, laying the foundation for the subsequent development of the dual carbon economy (Zheng et al. 2019; Lin and Jia 2019; Daryanto et al. 2019; Moran et al. 2020). This is also conducive to the formation of innovative talents and lays the foundation for the subsequent growth of a double carbon economy. In addition, CR is conducive to the advancement of energy efficiency in social and EG, the current main source of CR is EC. The use of non-renewable energy makes a sharp increase in CR, so the country is still in the stage of excessive non-renewable energy usage. Improving the efficiency of energy use is necessary. Given the generally low energy efficiency of traditional industrial markets, it is necessary to use CR policies to regulate the market and society in policy and infrastructure to promote energy efficiency (Mahi et al. 2021; Iris and Lam 2019; Wang et al. 2019). In the development of economic pathways guided by the DCG, CR policies are appropriate to the current state of regional EG and the state of the energy industry are essential.

Analysis of the EG impact of the double carbon constraint

The analysis of the impact of EG under the double carbon constraint focuses on the relation between CR and EG. Conventional theory suggests that the overall environmental quality of a country is closely related to its EG. In the case of a general increase in national income, the higher the national income, the worse the overall environmental quality of the country. In fact, when the economy develops to a higher level, the deterioration of environmental quality will be somewhat curbed and will gradually improve with the increase of national income (Wu et al. 2019; Miner et al. 2022; Li et al. 2021). The relationship between CR and Gross Domestic Product (GDP) per capita is not a simple one-to-one relationship, but in fact CR are influenced by many other factors. For example, the size of a society's population is closely related to the size of electricity consumption, which in turn is related to the EC of electricity and heat, and thus to the size of CR. Population size and CR are likely to have a positive correlation. In addition, factors such as the proportion of renewable energy in the social environment and the intensity of energy use are also strongly correlated with CR from EC (Waheed et al. 2019; Rehman et al. 2021; Sun et al. 2020). Foreign Direct Investment (FDI) is also a crucial factor. In the context of global economic shift, the investment of developed countries in developing countries is likely to form a kind of transfer of EC and environmental pollution, which is likely to increase CR significantly. However, such investments may also create regional technological and infrastructural development, which in turn may benefit to the CR. In either case, this external economic factor is a necessary consideration for China, a large developing economy in the world. Analyzed from the bad effect of EC on EG, the EG model of developing countries is predominantly crude. The low use of energy and the irrational structure of EC limit the EG. At the same time, as a factor of production, energy is an intrinsic driving force to constantly raise EG, but EC has an impact on the ecological environment and global climate. Energy is a natural environmental resource, and the continuous change of the ecological environment and the consumption process of limited energy in turn affect the sustainability of the economy. Consequently, there is a close interaction between EC, ecological environment and EG. CR can describe the ecological environment, so there is a close relationship among EC, CR and EG.

Overall, in the current discussion of the impact of the CR policy on EG, this impact is divided into two active factors and one passive factor. EG is a passive factor, while environmental and energy factors are active factors. In light of this evidence, research in relevant fields has concluded that there is no straightforward linear relationship between carbon emissions and per capita GDP. Instead, a complex set of factors exerts influence. Similar to previous studies, this study divides the active factors into two aspects, namely carbon emission factor and EC factor. However, this study analyzes the overall trend from a long-term and short-term perspective, while analyzing the decoupling effect in the short term, providing a more comprehensive analysis. Based on the above discussion, the study proposes the following hypotheses.

H1: The regional population, GDP per capita, the amount of actual FDI utilized in the region, and the level of technological progress in the study area all show positive correlations with CR in the Yangtze River Delta (YRD) region in the long-term perspective.

H2: The decoupling status of the YRD region as a whole shows a gradually improving trend, and the influence of the EC and CR factors will gradually converge in the development process.

Model construction

Environmental kuznets curve

The study analyzes the relationship between CR and EG from both long-term and short-term perspectives. To analyze the long-term relationship between carbon emissions reduction and EG, it is necessary to establish a link between carbon emissions and EG. The environmental Kuznets curve can be employed to demonstrate the relationship between environmental quality and EG. Therefore, this study uses the environmental Kuznets curve as the basic trend analysis tool.

The environmental Kuznets curve, based on the Kuznets curve, is a common tool for analyzing the relationship between environmental quality and EG. This curve can reveal the long-term dynamic relationship between the environment and development, so it is more reasonable to choose this model for long-term analysis. However, the environmental Kuznets curve has certain limitations, as it assumes a functional relationship between carbon emissions and EG, ignoring other factors that may affect environmental quality.

The environmental Kuznets curve originates from the Kuznets curve, a curve hypothesis that relates environmental quality to EG. It believes that during the regional EG, the overall environmental quality of the region decreases gradually with the growth of national income. It can represent the fitting relationship between CR and EG. However, when the economy of the region develops to a certain level, the trend of decreasing environmental quality will be curbed, and then the regional economic level and the regional environmental quality number level will rise simultaneously. The study analyzes the shape of environmental Kuznets curve based on the study area and constructs primary, secondary and tertiary environmental Kuznets curve equations to study the relationship between CR and GDP per capita in the region. The primary environmental Kuznets curve equation is shown in Eq. (1).

$$\ln I = c + \alpha lnA + e \tag{1}$$

In Eq. (1), I means CO_2 reduction. A means the level of GDP per capita. c represents other control variables that affect the environment. e is the random error term. α represents the parameter to be estimated. The equation of the secondary environmental Kuznets curve is shown in Eq. (2).

$$\ln I = c + \beta_1 lnA + \beta_2 (lnA)^2 + e \tag{2}$$

In Eq. (2), β denotes the parameter to be estimated.

$$\ln I = c + \gamma_1 lnA + \gamma_2 (lnA)^2 + \gamma_2 (lnA)^3 + e \tag{3}$$

γ in Eq. (3) denotes the parameter to be estimated. The correspondence between the values of the parameters for the environmental Kuznets curve fitting and the shape of the curve is shown in Table 2.

Table 2 Correspondence between the values of the parameters of the environmental kuznets curve fitting and the shape of the curve

Curve Type	The parameter value body appears	Correlation between CR and EG	Curve shape embodiment
Parallel x-axis	$\gamma1 = 0, \gamma2 = 0, \gamma3 = 0$	No correlation	No reflection
Linear	$\gamma1 < 0, \gamma2 = 0, \gamma3 = 0$	GDP per capita and CR show a negative correlation	Linearly decreasing synchronously
	$\gamma1 > 0, \gamma2 = 0, \gamma3 = 0$	GDP per capita and CR show a positive correlation	Synchronous increment in a linear fashion
Quadratic	$\gamma1 < 0, \gamma2 > 0, \gamma3 = 0$	CR decrease and then increase when GDP per capita increases	U-shape
	$\gamma1 > 0, \gamma2 < 0, \gamma3 = 0$	CR increase and then decrease when GDP per capita increases	Inverted U-shape
Cubic	$\gamma1 > 0, \gamma2 < 0, \gamma3 > 0$	CR increase and then decrease when GDP per capita increases, and then continue to increase	N shape
	$\gamma1 < 0, \gamma2 > 0, \gamma3 < 0$	CR decrease and then increase when GDP per capita increases, and then continue to decrease	Inverted N shape

The curves include linearly decreasing and increasing, U-shaped, inverted U-shaped, N-shaped and inverted N-shaped, which can be separated out by the difference in the parameter states

Random regression impact model construction

On the basis of fitting the relationship between carbon emissions and EG, this study adopts the commonly used stochastic regression impact model in this field to analyze the influencing factors of carbon emissions.

In this type of analysis, random regression models are commonly used methods to analyze the impact of influencing factors on specific variables, and can quantitatively analyze the complex relationships of multiple influencing factors. This model is frequently employed in research endeavors within the domains of environmental economics and social sciences. It enables the estimation of the influence of disparate independent variables on a dependent variable. Nevertheless, random regression models are subject to certain constraints, as they presume linear correlations between variables. However, these relationships must be validated in practical settings.

The study uses a random regression model as the main instrument to find the factors influencing regional CR, and the standard form of the random regression model is shown in Eq. (4).

$$I = aP^{b}A^{c}T^{d}e \tag{4}$$

In Eq. (4) a is the model coefficients. I means the environmental pressure element. P represents the population size factor. A represents the regional affluence level factor. T represents the regional technological progress factor. e represents the random error term. b , c and d represent the parameters to be estimated for the corresponding impact factors. In the practical application of the model, the model needs to be logarithmicized as shown in Eq. (5).

$$\ln I = \ln a + b\ln P + c\ln A + d\ln T + \ln e \tag{5}$$

After adding the elasticity coefficient, the model evolves to Eq. (6).

$$\ln I = \ln a + \alpha_1 \ln P + \alpha_2 \ln A + \alpha_3 \ln F + \alpha_4 \ln T + \ln e \tag{6}$$

In conjunction with the study population, I in Eq. (6) represents the CO_2 emissions. P represents the number of population in the study region. A represents the level of GDP per capita in the study region. F represents the amount of actual utilization of FDI in the study region. T represents the level of technological progress in the study region. In addition, α_1, α_2, α_3, and α_4 represent the elasticity coefficients, respectively. a expresses the model coefficients. e represents the random error term.

Decoupling model construction

After completing the long-term perspective modeling, this study adopted a decoupling model that can describe the short-term relationship to analyze the short-term relationship between carbon emissions and economic benefits. This model can describe the connection between blocking EG and environmental pollution.

The decoupling model is widely used in the decision-making process of policy makers on environmental protection measures. It is capable of effectively evaluating the independence between EG and environmental impact, as well as measuring the relationship between environmental load and EG. Choosing this model is reasonable. The limitation is that it may contain the influence of other economic dynamics within it.

The decoupling model and the environmental Kuznets curve explore two sides of the correlation between the two factors of CR and EG. The environmental Kuznets curve is used to investigate the long-term trend relationship between CR and EG, while the decoupling model is applied to investigate the interaction between the two factors in the short run. The decoupling theory mainly describes the role of a factor that blocks the association between environmental pollution and EG, and its main calculation is shown in Eq. (7).

$$E\left(I,GDP\right)=\frac{\%_{\Delta I}}{\%_{\Delta GDP}} \tag{7}$$

In Eq. (7), $E\left(I,GDP\right)$ represents the decoupling index between EG and CR. $\%_{\Delta I}$ represents the growth rate of CO_2 emissions. $\%_{\Delta GDP}$ represents the growth rate of economic level. The type of decoupling is divided into two directions of action, decoupling and negative decoupling. The decoupling effect includes recessionary, weak and strong decoupling. Negative decoupling includes expansionary, weak negative and strong negative decoupling. The specific decoupling types are shown in Fig. 1.

The study introduces the concept of EC into the decoupling model, and then builds an exploratory model of the triangular correlation effect between EC, CO_2 and EG. The specific formula is shown in Eq. (8).

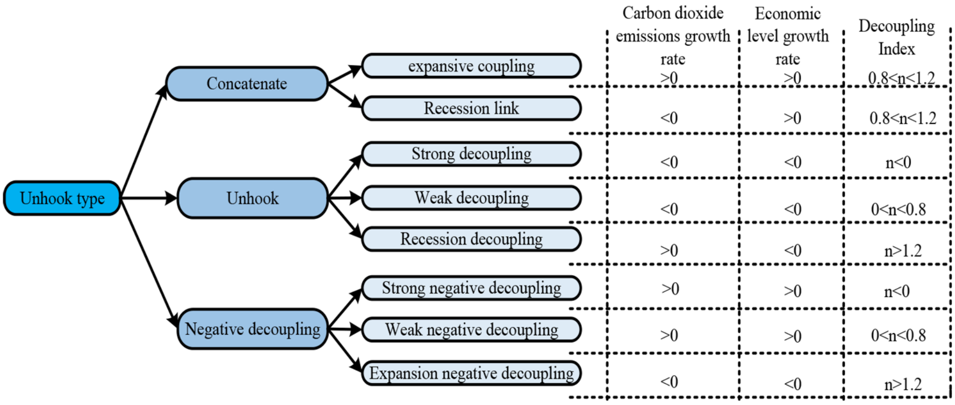
$$E\left(I,GDP\right)=\frac{\%_{\Delta I}}{\%_{\Delta TE}}\times\frac{\%_{\Delta TE}}{\%_{\Delta GDP}}=E\left(I,TE\right)\times E\left(TE,GDP\right) \tag{8}$$

In Eq. (8), $\%_{\Delta TE}$ denotes the growth rate of EC. $E\left(I,TE\right)$ denotes the decoupling index between EC and CR, which can be called the CR factor. $E\left(TE,GDP\right)$ denotes the decoupling index between EC and EG, which can be referred to as the EC factor.

Impact evaluation model construction

The decoupling model is a representation of the short-term relationship. To further explore the dominant influencing factors of the decoupling index between carbon emissions and EG, the study uses an impact evaluation model for further analysis.

The impact evaluation model is capable of calculating the decoupling index between carbon emissions and EG, and subsequently evaluating the influencing factors between them. This enables the exploration of the impact of different model factors on the



	Carbon dioxide emissions growth rate	Economic level growth rate	Decoupling Index
expansive coupling	>0	>0	0.8<n<1.2
Recession link	<0	>0	0.8<n<1.2
Strong decoupling	<0	<0	n<0
Weak decoupling	<0	<0	0<n<0.8
Recession decoupling	>0	<0	n>1.2
Strong negative decoupling	>0	>0	n<0
Weak negative decoupling	>0	>0	0<n<0.8
Expansion negative decoupling	<0	<0	n>1.2

Fig. 1 Decoupling types

decoupling relationship. However, the limitation is that the impact evaluation model adopts a logarithmic accounting approach, which may include non-linear explanatory effects.

The impact evaluation model designed in the study is based on the role of CR and EC factor in the decoupling CR from EG. The model uses the CR and EG decoupling index as the base to calculate the logarithm of the impact factor, and then conducts the corresponding impact evaluation. Due to the fact that the basis in practical applications must be a positive number other than 1, the decoupling index of CR and EG should not exceed 1, i.e. strong decoupling, strong negative decoupling, and linkage state values are all 1. The situation where the impact factor is not greater than 0 will no longer be considered. When the decoupling index of CR and EG is above 1, the logarithm value is often opposite to the factor influence evaluation result. The specific model form is shown in Eq. (9).

$$F_i = \begin{cases} -\log_{E(I,GDP)} Ei, \; E(I,GDP) > 1 \\ \log_{E(I,GDP)} Ei, \, E(I,GDP) < 1 \end{cases} \tag{9}$$

In Eq. (9) F_i is the decoupling factor impact performance. E_i denotes the CR and the EC factor.

Model Data sources

The YRD region between 2008 and 2021 is chosen as the main target of the study because it is one of the most economically developed regions in China and has the most significant correlation between economy and environment. The YRD region is still in a period of rapid development, and the conflict between energy demand, environmental pollution and EG is bound to become more acute under the rapid development. The YRD region is chosen as the research object to answer the environmental-economic correlation problem faced by the high EG region on the one hand, and to provide an ex ante basis for the development path planning of other regions on the other hand. The study uses the China Energy Statistical Yearbook and the statistical yearbooks of the cities in the YRD as the main data sources, and when there are missing data, the study uses the moving average method to supplement them.

The moving average method can handle smooth short-term fluctuations, but this study involves long-term trend analysis. Therefore, multiple imputation techniques are further introduced to fill in missing values. This method accounts for the potential variability of the data by generating multiple highly probable imputation values. This approach fully considers the overall distribution and uncertainty of the data, enhancing the reliability of the results.

Preliminary Processing

Since most countries do not directly publish data on carbon dioxide emissions, the study requires an estimate of CR. Since more than 90% of the domestic CR come from EC, it is reasonable to study the estimation based on EC of fossil fuels using the CR factor method. The specific calculation is shown in Eq. (10).

$$CO_{2t} = \Sigma E_{it} \cdot \mu_i \tag{10}$$

In Eq. (10), CO_{2t} is the CO_2 emissions (million tons) from EC in t year. E_{it} represents the consumption of fossil energy i in tons of standard coal equivalent in t year. μ_i represents the CO_2 emission factor of the fossil energy source i. Since the CO_2 emission factors of different types of fossil energy vary, the study sets the CO_2 emission factors according to the IPCC Guidelines as shown in Fig. 2.

Empirical analysis

Analysis of carbon emission impact factors

The study will analyze the long-run fitting relationship between CR and EG and the short-run role of CR in the empirical analysis. The short-term effect relationship is analyzed by decoupling analysis and decoupling factor influence analysis. In contrast, the long-term fit is analyzed empirically by using environmental Kuznets curve fitting analysis and random regression impact model. In the environmental Kuznets curve fitting analysis part, the study first performs a smoothness test for the fitted variables. The smoothness test can verify the smoothness of the time series data and avoid the phenomenon of pseudo-regression. The study mainly adopts the ADF test to perform the smoothness test. The fitted equations are used to logarithmize the data in the test process, which makes the linear trend of the data more significant. The specific test results are shown in Table 3.

In Table 3, the logarithm of regional CO_2 emissions is unstable. The logarithm of the regional GDP per capita level variable is similarly unstable. When the first-order difference between the logarithm of regional CO_2 emissions and the logarithm of regional GDP per capita level is performed, it shows the non-stationarity. However, the series data show stability when the logarithm of regional CO_2 emissions is second-order differenced from the logarithm of regional GDP per capita level. Since all the original variables

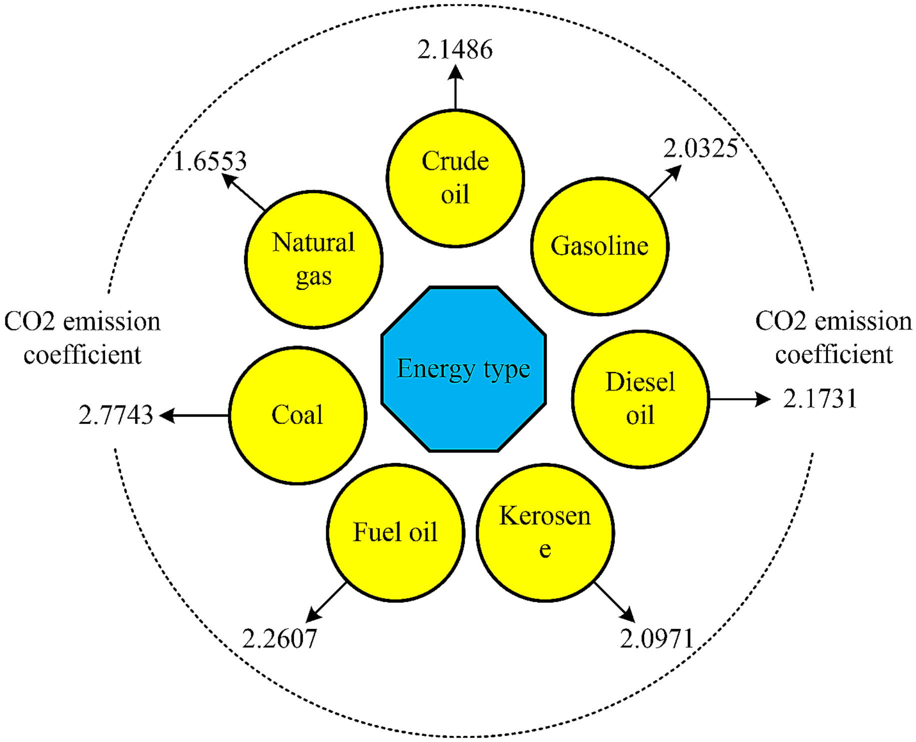


Fig. 2 CO_2 Emission coefficient

Table 3 Stability test of carbon emission influence factors

Variable Type	ADF value	10% Threshold	5% critical value	1% critical value	Test results
Log regional CO_2 emissions	-1.6927	-3.2867	-3.6909	-4.5717	Unstable
Log of regional CO_2 emissions (first order difference)	-2.3923	-3.2657	-3.6909	-4.5717	Unstable
Log of regional CO_2emissions (second order difference)	-4.7935	-3.2976	-3.7106	-4.6163	Smooth and stable
Log regional GDP per capita level	-1.7477	-3.2868	-3.6907	-4.5718	Unstable
Log regional GDP per capita level (first order difference)	-1.3487	-3.2868	-3.6907	-4.5718	Unstable
Logarithm of regional GDP per capita level (second order difference)	-3.8937	-3.2977	-3.7106	-4.6163	Smooth and stable

Table 4 Fitting results

Fitting results of each ECK curve equation	Fitting equation	R^2	R^2 (adjustment)	F-value	P-value
	linear equation	0.9662	0.9645	515.2547	0.000
	Quadratic equation	0.9698	0.9663	272.3716	0.000
	cubic equation (math.)	0.9926	0.9911	702.1875	0.000
Results of fitting the equation of the triple ECK curve	Variables	Coefficient	Standard Error	t-value	F-value
	Regional GDP per capita level	495.092	72.168	6.8603	0.000
	Logarithm of the population count of the study area (first order difference)	-146.183	21.434	-6.8205	0.000
	Logarithm of the population count of the study area (second order difference)	14.618	2.1176	6.9006	0.000
	Constants	-0.485	0.0696	-6.9452	0.000

exhibit a second-order single integer series, there is a stable relationship between regional CO_2 emissions and regional GDP per capita level, which is suitable for fitting. In fitting the environmental Kuznets curve, the study employs linear, quadratic, and cubic equations to fit them, respectively. The specific outcomes of this fitting are expressed in Table 4, which compares the fitting of the three equations.

In Table 4, the value of R^2 for the primary equation fit is 0.9662. The value of R^2 for the secondary equation fit is 0.9698. The value of R^2 for the tertiary equation fit is 0.9926. As for the value of R^2 (adjusted), the value of R^2 (adjusted) for the linear equation fit is 0.9645. The value of R^2 (adjusted) for the quadratic equation fit is 0.9663. The value of R^2 (adjusted) for the cubic equation fit is 0.9911. The three equations have the best fit in terms of R^2 and R^2 (adjusted) values. In terms of significance, the F-value of the three equations is 702.1875 and the p-value is 0.000, which shows a sufficient level of significance overall. This shows that the cubic equation has the best fit and can explain the relationship between CR and EG in the YRD more accurately. Therefore, the study mainly uses the cubic equation for fitting. From the fitting results, $\gamma 1<0$, $\gamma 1>0$, and $\gamma 1<0$. According to the correspondence table between the values of the parameters of environmental Kuznets curve fitting and the shape of the curve, the curve shows an inverted N-shaped state, i.e., the CR first decreases and then increases when the GDP per capita increases, and then continues to decrease. The study performs a smoothness test before conducting a random regression model analysis, as shown in Table 5.

From Table 5, The logarithm of regional carbon dioxide emissions and first-order difference show an unsteady state. Meanwhile, the logarithm and first-order difference of regional population, the logarithm and first-order difference of regional GDP per capita, the logarithm and first-order difference of regional actual utilization of FDI, and the

Table 5 Random regression model variable smoothness test

Variable Type	Calibration Type	ADF value	5% critical value	Test results
Log regional CO_2 emissions	(c, t,1)	-1.6927	-3.6907	Unstable
Log of regional CO_2 emissions (first order difference)	(c, t,0)	-2.3922	-3.6907	Unstable
Log of regional CO_2 emissions (second order difference)	(c, t,0)	-4.7935	-3.7105	Smooth and stable
Log population of the study area	(c, t,0)	-0.2527	-3.6737	Unstable
Logarithm of the population of the study area (first order difference)	(c, t,0)	-2.4207	-3.6907	Unstable
Logarithm of the population count of the study area (second order difference)	(c, t,1)	-6.0066	-3.7334	Smooth and stable
Log regional GDP per capita level	(c, t,1)	-1.7479	-3.6737	Unstable
Log regional GDP per capita level (first order difference)	(c, t,0)	-1.3487	-3.6908	Unstable
Logarithm of regional GDP per capita level (second order difference)	(c, t,0)	-3.8938	-3.7106	Smooth and stable
Logarithm of the actual amount of FDI utilized in the region	(c, t,3)	-2.7365	-3.7333	Unstable
Logarithm of the amount of actual FDI utilized in the region (first order difference)	(c, t,3)	-2.2134	-3.7596	Unstable
Logarithm of the amount of actual FDI utilized in the region (second order difference)	(c, t,1)	-4.5346	-3.7334	Smooth and stable
Logarithm of regional technological progress level	(c, t,0)	-0.5237	-3.6738	Unstable
Logarithm of regional technological progress level (first order difference)	(c, t,0)	-3.8172	-3.6909	Unstable
Logarithm of regional technological progress level (second order difference)	(c, t,4)	-4.0776	-3.8291	Smooth and stable

Note (c, t, k) represents the intercept term, trend term and lag term, respectively

logarithm and first-order difference of regional technological progress all show unstable states. However, the second-order differences of each variable show a smooth state, so there is a long-term stable equilibrium relationship between the variables. Based on this study, to avoid the multi-collinearity results that are easily generated by the traditional least squares method, the ridge regression method is used to fit. The specific outcomes are shown in Fig. 3.

In Fig. 3, the significance levels of the regression coefficients of all variables are below 5%. Among them, the significance levels of the regional population, the amount of regional actual utilization of FDI, and the level of technological progress in the study area are all below 1%. The overall fitting effect is good. The regression coefficient of regional population is 2.265, the regression coefficient of GDP per capita is 0.102, the regression coefficient of regional actual utilization of FDI is 0.102, and the regression coefficient of the technological progress in the study region is 0.069. The regression coefficients of all four variables are above 0. The regression coefficients of all four variables are above 0. The regional population, GDP per capita, the amount of actual FDI utilized in the region, and the technological progress in the study region all show a positive relationship with CR in the YRD region in the long run. Hypothesis 1 holds. However, there are still some differences in the influence of the factors, among which the influence of regional population is relatively large, followed by GDP per capita and the amount of actual utilization of FDI in the region, and finally the level of technological progress in the study region.

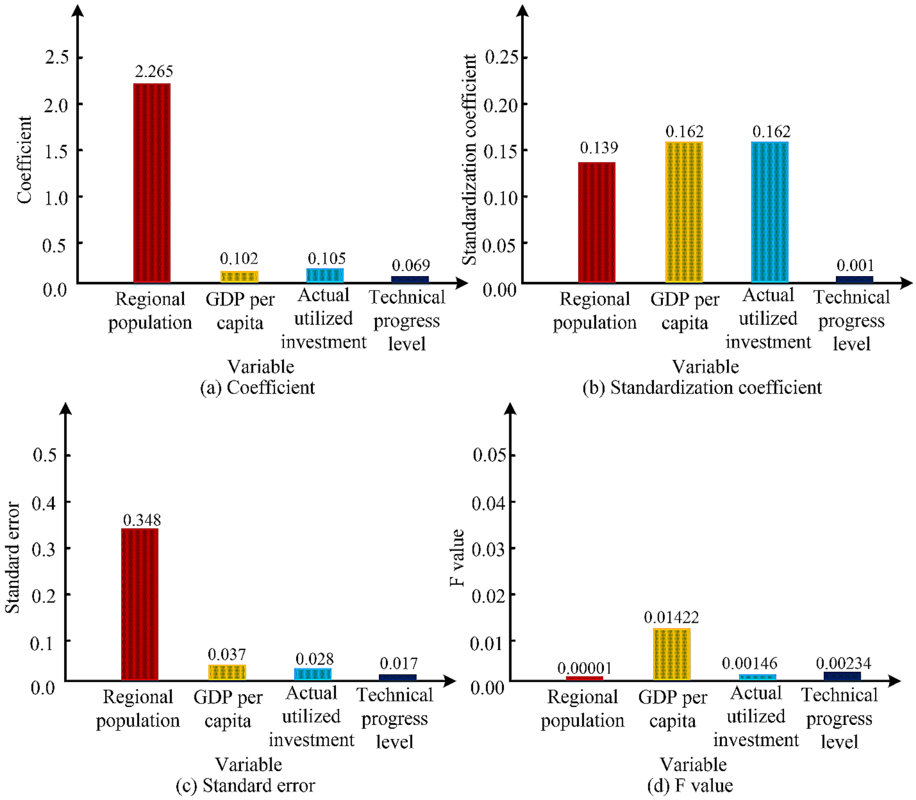


Fig. 3 Regression results

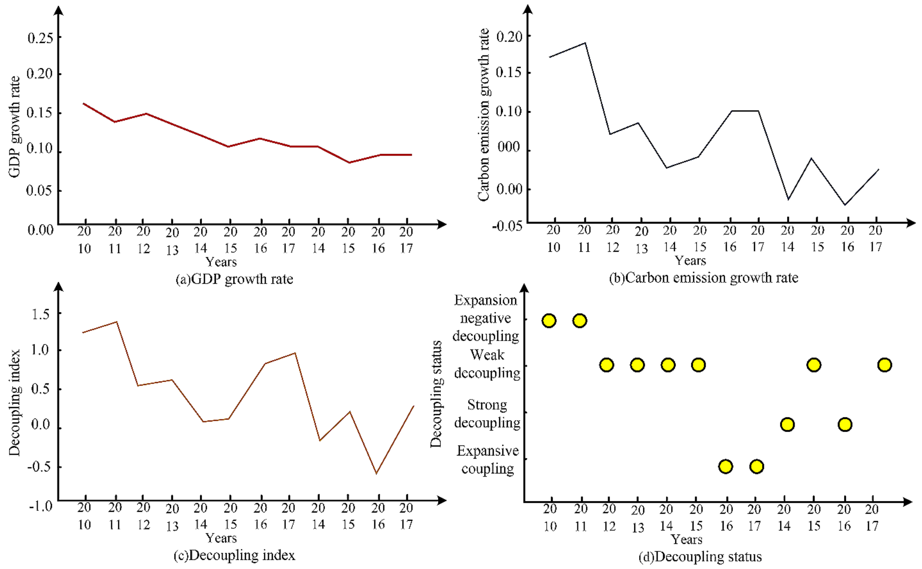


Fig. 4 Regional decoupling status from 2010 to 2021

Empirical analysis of the decoupling of regional CR and EG

The decoupling state of CR and EG in the YRD region between 2010 and 2021 is shown in Fig. 4.

In Fig. 4, the decoupling status of the YRD region as a whole shows a gradually improving trend during the study period. From the negative decoupling state of expansion in

2010, the decoupling state gradually evolves to a weak decoupling state. Although there are some years with strong decoupling, such as 2020 and 2018, the overall trend still seems to be mainly positive. Specifically, from 2010 to 2015, the decoupling state gradually changes from negative decoupling to weak decoupling, and the growth rate of CR shows a fluctuating downward trend. The main state transition point is in 2012, when the CR growth rate declines from 0.19 to 0.07, while the decoupling state changes from negative to weak decoupling. During the period from 2016 to 2021, the decoupling status shows some repetition and fluctuation, but still shows an overall positive trend. Among them, the negative growth rate of CR in 2018 and 2019 causes a sharp decrease in the decoupling index, which in turn creates a strong decoupling phenomenon in 2018 and 2019. However, from the overall trend, the YRD region shows a trend from expansionary linkage to weak decoupling between 2016 and 2021. While the economy is growing dramatically, the overall CR growth rate in the YRD region is decreasing continuously, decoupling state is also gradually improving. The results of the impact evaluation are presented in Table 6.

From Table 6, the relationship between the two elements of EC and EG has a volatility in terms of the EC factor. Overall, the weak decoupling is more dominant, with weak decoupling occurring in almost half of the years. Also from the perspective of the influence of the EC factor, the overall influence of the EC factor is relatively stable. Except for individual years such as 2010, 2011 and 2017, which show negative influence, the influence of all other years is positive. The overall influence of the CR factor shows a trend from negative influence to positive influence, but the overall influence water level is not high after the influence turns to positive influence. This indicates that the contribution of CR factors to the decoupling effect between CR and EG is not sufficient. In terms of decoupling status, the decoupling status of CR factors shows repeated fluctuations between expansionary linkage, recessionary linkage and weak decoupling. Among them, the expansionary link dominates and transforms into a weak decoupling state from 2019 onward. Although it is in an expansionary linkage, the final trend is still positive.

Table 6 Regional impact evaluation results for the period 2010 to 2021

Annual	Decoupling Index	EC factor	Decoupling state under EC factor correspondence	EC factor impact	CR factors	Decoupling state under CR factor correspondence	CR factor impact
2010	1.27	1.27	Expansion negative decoupling	-0.9756	1.02	Expansion Links	-0.0254
2011	1.43	1.45	Expansion negative decoupling	-1.0016	1.01	Expansion Links	0.0015
2012	0.55	0.54	Weak decoupling	1.0212	1.01	Expansion Links	-0.0205
2013	0.58	0.58	Weak decoupling	1.0065	1.02	Expansion Links	-0.0064
2014	0.22	0.22	Weak decoupling	0.9388	0.92	Expansion Links	0.0614
2015	0.23	0.28	Weak decoupling	0.9056	0.88	Expansion Links	0.0945
2016	0.83	0.86	Expansion Links	0.7891	0.97	Expansion Links	0.2109
2017	1.08	1.06	Expansion Links	-0.7192	1.04	Expansion Links	0.2808
2018	-0.07	-0.04	Strong decoupling	\	2.22	Recession Link	\
2019	0.31	0.41	Weak decoupling	0.7984	0.78	Weak decoupling	0.2054
2020	-0.49	-0.44	Strong decoupling	\	1.11	Recession Link	\
2021	0.36	0.44	Weak decoupling	0.7821	0.78	Weak decoupling	0.2187

Empirical analysis of the decoupling between urban CR and EG

The study divides the study period into two main periods, 2010–2015 period and 2016–2021 period, and analyzes on the basis for 25 cities in the YRD region, including Shanghai and Nanjing. The specific analysis results are shown in Table 7.

From Table 7, the YRD cities basically show four states: weak decoupling, negative decoupling, expansion linkage and strong decoupling. In 2010–2015 period, the YRD cities generally show weak decoupling as the dominant state, followed by expansion linkage and strong decoupling. The structure of negative decoupling with a little expansion appears, with 15 cities in weak decoupling, reaching nearly 60% of the total. The only city in the negative decoupling state of expansion is Taizhou. Meanwhile, during the period 2016–2021, the YRD cities in general show a repeated switch between strong decoupling and weak decoupling, with occasional negative decoupling and expansion linking the layout. Among them, there are 10 weakly decoupled cities and 11 strongly decoupled cities. The number of strongly decoupled cities has increased, accounting for nearly 44% of the total number of cities, while the number of weakly decoupled cities has slightly decreased. In summary, the overall decoupling status of cities in the YRD region during the study period shows a shift from negative decoupling of expansion to weak decoupling and then to strong decoupling, showing a tendency to change for the better. The

Table 7 Urban decoupling status for the period 2010 to 2021

YRD Cities	Period 2010–2015		For the period 2016–2021	
	Decoupling Index	Decoupling Status	Decoupling Index	Decoupling Status
Shanghai	0.35	Weak decoupling	-0.19	Strong decoupling
Nanjing	0.31	Weak decoupling	0.27	Weak decoupling
Wuxi	0.25	Weak decoupling	-0.27	Strong decoupling
Lishui	0.28	Weak decoupling	-0.27	Strong decoupling
Taizhou	2.66	Expansion negative decoupling	-0.83	Strong decoupling
Zhoushan	0.42	Weak decoupling	1.37	Expansion negative decoupling
Quzhou	0.07	Weak decoupling	0.29	Weak decoupling
Jinhua	0.86	Expansion Links	-0.27	Strong decoupling
Jiaxing	-0.08	Strong decoupling	-0.05	Strong decoupling
Huzhou	-0.34	Strong decoupling	0.08	Weak decoupling
Introduction	-0.26	Strong decoupling	0.07	Weak decoupling
Wenzhou	1.11	Expansion Links	0.45	Weak decoupling
Ningbo	0.89	Expansion Links	-0.24	Strong decoupling
Hangzhou	-0.06	Strong decoupling	-0.02	Strong decoupling
Suqian	0.62	Weak decoupling	0.82	Expansion Links
Taizhou	0.87	Expansion Links	0.47	Weak decoupling
Zhenjiang	0.03	Weak decoupling	0.35	Weak decoupling
Yangzhou	0.63	Weak decoupling	-0.34	Strong decoupling
Yancheng	-0.05	Strong decoupling	1.91	Expansion negative decoupling
Huai'an	0.34	Weak decoupling	0.03	Weak decoupling
Lianyungang	0.47	Weak decoupling	0.95	Expansion Links
Nantong	0.73	Weak decoupling	0.22	Weak decoupling
Suzhou	0.52	Weak decoupling	-0.06	Strong decoupling
Changzhou	0.17	Weak decoupling	0.17	Weak decoupling
Xuzhou	0.55	Weak decoupling	-0.19	Strong decoupling

results of the analysis of the influence of cities in the YRD during the period 2010–2015 are shown in Table 8.

From Table 8, during the period 2010–2015, in EC factor, the cities in the YRD region show a weak decoupling between EC and EG, supplemented by a strong decoupling, with occasional expansion linkage and negative decoupling of expansion. There are 16 cities with weak decoupling, accounting for 64% of the total number of cities. The strong decoupling cities are Jiaxing, Huzhou, Shaoxing, Hangzhou and Yancheng, accounting for 20% of the total number of cities. Meanwhile, from the influence values, the influence of EC factor in the strongly decoupled cities is negative, which proves that it does not contribute to positive influence, but the influence performance is more significant and common. In terms of CR factors, the relationship between EC and EG in the YRD region cities shows an expansionary linkage, supplemented by a recessionary decoupling and a weak decoupling. There are 17 cities with expansionary linkage, accounting for 68% of the total number of cities. Only three cities, namely Zhenjiang, Lianyungang and Changzhou, are weakly decoupled. The influence of CR factors of all weakly decoupled cities is positive. The results of the analysis of the influence of the YRD cities during the period of 2016–2021 are shown in Table 9.

Table 8 City impact analysis for the period 2010 to 2015

YRD Cities	Decoupling Index	EC factor	Decoupling state under EC factor correspondence	EC factor impact	CR factors	Decoupling state under CR factor correspondence	CR factor impact
Shanghai	0.35	0.38	Weak decoupling	0.9283	0.94	Expansion Links	0.0719
Nanjing	0.31	0.32	Weak decoupling	1.0022	1.01	Expansion Links	-0.0023
Wuxi	0.25	0.27	Weak decoupling	0.9314	0.93	Expansion Links	0.0689
Lishui	0.28	0.27	Weak decoupling	0.9277	0.92	Expansion Links	0.9276
Taizhou	2.66	2.65	Expansion negative decoupling	-0.9903	1.03	Expansion Links	-0.9903
Zhoushan	0.42	0.41	Weak decoupling	0.9857	0.98	Expansion Links	0.9856
Quzhou	0.07	0.08	Weak decoupling	0.9642	0.92	Expansion Links	0.9642
Jinhua	0.86	0.86	Expansion Links	1.1278	1.03	Expansion Links	1.1278
Jiaxing	-0.08	-0.08	Strong decoupling	\	1.27	Recession decoupling	\
Huzhou	-0.34	-0.32	Strong decoupling	\	1.04	Recession Link	\
Introduction	-0.26	-0.24	Strong decoupling	\	1.13	Recession Link	\
Wenzhou	1.11	1.07	Expansion Links	-0.8492	1.04	Expansion Links	-0.8492
Ningbo	0.89	0.87	Expansion Links	1.1175	1.03	Expansion Links	1.1175
Hangzhou	-0.06	-0.03	Strong decoupling	\	4.98	Recession decoupling	\
Suqian	0.62	0.63	Weak decoupling	0.9472	0.99	Expansion Links	0.0531
Taizhou	0.87	0.82	Weak decoupling	1.8645	1.13	Expansion Links	-0.8645
Zhenjiang	0.03	0.04	Weak decoupling	0.8096	0.45	Weak decoupling	0.1904
Yangzhou	0.63	0.69	Weak decoupling	0.7975	0.93	Expansion Links	0.2028
Yancheng	-0.05	-0.02	Strong decoupling	\	4.08	Recession decoupling	\
Huai'an	0.34	0.35	Weak decoupling	0.9677	0.97	Expansion Links	0.0324
Lianyungang	0.47	0.68	Weak decoupling	0.4672	0.68	Weak decoupling	0.5334
Nantong	0.73	0.73	Weak decoupling	0.9638	0.97	Expansion Links	0.0364
Suzhou	0.52	0.52	Weak decoupling	0.9273	0.96	Expansion Links	0.0728
Changzhou	0.17	0.26	Weak decoupling	0.7434	0.65	Weak decoupling	0.2571
Xuzhou	0.55	0.53	Weak decoupling	0.9735	0.98	Expansion Links	0.0262

Table 9 City impact analysis for the period 2016–2021

YRD Cities	Decoupling Index	EC factor	Decoupling state under EC factor correspondence	EC factor impact	CR factors	Decoupling state under CR factor correspondence	CR factor impact
Shanghai	-0.19	-0.07	Strong decoupling	-0.07	\	Recession decoupling	\
Nanjing	0.27	0.34	Weak decoupling	0.35	0.1236	Expansion Links	0.1234
Wuxi	-0.27	-0.18	Strong decoupling	-0.18	\	Recession decoupling	\
Lishui	-0.27	-0.29	Strong decoupling	-0.29	\	Recession Link	\
Taizhou	-0.83	-0.82	Strong decoupling	-0.81	\	Recession Link	\
Zhoushan	1.37	1.14	Expansion Links	1.13	-0.06193	Expansion negative decoupling	-0.6193
Quzhou	0.29	0.36	Weak decoupling	0.36	0.1786	Weak decoupling	0.1784
Jinhua	-0.27	-0.24	Strong decoupling	-0.24	\	Recession decoupling	\
Jiaxing	-0.05	-0.02	Strong decoupling	-0.02	\	Recession decoupling	\
Huzhou	0.08	0.09	Weak decoupling	0.11	0.0345	Expansion Links	0.0342
Introduction	0.07	0.22	Weak decoupling	0.23	0.4826	Weak decoupling	0.4824
Wenzhou	0.45	0.43	Weak decoupling	0.44	0.0137	Expansion Links	0.0144
Ningbo	-0.24	-0.17	Strong decoupling	-0.15	\	Recession decoupling	\
Hangzhou	-0.02	-0.03	Strong decoupling	-0.02	\	Recession Link	\
Suqian	0.82	0.87	Expansion Links	0.87	0.2838	Expansion Links	0.2874
Taizhou	0.47	0.49	Weak decoupling	0.49	0.0704	Expansion Links	0.0703
Zhenjiang	0.35	0.35	Weak decoupling	0.35	0.0568	Expansion Links	0.0567
Yangzhou	-0.34	-0.29	Strong decoupling	-0.27	\	Recession decoupling	\
Yancheng	1.91	1.91	Expansion negative decoupling	1.91	-0.0048	Expansion Links	-0.0048
Huai'an	0.03	0.05	Weak decoupling	0.05	0.1563	Weak decoupling	0.1567
Lianyungang	0.95	0.97	Expansion Links	0.97	0.6527	Expansion Links	0.6527
Nantong	0.22	0.23	Weak decoupling	0.23	0.0854	Expansion Links	0.0854
Suzhou	-0.06	-0.03	Strong decoupling	-0.02	\	Recession decoupling	\
Changzhou	0.17	0.26	Weak decoupling	0.26	0.1555	Weak decoupling	0.1561
Xuzhou	-0.19	-0.19	Strong decoupling	-0.18	\	Recession Link	\

In Table 9, during the period 2016–2021, in EC factor, a strong decoupling and weak decoupling between consumption energy and EG intermittently occurs in the cities of the YRD region. In addition, the occurrence of expansion negative decoupling and expansion linkage states is not uncommon. There are 10 cities with weak decoupling, accounting for 40% of the total number of cities. The number of cities showing strong decoupling is 11, accounting for 44% of the total number of cities. The number of strongly decoupled cities has increased compared to the period 2010–2015. At the same time, the influence of EC factor in strongly decoupled cities is still negative, which proves that it does not contribute to positive influence, but the influence is more significant and widespread. In terms of CR factor, the relationship between EC and EG in YRD cities is mainly declining decoupling and expansionary linkage, with occasional weak decoupling and declining linkage. Among them, only Changzhou, Huai'an and Quzhou show weak decoupling. The number of cities with expansion linkage is 9, which is less than the period of 2010–2015. All weakly decoupled cities have positive values for the influence of the CR factor, indicating a positive contribution. The cities that are in a weakly decoupled state under the CR factor also show a weak decoupling state under the EC factor, while the influence direction is the same, which proves that the influence of the CR factor and the EC factor show a certain convergence effect.

In summary, the YRD urban agglomeration shows the characteristics of the stage impact of decoupling influence factors on different cities with differences, but the overall trend is positive. Meanwhile, from the perspective of different factor influences, the EC factor is more prevalent and significant in the decoupling state of cities under the current development state of the YRD. More negative influences are also generated. In contrast, the positive influence of CR factor is more stable. Both the CR factor and the EC factor show positive effects on the decoupling state of the city, forming a positive effect, and the responses gradually converge. Hypothesis 2 holds.

From a long-term perspective, during the study period, cities in the YRD region gradually shifted from weak coupling to strong coupling, with occasional expansion coupling and negative coupling. From the perspective of environmental coupling factors, most cities exhibit a stable positive impact, indicating that under sustained EG, with the improvement of environmental policies and technologies, the environment will not only not deteriorate but also improve to a certain extent. From the perspective of CR factors, some cities exhibit a state of expansion coupling and weak coupling between CR and EG, indicating that EG can have a restraining effect on the growth of carbon emissions. This indicates that with the support of policies and technology, there is a high possibility of green EG.

The study by Solomon Prince Nathaniel et al. showed that economic and population growth increased carbon dioxide emissions, while FDI reduced carbon dioxide emissions (Nathaniel et al. 2023). This study also analyzed the impact of economic and population growth on carbon emissions and identified them as the main influencing factors. However, this study emphasized the importance of decoupling EC from carbon emissions and EG. Hossein Ali Fakher et al. found that technological innovation helps improve environmental quality, and the study also found the existence of environmental Kuznets curves (Fakher and Ahmed 2023). This study was based on the environmental Kuznets curve, but it focused more on the relationship between carbon emissions and EG. It also examined the significant regulatory role of non-financial factors between technological innovation and environmental indicators. Hossein Ali Fakher et al. argued that non-renewable energy could lead to environmental degradation, while renewable energy could have a positive impact on the environment (Fakher et al. 2023). This study also believed that renewable energy would have a positive impact on the environment, and factors such as population and foreign trade would also have a certain impact. Overall, this study highlighted the link between carbon emissions and EG, which helped promote the further development of CR policies.

Conclusions and recommendations

The study considers CR and EG as correlated factors, and combines the CR context of the DCG. The study takes the YRD region, which has a high level of carbon EC, as the main research object, and conducts the factor impact analysis from two perspectives of long-term and short-term effects. The long-term effect analysis uses two models: the environmental Kuznets curve and the random regression impact model, while the short-term effect analysis uses two models: the decoupling model and the impact evaluation model. The empirical results show that the regional population, GDP per capita, the amount of FDI actually utilized in the region, and the level of technological progress in the study area all show positive correlations with CR in the YRD region in the long-term. The influence of regional population is relatively larger, followed by GDP per capita and the amount of actual utilization of FDI in the region, and finally the level of technological progress in the study region, and hypothesis 1 is valid. The YRD urban agglomerations have stage differences but show an overall positive trend, while the CR and EC factor show a convergent effect on the decoupling state over time, and hypothesis 2 holds.

With the findings, the study suggests that the YRD region should maintain the current trend of gradually improving the decoupling status of urban agglomerations in the subsequent development. The positive effect of the stable CR factor should be utilized and the basic CR policy should be emphasized. In EC factor, localities should keep the characteristics that have significant effects and remove those that may cause negative effects. Improving energy efficiency is the main goal, which is to lay the foundation for a comprehensive transformation of renewable EC structure. When controlling policy elements, it needs to pay full attention to the control of city size and population size, and more aggressive promotional policies should be introduced in terms of both FDI and regional technological innovation. The integration of CR reduction policies with local industrial market development can achieve both environmental and economic effects.

In specific policy recommendations, the study proposes three main recommendations:

(1) Given the close correlation between EG and carbon emissions, it is recommended that a carbon trading market be established with cities as regional units. This would entail the establishment of a sound carbon emission quota system and the implementation of a carbon quota trading system to assist enterprises in achieving their CR goals. At the same time, it is necessary to strengthen the operation of urban governance, promote the technological transformation of high emission enterprises, and improve the efficiency of social responsibility.

(2) Given the positive correlation between FDI and carbon emissions, it is recommended to improve the foreign investment approval system and guide foreign investment in low-carbon technologies. For foreign-funded projects with high carbon emissions, strict environmental assessment standards and control procedures should be established to reduce the entry rate of high carbon emitting enterprises from the source. Foreign invested enterprises can also be encouraged to adopt green technologies to promote the green transformation of the domestic market.

(3) Given the positive correlation between FDI and carbon emissions, it is recommended to establish a special fund and financing support system for the research and development of green technologies. Enterprises can also be encouraged to develop energy-saving and emission reduction technologies by providing tax exemptions and direct subsidies.

Although the study has drawn comprehensive conclusions, this study mainly focuses on factors within China and does not pay attention to special situations in other countries and regions. A more targeted analysis of the special situations of other countries and regions is the future research direction.

Author contributions

Xiaowen Wang made all the contributions in this research.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethical approval

Not Applicable.

Consent for publication

Not Applicable.

Consent to participate

Not Applicable.

Competing interests

The authors declare no competing interests.

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References

Aoki Y, Bauer M, Braun T, Cadge JA, Clarke GE, Durand DJ, Eisenstein O, Gallarati S, Greaves M, Harvey J (2019) Mechanistic insight into organic and industrial transformations: general discussion. Faraday Discuss 220:282–316. https://doi.org/10.1039/C9FD90072A

Bai Q, Jin M, Xu X (2018) Effects of carbon emission reduction on supply chain coordination with vendor-managed deteriorating product inventory. Int J Prod Econ 208:83–99. https://doi.org/10.1016/j.ijpe.2018.11.008

Cao K, Chen Y, Qiang B (2019) Research on the construction of green management information system for sustainable development. IOP Confer Ser Mater Sci Eng 688:055041. https://doi.org/10.1088/1757-899X/688/5/055041

Chuai X, Huang X, Wang W, Wen J, Chen Q, Peng J (2012) Spatial econometric analysis of carbon emissions from energy consumption in China. J Geogr Sci 22(4):630–642. https://doi.org/10.1007/s11442-012-0952-z

Daryanto Y, Wee HM, Astanti RD (2019) Three-echelon supply chain model considering carbon emission and item deterioration. Transp Res Pt E-Logist Transp 122:368–383. https://doi.org/10.1016/j.tre.2018.12.014

Dong F, Dai Y, Zhang S, Zhang X, Long R (2018) Can a carbon emission trading scheme generate the Porter effect? Evidence from pilot areas in China. Sci Total Envir 653:565–577. https://doi.org/10.1016/j.scitotenv.2018.10.395

Fakher HA, Ahmed Z (2023) Does financial development moderate the link between technological innovation and environmental indicators? An advanced panel analysis. Financial Innov 9(1):112. https://doi.org/10.1186/s40854-023-00513-2

Fakher HA, Ahmed Z, Acheampong AO, Nathaniel SP (2023) Renewable energy, nonrenewable energy, and environmental quality nexus: an investigation of the N-shaped environmental Kuznets curve based on six environmental indicators. Energy 263:125660. https://doi.org/10.1016/j.energy.2022.125660

Iris C, Lam JSL (2019) A review of energy efficiency in ports: operational strategies, technologies and energy management systems. Renew Sustain Energy Rev 112:170–182. https://doi.org/10.1016/j.rser.2019.04.069

Jiang L, Chang H, Zhao S, Dong J, Lu W (2019) A travelling salesman problem with carbon emission reduction in the last mile delivery. IEEE Access 7:61620–61627. https://doi.org/10.1109/ACCESS.2019.2915634

Li X (2021) Study on the impact of energy rebound effect on carbon emission reduction at different stages of urbanization in China. Ecol Indic 120(7):106983. https://doi.org/10.1016/j.ecolind.2020.106983

Li J, Gong S (2020) Coordination of closed-loop supply chain with dual-source supply and low-carbon concern. Complex 2020(5):1–14. https://doi.org/10.1155/2020/7506791

Li H, Peng W (2020) Carbon tax, subsidy, and emission reduction: analysis based on dsge model. Complexity. 2020(6), 1–10. https://doi.org/10.1155/2020/6683482

Li Z, Wang J (2021) Spatial emission reduction effects of China's carbon emissions trading: quasi-natural experiments and policy spillovers. Chin J Popul Resour Environ 19(3):246–255. https://doi.org/10.1016/j.cjpre.2021.12.027

Li Z, Shao S, Shi X, Sun Y, Zhang X (2018) Structural transformation of manufacturing, natural resource dependence, and carbon emissions reduction: evidence of a threshold effect from China. J Clean Prod 206:920–927. https://doi.org/10.1016/j.jclepro.2018.09.241

Li ZZ, Li RYM, Malik MY, Murshed M, Umar M (2021) Determinants of carbon emission in China: how good is green investment? Sustain. Reprod Consum 27:392–401. https://doi.org/10.1016/j.spc.2020.11.008

Lin B, Jia Z (2019) What will China's carbon emission trading market affect with only electricity sector involvement? A CGE based study. Energ Econ 78:301–311. https://doi.org/10.1016/j.eneco.2018.11.030

Liu Y, Niu D (2021) Coupling and coordination analysis of thermal power carbon emission efficiency under the background of clean energy substitution. Sustainability 13(23):1–17. https://doi.org/10.3390/su132313221

Liu N, Liu J, Jia D, Huang Y, Luo J, Mamat X, Yu Y, Dong Y, Hu G (2019a) Multi-core yolk-shell like mesoporous double carbon-coated silicon nanoparticles as anode materials for lithium-ion batteries. Energ Storage Mater 18:165–173. https://doi.org/10.1016/j.ensm.2018.09.019

Liu C, Jiang Y, Xie R (2019b) Does income inequality facilitate carbon emission reduction in the US? J Clean Prod 217:380–387. https://doi.org/10.1016/j.jclepro.2019.01.242

Mahi M, Ismail I, Phoong SW, Isa CR (2021) Mapping trends and knowledge structure of energy efficiency research: what we know and where we are going. Environ Sci Pollut Res 28(27):35327–35345. https://doi.org/10.1007/s11356-021-14367-7

Miner KR, Turetsky MR, Malina E, Bartsch A, Tamminen J, McGuire AD, Fix A, Sweeney C, Elder CD, Miller CE (2022) Permafrost carbon emissions in a changing Arctic. Nat Rev Earth Environ 3(1):55–67. https://doi.org/10.1038/s43017-021-00230-3

Moran D, Wood R, Hertwich E, Mattson K, Rodriguez JFD, Schanes K, Barrett J (2020) Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. Clim Policy 20(sup1):S28–S38. https://doi.org/10.1080/14693062.2018.1551186

Mossberg J, Söderholm P, Frishammar J (2021) Challenges of sustainable industrial transformation: S wedish biorefinery development and incumbents in the emerging biofuels industry. Biofuels Bioprod Biorefining 15(5):1264–1280. https://doi.org/10.1002/bbb.2249

Nathaniel SP, Solomon CJ, Ajide KB, Ahmed Z, Fakher HA (2023) Striving towards carbon neutrality in emerging markets: the combined influence of international tourism and eco-friendly technology. Int J Sustainable Dev World Ecol 30(7):760–775. https://doi.org/10.1080/13504509.2023.2195831

Qin Z, Xizhe P, Zhiming LU, Kaiya WU (2009) Factors decomposition and empirical analysis of variations in energy carbon emission in China. Resour Sci DOI. https://doi.org/10.1007/978-3-642-00205-2_9

Rehman A, Ma H, Ozturk I (2021) Do industrialization, energy importations, and economic progress influence carbon emission in Pakistan. Environ Sci Pollut Res 28(33):45840–45852. https://doi.org/10.1007/s11356-021-13916-4

Shen X (2022) Experimental and numerical study on the insulation performance of a photo-thermal roof in hot summer and cold winter areas. Bldg 12(4):410. https://doi.org/10.3390/buildings12040410

Shen J, Tang P, Zeng H (2020) Does China's carbon emission trading reduce carbon emissions? Evidence from listed firms. Energ Sustain Dev 59:120–129. https://doi.org/10.1016/j.esd.2020.09.007

Sovacool BK, Schmid P, Stirling A, Walter G, Mackerron G (2020) Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power. Nat Energ 5(11):928–935. https://doi.org/10.1038/s41560-020-00696-3

Sun L, Qin L, Taghizadeh-Hesary F, Zhang J, Mohsin M, Chaudhry I (2020) Analyzing carbon emission transfer network structure among provinces in China: new evidence from social network analysis. Environ Sci Pollut Res 27(18):23281–23300. https://doi.org/10.1007/s11356-020-08911-0

Waheed R, Sarwar S, Chen W (2019) The survey of economic growth, energy consumption and carbon emission. Energ Rep 5:1103–1115. https://doi.org/10.1016/j.egyr.2019.07.006

Wang L, Dykstra JE, Lin S (2019) Energy efficiency of capacitive deionization. Environ Sci Technol 53(7):3366–3378. https://doi.org/10.1021/acs.est.8b04858

Wu Y, Tam VWY, Shuai C, Shen LY, Zhang Y, Liao SJ (2019) Decoupling China's economic growth from carbon emissions: empirical studies from 30 Chinese provinces (2001–2015). Sci Total Envir 656:576–588. https://doi.org/10.1016/j.scitotenv.2018.11.384

Yang C (2020) The transformation of foreign investment-induced 'exo (genous)-urbanisation' amidst industrial restructuring in the Pearl River Delta, China. Urban Stud 57(3):618–635. https://doi.org/10.1177/0042098019859266

Yuan Y, Hu B, Tong C, Bai Y, Lu C (2019) Novel quaternized carbon dots modified polysulfone-based anion exchange membranes with improved performance. Int J Hydrogen Energ 44(39):22181–22193. https://doi.org/10.1016/j.ijhydene.2019.06.173

Zheng J, Mi Z, Coffman DM, Milcheva S, Shan Y, Guan D, Wang S (2019) Regional development and carbon emissions in China. Energ Econ 81:25–36. https://doi.org/10.1016/j.eneco.2019.03.003

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