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Carbon Emission and Industrial Structure Adjustment in the Yellow River Basin of China: Based on the LMDI Decomposition Model

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ABSTRACT

In the context of promoting high-quality development in the Yellow River Basin (YRB) of China, urgent action is needed to achieve the "Dual Carbon" goal through energy savings, emission reductions, and industrial upgrading. This study measures carbon emissions from eight types of energy consumption across 43 industries from 2000 to 2019. Using the Kaya-LMDI model, factors affecting carbon emissions are analyzed, and the relationship between industrial structure and carbon emissions is explored through the coefficient of variation (CV). The findings reveal that coal consumption remains significantly higher than other energy sources, and the effect of energy structure adjustment on carbon emission reduction is limited compared to the impact of energy consumption increase on carbon emission growth. Moreover, the economic output effect is identified as the primary driving factor of carbon emissions, while energy utilization rate is crucial in achieving energy savings and emission reductions. Finally, the CV of carbon emissions across 43 industries is increasing. Based on these results, we suggest several policy recommendations, including prioritizing ecological concerns, developing comprehensive and scientifically sound plans, optimizing energy consumption structure, improving energy utilization efficiency, and adjusting industrial structure to promote sustainable development in the YRB.

INTRODUCTION

In the new era, China's YRB faces multiple opportunities, such as the new development pattern of "Double Cycle," the strategy of ecological protection and high-quality development, and the coordinated development of regions. In September 2020, General Secretary Xi Jinping stated that "China will strive to achieve a carbon peak by 2030 and strive to achieve carbon neutrality by 2060." "Dual Carbon" is a strategic move to achieve high-quality development, which brings about profound changes in the economy and society. The economic activities in the YRB should be limited to the sustainable range of resources and environment; new emerging industries should be developed to promote clean production for sustainable, high-quality development. The principles for functional positioning and governance systems in the YRB are "water conservation priority" and "integrated planning, coordinated promotion." On the one hand, 9 provinces along the YRB are subject to the dilemma of water shortage and a fragile ecological environment; on the other hand, they face challenges such as the slow transformation of industry upgrading and backward development of strategic emerging industries (Song 2021). Under the "Dual Carbon" goal, the YRB should urgently replace the old drivers, improve energy utilization, upgrade the industry, and implement an innovation-driven development strategy.

In terms of industrial structure and carbon emissions, from the existing research results, there are significant regional differences in the relationship between industrial structure and carbon emissions, and the way and intensity of industrial structure in different regions are different. There was an obvious inconsistency between carbon emission efficiency and the industrial structure upgrade in China from the aspect of regional dynamic distribution in 1997-2016 (Zhou & Wang 2019). The upgrading industrial structure effectively restrained carbon emissions at the national level and in the eastern region, while the central and western regions increased carbon emissions in 2004-2008 (Wang & Wang 2019). Industrial structure upgrades and carbon emissions efficiency in the central region of China have not yet formed a two-way interaction. Carbon emissions efficiency has insufficient impetus to improve industrial structure upgrades (Liu et al. 2022). The distortion of the industrial structure will lead to increased local carbon emission intensity and produce reverse spillover to adjacent areas (You et al. 2022). Research on the correlation between carbon emissions and industrial structure in the Yellow River Basin shows that industries have shown high energy consumption and high emissions for a long time in YRB (Zhao et al. 2023, Ren & Dou 2022), and the carbon emission efficiency of 9 provinces in YRB is significantly different (Zhang & Xu 2022).

LMDI is the most widely used factor decomposition model. ANG Beng Wah analyzed and studied decomposition methods in the energy field and compared them with specific examples, concluding that LMDI is more suitable for decomposition research of problems in the field of energy (Ang 2004, 2015). Related research includes carbon emissions of a specific industry, such as the steel industry (Pan et al. 2023), transportation industry (Yang et al. 2022), and carbon emissions in a certain region, such as a national region, a certain province (Liu. et al. 2023) or the Yellow River Basin (Chen et al. 2022), the Yangtze River (Hu et al. 2022), etc. It is considered that the LMDI method is very suitable for the decomposition analysis of energy consumption and carbon emissions (Su et al. 2023).

Through a review of previous studies, we found that the existing studies have made some achievements in coordinating the contradiction between the development of the economy and emission reduction. Still, there are some gaps in the literature. Firstly, existing studies have mainly focused on overall industrial structure, rationalization of industrial structure, advanced industrial structure, and a specific industry or province and region. Still, few have examined the carbon emissions from energy consumption in the different industries. Secondly, fewer studies have paid high attention to the YRB. Thirdly, the existing research on carbon emissions in the YRB is mainly about the emission characteristics of a certain industry while ignoring the carbon emission characteristics of the different industries in the YRB.

To fill the gap, this paper takes 43 industries of the five major industries in the YRB as research objects from the perspective of industry segmentation, which can reflect the distribution of carbon emissions of industries in the upstream, midstream, and downstream of the YRB. Our paper could be conducive to effectively formulating industrial development policies to control carbon emissions. Based on previous relevant studies, this paper constructs the LMDI model. It decomposes the carbon emission influencing factors of energy consumption into the energy structure effect, energy intensity effect, industrial structure effect, economic output effect, and population size effect. We analyze its contribution rate to carbon emission, respectively, and the regional differences and reasons for carbon emission intensity of industries in the YRB according to the CV method.

Actuality of Energy Consumption in the YRB

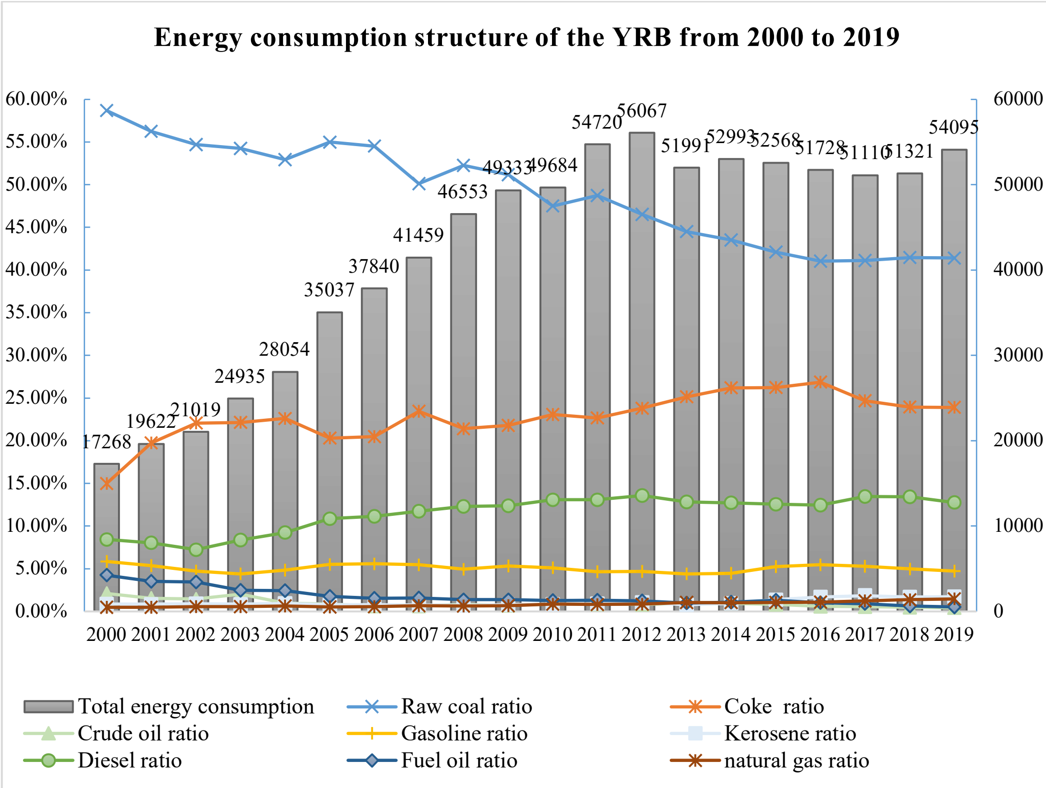
As a whole, from 2000 to 2019, the total energy consumption (converted into standard coal, similarly hereinafter) of the YRB increased from 17267.99 million tons to 54094.51 million tons with an average annual growth of 13.53%, reaching its highest value in 2012, and then showed a downward trend (see Fig. 1). In the energy consumption structure, coal accounted for the largest proportion, accounting for 77.29% on average, oil accounted for 21.82% on average, and natural gas accounted for 0.89% on average. The proportion of coal consumption gradually and slowly decreased in the fluctuation, with an average annual decrease of 0.13%; the proportion of petroleum consumption continued to rise slowly, with an average annual increase of 0.15%; the proportion of natural gas consumption grew fastest, with an annual increase of 6.53%.

Specifically, the raw coal consumption was more than 50% in 2000~2009, and in 2010, the proportion began to decline year by year and maintained at about 41% in 2016~2019. Coke consumption showed a slow growth trend in 2000~2016, with an average annual growth rate of 11.08%, and a downward trend in 2017, 2018, and 2019. Crude oil consumption decreased by 2.65% annually in 2000~2019. Gasoline consumption fluctuated slightly, with an average annual growth rate of 5.04%. Kerosene consumption showed a slow upward trend, with the highest proportion of 1.84% in 2017, and began to decline after 2017. Diesel consumption increased slowly, with an average annual growth of 8.53%. Fuel oil consumption decreased slowly, with an average annual decline of 4.93%. Natural gas consumption accounted for the least, increasing with an annual growth of 12.55%. It can be seen that after the “Action Plan for the Prevention and Control of Air Pollution” issued by China’s State Council in 2013, which emphasized that “Coal consumption must be strictly controlled,” nine provinces along the YRB promulgated the “Regulations on the Prevention and Control of Air Pollution” in 2018. The total coal consumption in the YRB has been reduced to a certain extent.

MATERIALS AND METHODS

Data Sources and Theoretical Models

Study area: The Yellow River basin covers 7 provinces (Gansu, Shangxi, Shanxi, Henan, Shandong, Sichuan, and 2 autonomous regions (Inner Mongolia, Ningxia). We use the



Note: Total energy consumption is converted into standard coal, and the unit is 10,000 tons.

Fig. 1: Energy consumption structure of the YRB from 2000 to 2019.

word "province" to refer to these study areas throughout the rest of the paper. Upstream includes Gansu, Inner Mongolia, Ningxia, Qinghai, and Sichuan; midstream Qinghai) and includes Shangxi and Shaanxi; downstream includes Henan and Shandong. As shown in Fig. 2. The data are derived from the China Statistical Yearbook (2001-2020), China's Energy Statistical Yearbook (2001–2020), Provincial Statistical Yearbook (2001-2020), and Carbon Emission Accounts & Dataset.

Data source and data processing: The research objects of this paper include five industries (agriculture, the secondary industry, construction industry, transportation, post and telecommunications and software industry, wholesale and retail, and accommodation and catering industries involving 43 departments of carbon emission (see Table 1) and 8 major fossil energy sources (coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas). According to the method provided by the Intergovernmental Panel on Climate Change (IPCC 2006) (Ren et al. 2019, He et al. 2021, Tang & Zhang 2022), the net calorific value (NCV) of energy and CO_2 emission factor (CEF) of each kind of fossil energy refer to Cheng Yeqing's research result (Cheng et al. 2014).The carbon emissions from energy consumption in the YRB are estimated (see Equation (1)).

$$C = \sum_{i} Qf_i \times NCV_i \times CEF_i \times 10^{-9} \quad ...(1)$$

Here, C is the total carbon emissions from energy consumption; Qf_i is the consumption of the energy type i; NCV_i is the net calorific value of the energy type i; CEF_i is the carbon dioxide emission factor of the energy type i; i denotes energy type, i=1,2, …8.

Kaya-LMDI Model: The Japanese scholar Kaya Yoichi creatively proposed the Kaya identity and rewrote the Kaya identity in order to facilitate the analysis of different energy carbon emissions in different industries (see Equation (2)) (Kaya 1989).

$$C=\sum_{ij} C_{ij}=\sum_{ij} \frac{C_{ij}}{E_{ij}} \times \frac{E_{ij}}{E_i} \times \frac{E_i}{Q_i} \times \frac{Q_i}{Q} \times \frac{Q}{P} \times P \quad ...(2)$$

Here, C is the total carbon emissions from energy consumption; C_{ij} is the carbon emissions from the energy type j in the industry sector i; E_{ij} is the consumption of energy type j in the industry sector i; E_i is the total energy consumption in the industry sector i; Qi is the output value

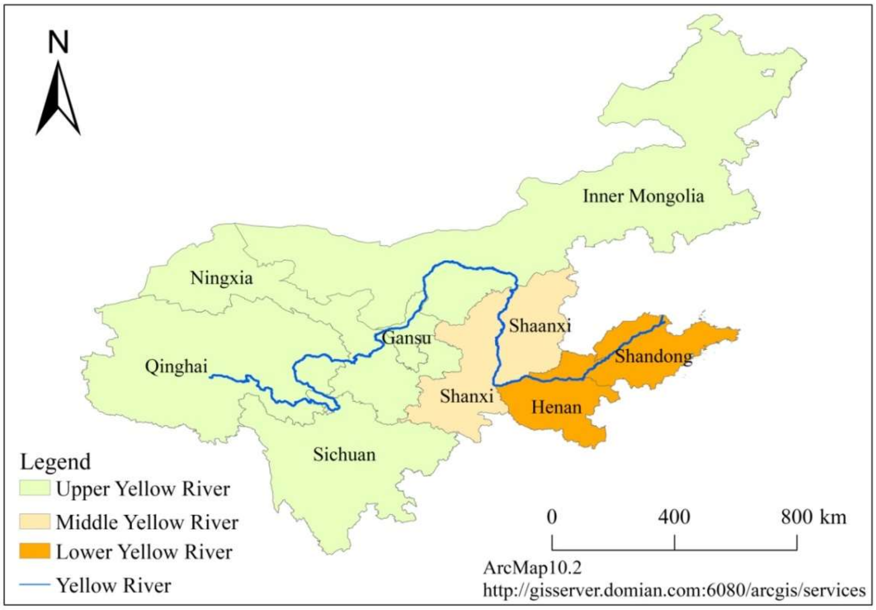


Fig. 2: The research areas of the Yellow River Basin.

Table 1: Departments of carbon emission.

Industry number	Industry name	Industry number	Industry name
1	Agriculture, forestry, animal husbandry and fishery	23	Chemical Fiber
2	Coal Mining and Dressing	24	Rubber Products
3	Petroleum and Natural Gas Extraction	25	Plastic Products
4	Ferrous Metals Mining and Dressing	26	Nonmetal Mineral Products
5	Nonferrous Metals Mining and Dressing	27	Smelting and Pressing of Ferrous Metals
6	Nonmetal Minerals Mining and Dressing	28	Smelting and Pressing of Nonferrous Metals
7	Other Minerals Mining and Dressing	29	Metal Products
8	Food Processing	30	Ordinary Machinery
9	Food Production	31	Equipment for Special Purpose
10	Wine, beverage, and refined tea manufacturing	32	Transportation Equipment
11	Tobacco processing	33	Electric Equipment and Machinery
12	Textile industry	34	Electronic and Telecommunications Equipment
13	Garments and Other Fiber Products	35	Instruments, Meters, Cultural and Office Machinery
14	Leather, Furs, Down, and Related Products	36	Other Manufacturing Industry
15	Timber Processing, Bamboo, Cane, Palm & Straw Products	37	Scrap and waste
16	Furniture Manufacturing	38	Electric Power, Steam, and Hot Water Production and Supply
17	Papermaking and Paper Products	39	Gas Production and Supply
18	Printing and Record Medium Reproduction	40	Tap Water Production and Supply
19	Cultural, Educational, and Sports Articles	41	Construction
20	Petroleum Processing and Coking	42	Transport, Storage, Postal & Telecommunications Services
21	Raw Chemical Materials and Chemical Products	43	Wholesale, Retail Trade and Catering Service
22	Medical and Pharmaceutical Products		

in the industry sector i; Q is the gross domestic product; P is the population size; i denotes different industry types, i=1, 2, 3, …, 43; j denotes different energy types, j=1, 2, 3,..., 8.

Based on this, drawing on previous studies (Chen et al. 2022, Li & Wang 2008, Zhou et al. 2020, Wu et al. 2023, Jiang et al. 2021, Lai et al. 2021), this paper decomposes the carbon emission impact factors of energy consumption into carbon emission factor effect ($\Delta C_{\frac{C_{ij}}{E_{ij}}}$), energy structure effect ($\Delta C_{\frac{E_{ij}}{E_i}}$), energy intensity effect ($\Delta C_{\frac{E_i}{Q_i}}$), industrial structure effect ($\Delta C_{\frac{Q_i}{Q}}$), economic output effect ($\Delta C_{\frac{Q}{P}}$) and population size effect (ΔC_P). Based on Equation (2), according to the LMDI decomposition method (additive model), the total effect of carbon emissions is expressed as:

$$\Delta C_{tot} = C^t - C^0 = \sum_i \sum_j \left(\Delta C_{\frac{E_{ij}}{E_i}} + \Delta C_{\frac{E_i}{Q_i}} + \Delta C_{\frac{Q_i}{Q}} + \Delta C_{\frac{Q}{P}} + \Delta C_P\right) \quad ...(3)$$

C^0 is the total carbon emissions in the base period; C^t is the total carbon emissions in the period t; carbon emission factor effect is $\Delta C_{\frac{C_{ij}}{E_{ij}}}=0$ (The CV of carbon emission from various energy sources remains unchanged.) The contribution value and contribution rate of each decomposition factor are shown in Table 2:

LMDI Decomposition of Carbon Emissions from Energy Consumption

The carbon emission of the YRB is calculated according to Equation (1), and Equation decomposes the influencing factors (4) ~ (13). The empirical results are shown in Fig. 2. On the whole, the total effect of carbon emissions in the YRB increased by 5174.58 million tons annually from 2000 to 2019, of which 13699.45 million tons increased annually due to the growth of population scale and the improvement of economic output, and 8524.87 million tons decreased annually due to the reduction of industrial structure, the reduction of energy intensity and the adjustment of energy structure.

RESULTS AND DISCUSSION

Energy Structure Effect

The average value of the energy structure effect was (-586.01) million tons from 2000 to 2019, and the average contribution to carbon emissions from energy consumption in the YRB was (-11.32%). Hence, the structure effect was not very obvious. The impact of structural effects on carbon emissions in 2001~2004, 2005~2007, 2008~2010, 2011~2013, and 2014~2019 was mainly negative. The change in the energy consumption structure in the YRB mainly causes this situation. The proportion of raw coal consumption in the total energy consumption in the YRB decreased by 5.89% in 2004, 8.87% in 2007, 9.10% in 2010, 8.64% in 2013, and 4.92% in 2019, respectively, compared with 2001, 2005, 2008, 2011 and 2014. The energy structure effect was positive in 2000~2001, 2004~2005, 2007~2008, 2010~2011, and 2013~2014, indicating that the energy structure was not reasonable during this period, which led to the increase of carbon emissions in the YRB. During this period, the consumption of raw coal and coke increased significantly. The proportion of raw coal consumption increased by 3.84% in 2005, 4.28% in 2008, and 2.58% in 2011, respectively, compared with 2004, 2007, and 2010, and the proportion of coke consumption increased by 4.27% in 2011 compared with 2010. Because the carbon emission coefficients of raw coal and coke are the largest, the consumption of coal and coke has the most significant impact on carbon emissions when other coefficients remain unchanged. So, the role of

Table 2: Contribution value and contribution rate.

Decomposition factors	Contribution value	Contribution rate
energy structure	$\Delta C_{\frac{E_{ij}}{E_i}}=\frac{C_{ij}^t-C_{ij}^0}{\ln C_{ij}^t-\ln C_{ij}^0}\cdot\left[\ln\left(\frac{E_{ij}}{E_i}\right)^t-\ln\left(\frac{E_{ij}}{E_i}\right)^0\right]$ (4)	$r_{\frac{E_{ij}}{E_i}}=\frac{\Delta C_{\frac{E_{ij}}{E_i}}}{\Delta C_{tot}}$ (9)
energy intensity	$\Delta C_{\frac{E_i}{Q_i}}=\frac{C_{ij}^t-C_{ij}^0}{\ln C_{ij}^t-\ln C_{ij}^0}\cdot\left[\ln\left(\frac{E_i}{Q_i}\right)^t-\ln\left(\frac{E_i}{Q_i}\right)^0\right]$ (5)	$r_{\frac{E_i}{Q_i}}=\frac{\Delta C_{\frac{E_i}{Q_i}}}{\Delta C_{tot}}$ (10)
industrial structure	$\Delta C_{\frac{Q_i}{Q}}=\frac{C_{ij}^t-C_{ij}^0}{\ln C_{ij}^t-\ln C_{ij}^0}\cdot\left[\ln\left(\frac{Q_i}{Q}\right)^t-\ln\left(\frac{Q_i}{Q}\right)^0\right]$ (6)	$r_{\frac{Q_i}{Q}}=\frac{\Delta C_{\frac{Q_i}{Q}}}{\Delta C_{tot}}$ (11)
economic output	$\Delta C_{\frac{Q}{P}}=\frac{C_{ij}^t-C_{ij}^0}{\ln C_{ij}^t-\ln C_{ij}^0}\cdot\left[\ln\left(\frac{Q}{P}\right)^t-\ln\left(\frac{Q}{P}\right)^0\right]$ (7)	$r_{\frac{Q}{P}}=\frac{\Delta C_{\frac{Q}{P}}}{\Delta C_{tot}}$ (12)
population size	$\Delta C_P=\frac{C_{ij}^t-C_{ij}^0}{\ln C_{ij}^t-\ln C_{ij}^0}\cdot\left[\ln P^t-\ln P^0\right]$ (8)	$r_P=\frac{\Delta C_P}{\Delta C_{tot}}$ (13)

energy improvement in the YRB in emission reduction needs to be further improved over a long period of time.

Energy Intensity Effect

The average energy intensity effect was (-6401.24) million tons from 2000 to 2019, and the average contribution to the carbon emissions from energy consumption in the YRB was (-123.71%). Energy intensity reflects the efficiency of energy economic activities, and the decrease indicates the improvement of energy utilization efficiency (Adewale et al. 2023). The energy structure effect was positive in the five time periods of 2000~2001, 2002~2003, 2004~2005, 2008~2009, and 2018~2019. To some extent, it can be seen that the energy utilization technology in the YRB still has a large room for improvement. Further analysis shows that industrial energy intensity had the greatest impact on energy intensity in 2000~2001, 2002~2003, and 2018~2019, while transportation energy intensity had the greatest impact in 2004~2005 and 2008~2009. So, the industry and transportation urgently need to innovate energy application technology, and the most important way to save energy and reduce emissions is to improve energy efficiency in the YRB.

Industrial Structure Effect

The average value of industrial structure effect was (-1537.61) million tons from 2000 to 2019, and the average contribution to the carbon emissions from energy consumption in the YRB was (-29.71%), which is not a high percentage. The effect of industrial structure in the YRB harmed carbon emissions in 2000~2001 and 2009~2019, while it had a positive effect in 2002~2008. The secondary industry is the largest energy-consuming profession. The average proportion of the secondary industry output value to GDP in the YRB in 2000~2019 was about 40%, and its average annual proportion to total energy consumption was 78.42%. In contrast, the proportion of the secondary industry output value to GDP showed a downtrend after 2008, with an average annual decline of 0.23%. We find that the change in the proportion of the secondary industry output value in the YRB significantly impacts the industrial structure effect. Therefore, the YRB should focus on controlling carbon emissions from the secondary industry, actively adjusting industrial structure, and developing the tertiary industry.

Economic Output Effect

The average economic output effect was 12490.04 million tons from 2000 to 2019, with an average contribution of 241.37%. The growth of carbon emissions caused by economic growth in 2010~2011 was 22991.67 million tons. It can be seen that the economic output effect is the most important driving factor for the growth of carbon emissions and has a positive contribution to the YRB. Concurrently, the rapid and sustained economic growth has led to a large

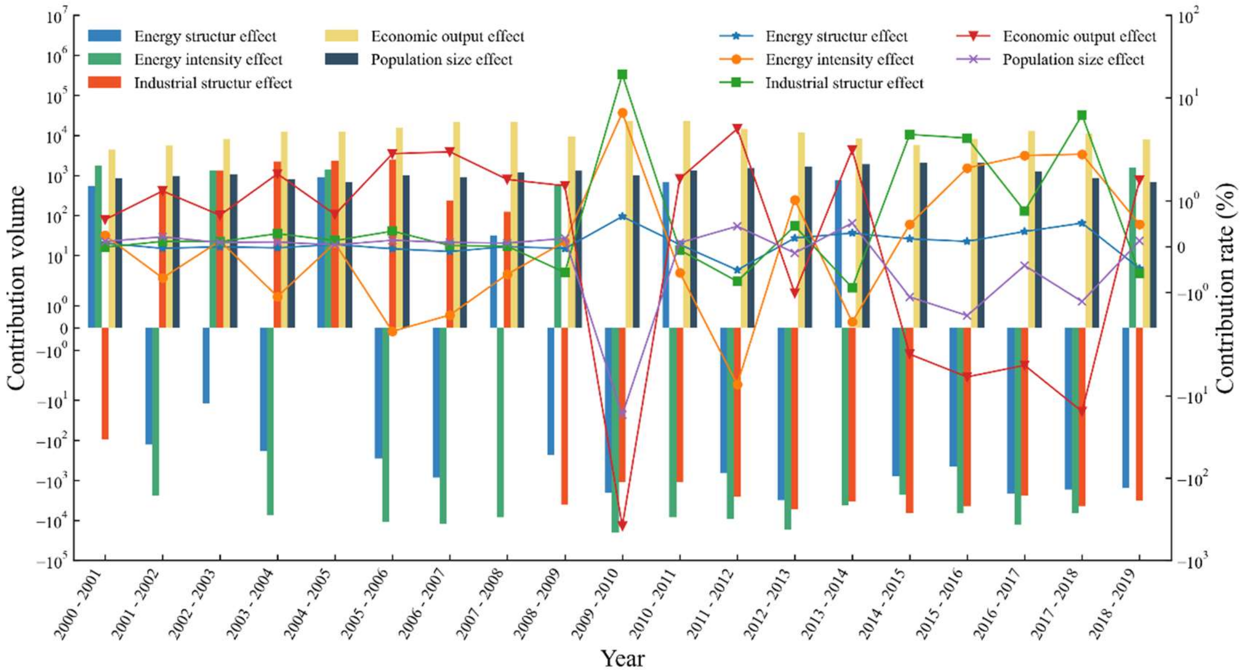


Fig. 3: Influencing Factors of Carbon Emissions in the YRB from 2000 to 2019. (contribution volume: million tons /contribution rate).

consumption of energy and increasing carbon emissions. For example, the per capita GDP of the YRB increased from 51535 yuan to 497258 yuan from 2000 to 2019, with an average annual growth of 12.67%. The cumulative economic output effect was 126203.59 million tons from 2000 to 2019, accounting for 53.18% of the total economic output effect. Therefore, the YRB should change its development concept, take resource-carrying capacity as a constraint, change from quantity growth to quality improvement, and explore the green and low-carbon development path (Xu et al. 2022).

Population Size Effect

The population size effect of the YRB is positive, so the increase in population size leads to the growth of carbon emissions. The average population size effect was 1209.41 million tons, and the average contribution to carbon emissions from energy consumption in the YRB was 23.37% from 2000 to 2019.

Analysis of Regional Differences in Carbon Emission of 43 Intensities

Based on China's goal of a green, low-carbon circular economic system by 2025, public policies have supported green finance, the investment and financing system compatible with the "Double Carbon" goal. The government strictly controls high-carbon industries such as steel, coal, electrolytic aluminum, cement, and petrifaction through various measures to enhance the application level of low-carbon technology, which is conducive to the restructuring of energy consumption structure and the upgrading of industrial structure. However, due to the huge differences in regional ecological resources in China, the spatial layout and utilization level of land are different, so eastern, central, and western China have different missions and responsibilities of ecological civilization. At this stage, there are obvious regional differences in carbon emissions from 43 industries in the YRB (see Fig. 3). Therefore, the industrial division planning of the YRB should consider the differential characteristics of production factors, natural endowment, and ecological carrying capacity in the upstream, midstream and downstream, and try to avoid industrial isomorphism and disorderly competition, to improve energy production efficiency.

(1). The CV ranges of carbon emission in 43 industries were 7.09%~35.71% in 2000, 25.45%~83.54% in 2005, 26.62%~69.34% in 2010, 23.3%~101.45% in

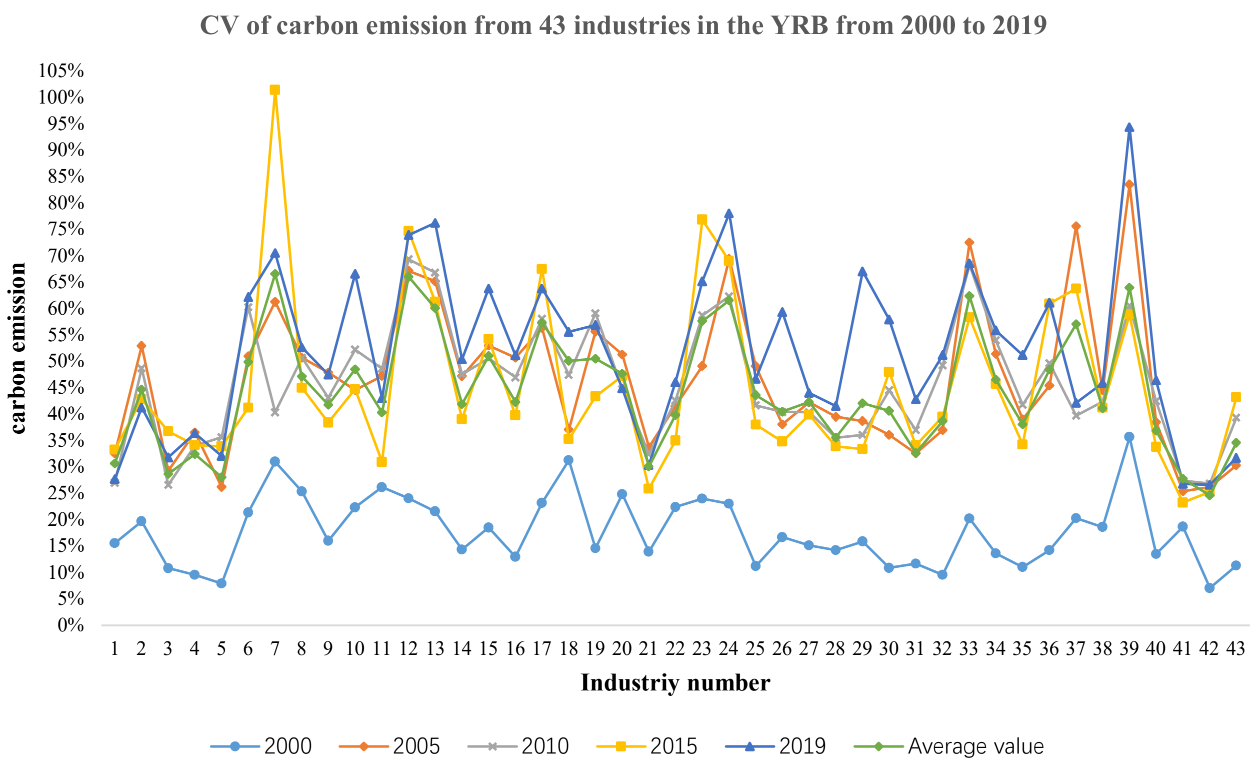


Fig. 4: CV of carbon emission from 43 industries in the YRB from 2000 to 2019.

2015, 26.62%~94.38% in 2019. To a certain extent, the improvement of the CV reflects the irrationality of the industrial structure in the YRB. In the future, the YRB should actively reduce industrial carbon emissions through reasonable industrial spatial layout and scientific regional industrial planning.

(2). The CV of carbon emissions in 43 industries were significantly higher in 2001 compared with 2000, and especially "Petroleum and Natural Gas Extraction," "Cultural, Educational and Sports Articles," "Smelting and Pressing of Ferrous Metals" have increased more than twice. The CV of carbon emissions from "Other Minerals Mining and Dressing," "Textile industry," "Garments and Other Fiber Products," "Rubber Products," "Electric Equipment and Machinery," and "Gas Production and Supply" were more than 60% on average in 2000~2019. The CV of carbon emission from "Scrap and waste" reached 104.5% in 2011. This means the range of carbon emission intensity of these industries varies greatly. So, the 9 provinces in the YRB should further strengthen the coordination. For example, industrial planning should be carried out according to regional carbon productivity, and the regions with low carbon emission intensity can relatively increase the industrial scale to reduce the industrial scale of regions with high carbon emission intensity.

(3). In 2000~2019, the CV of carbon emission in "Agriculture, forestry, animal husbandry, and fishery," "Coal Mining and Dressing," "Petroleum and Natural Gas Extraction," "Other Minerals Mining and Dressing," "Papermaking and Paper Products," "Petroleum Processing and Coking," "Chemical Fiber," "Scrap and waste," "Wholesale, Retail Trade, and Catering Service" showed a downward trend; the CV of carbon emission in "Ferrous Metals Mining and Dressing," "Smelting and Pressing of Ferrous Metals," "Construction," "Transport, Storage, Postal & Telecommunications Services" remains stable; the CV of carbon emission in 30 industries including "Nonferrous Metals Mining and Dressing," "Nonmetal Minerals Mining and Dressing," "Food Processing," "Food Production," "Wine, beverage and refined tea manufacturing," etc. had an upward trend. It can be seen that the regional difference in carbon production efficiency of 69.77% of the 43 industries has a trend of expanding, which indicates that there are problems such as incompatibility between industrial development planning and local resource conditions, low industrial production efficiency, low energy utilization, and waste of resources in different regions of the YRB.

CONCLUSIONS

Our paper aimed to analyze the characteristics of energy consumption from 43 industries in the YRB and provide a scientific basis for formulating differentiated carbon emission reduction policies. In this paper, the LMDI model was employed to decompose influencing factors of carbon emissions in the YRB, and the CV method was introduced to dynamically analyze the regional differences in carbon emission of 43 intensities. The main conclusions are as follows.

(1) From the energy consumption in the YRB (see Fig. 1), the proportion of coal in the energy consumption structure of the YRB is the highest, with a slight decline trend; the proportion of oil and natural gas is limited. The total carbon emissions of the YRB showed an increasing trend in 2000~2012, especially with a rapid growth rate in 2000~2006 and a slight downward trend in 2013-2019.

(2) The empirical analysis of factor decomposition of carbon emissions in the YRB shows that, on the whole, the economic output effect and population size effect have a positive impact on the carbon emissions from energy consumption, and the economic output effect is the most important driving factor of carbon emissions in the YRB. The energy structure effect, energy intensity effect, and industrial structure effect have a negative impact on carbon emissions. Still, the energy structure and industrial structure effects have a limited inhibiting effect, while reducing energy consumption per unit GDP has a strong inhibiting effect. In recent years, the YRB has actively transformed industrial structures to promote green development, inhibiting carbon emissions. Still, the inhibition effect is limited due to the path dependence on high energy-consuming industries. Therefore, the carbon emissions of the YRB show a trend of robust increase at this stage.

(3) From the fluctuation of the CV of carbon emission (see Fig. 3), we can see that the regional differences in carbon emission intensity of 43 industries in the YRB are significant. The regional difference in carbon production efficiency of 69.77% of industries had an expanding trend. So, many problems must be solved, such as incompatibility between industrial development planning and local resource conditions, low industrial production efficiency, low energy utilization, and waste of resources in different regions of the YRB.

SUGGESTIONS

In this paper, the LMDI model is used to illustrate the macro impact of the changes of various factors on the carbon emission of provinces in the YRB. Still, it is difficult to quantitatively describe the spatial correspondence between carbon emission and the changes in various factors and their coupling mechanism, which is also an issue we must study in depth in the future. Therefore, some suggestions are based on this paper's research object, method, and content.

Adhering to the principle of ecological priority and planning scientifically: Our study shows that coal accounts for the largest share of energy consumption in the YRB. On the one hand, the YRB should always adhere to the principle of "Deciding production by water," strengthen water environment governance, promote water conservation projects, carry out water and soil loss control, promote intensive water, implement the strictest ecological protection system, and establish ecological compensation mechanism (Wei et al. 2023). On the other hand, the YRB should keep a close watch on the national special planning and strive to incorporate more projects into the national strategic planning. The development planning of the 9 provinces in the YRB should be differentiated and connected so that the spatial layout of urban agglomeration can be scientifically arranged. After that, the YRB can lead the adjustment of energy structure, ecological governance, and industrial layout through spatial planning and form a community of shared future in the YRB (Song & Feng 2022).

Optimizing energy consumption structure and improving energy utilization efficiency: From the energy intensity effect, the energy utilization technology in the YRB still has room for improvement. Authorities in the YRB should strengthen source control, strictly control high coal-consuming projects, strictly control total coal consumption, and increase the proportion of natural gas, photovoltaic, wind power, biomass, and other energy consumption. The upper reaches of the YRB should rationally use abundant water resources and vigorously develop new energy sources, such as wind and solar energy, to promote energy complementarity. The middle and lower reaches have a certain industrial foundation and geographical advantages, and they should develop clean energy sources such as natural gas, wind energy, and solar energy to enhance the renewable energy consumption ratio. In addition, economic and social development is highly dependent on high-coal consumption industries, and the development of strategic emerging industries and new energy industries lack enough support, which leads to the fact that it still takes some time to adjust the energy structure. Therefore, the 9 provinces should further replace fossil energy with electric energy and strengthen the application of ecological technology to improve energy efficiency.

Adjusting the industrial structure and raising the quality of economic development: This research finds that the contribution of the industrial structure effect to the carbon emissions in the YRB is not high. The industrial structure of the YRB is mainly resource-intensive industries such as coal and steel, and its economic development is highly dependent on resource-based industries. So transforming traditional industries, achieving energy conservation and efficiency improvement, and improving the green production level of traditional industries such as coal, steel, non-ferrous metals, petrochemical, and chemical industries, are important ways to achieve reducing emissions (Wang et al. 2022). Therefore, the YRB should actively promote the deep integration of information and artificial intelligence technology with traditional industries and use digital technology to empower traditional industries such as coal, petroleum, chemical, electricity, building materials, metal smelting, and equipment manufacturing in the upper and middle reaches of the YRB. At the same time, it is necessary to further promote the rapid development of modern service industries such as financial business, tourism, energy-saving environmental protection industry, science and technology services, and other modern service industries. For example, Jinan, Xi'an, Qingdao, and Zhengzhou should develop high-end manufacturing by building industrial innovation chains and value chains in combination with artificial intelligence, blockchain, and life science. The resource-based cities in the YRB should also further promote the transformation of the energy production base to the energy service center, strengthen the brand building, and extend to the high-end value chain.

Integrating innovative resources within the watershed and strengthening technological support: Local governments in the YRB should take more responsibility for integrating, opening, and sharing scientific and technological resources. They should further make full use of 9 double first-class universities, 3 national laboratories, 5 national innovation demonstration zones (Xi'an, Chengdu, Shandong Peninsula, Zheng-luo-xin, and Lanbai), as well as scientific research institutes, enterprise scientific research facilities, key laboratories and other scientific and technological resources in the YRB to improve the utilization efficiency of existing innovation resources. The YRB still needs to actively cooperate with the comprehensive national science centers (such as Huairou Beijing, Zhangjiang Shanghai, Greater Bay Area, and Hefei Anhui) and establish local, regional scientific and technological innovation centers to improve the overall scientific and technological innovation capacity. In addition, national or regional central cities such as Chengdu, Zhengzhou, Xi'an, Jinan, and Qingdao should seize opportunities in the new round of national innovation resource layout and strive for the construction of high-end innovation platforms such as national science centers, national laboratories, comprehensive national industrial innovation centers, national technology innovation centers, and national manufacturing innovation centers. Moreover, 9 provinces should increase investment in innovation and promote the transformation and application of green technology services and achievements. Based on improving the investment mechanism for scientific and technological innovation and increasing financial investment, the governments should increase tax deductions and incentives and increase the proportion of R&D expenses deducted by enterprises to encourage and support enterprise innovation. At the same time, the 9 provinces should jointly establish a technology transfer and cooperation network in the YRB as soon as possible to promote collaborative cooperation and common development in terms of high-quality supply of scientific and technological achievements, precise integration of technology supply and demand, talent cultivation for technology transfer, and ecological construction for technology transfer and transformation.

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