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Analysis of CO₂ Emission Drives Based on Energy Consumption and Prediction of Low Carbon Scenarios: a Case Study of Hebei Province

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Abstract

The rapid consumption of energy has caused a surge in carbon emissions and led to serious ecological problems. This paper takes Hebei Province as the research area. First, carbon emissions related to energy consumption are calculated from 2001 to 2015, and then the decomposition analysis of the carbon emissions data is performed by using the LMDI method based on the extended IPAT model. Finally, according to the potential drivers derived from the decomposition results and the future trend of low-carbon development, three scenarios are set up, namely inertial emission reduction scenarios, relative emission reduction scenarios, and absolute emission reduction scenarios. The results show that the overall carbon emissions from 2001 to 2015 are on an upward trend, increasing by 4.08 times during the study period. Economic progress is the main driving factor for the rising CO, in emitter, followed by energy consumption structure and population size, and the effect of technological progress has inhibited the increasing carbon emissions. The gradual optimization of Hebei's industrial structure has changed the industrial structure effect from promotion to suppression. The final scenario analysis indicates that the relative emission reduction scenario and absolute emission reduction scenario can both achieve the Copenhagen emissions reduction target and the Paris Agreement target, but the relative emissions reduction scenario has become the most reasonable low-carbon pathway. Finally, by designing and implementing a local carbon emissions trading system, regional development could be encouraged to be closer to a relative emissions reduction scenario. Low-carbon transformation in other regions would be exerted by the avenue opened by this paper.

Keywords: drive factors, LMDI, low-carbon development, scenario analysis, Hebei Province

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Introduction

It is imperative for each country to respond to the harsh changes in the global climate. The Intergovernmental Panel on Climate Change (IPCC) released the fifth climate assessment report, saying that the dramatic increase in carbon dioxide (CO₂) emissions embodied in energy consumption and its cumulative effect are the main reasons for global climate change [1]. According to the data provided by the International Energy Agency (IEA), global CO, emissions from the 1990s to 2016 increased from 23.6 billion tons to around 31.6 billion tons [2]. Without more ambitious effective measures to mitigate climate change, CO, emissions are expected to increase by 50% in 2050. This would lead to a global average temperature of 3.2-4 degrees above pre-industrial levels [1]. Therefore, countries or regions need to deploy low-carbon development strategies and related policy instruments. While effectively reducing CO₂ emissions, they also need to balance and coordinate the relationship between industrial development and the ecological environment.

As the average growth rate of China's gross domestic product (GDP) has exceeded 9% over the past four decades and the development of domestic energyintensive industries [3-4], China has become the highest CO₂ emitter in the world (Fig. 1) [2]. Therefore, China is facing huge pressure on CO, emissions reduction. In order to better fulfill its obligations, China has come up with serious emissions reduction statements and decisions. At the United Nations Climate Change Conference in Copenhagen in 2009, China promised that by 2020 the CO₂ emissions per unit of gross domestic product (GDP) will be 40-45% lower than in 2005. In 2016, when the Paris climate agreement was signed, the Chinese government declaimed that the unit's GDP would fall by 60-65% compared to 2005, and China's carbon emissions would reach their peak in 2030, which marked a decision transfer from relative emission reductions to absolute emission reductions. However, the carbon peak does not naturally come along

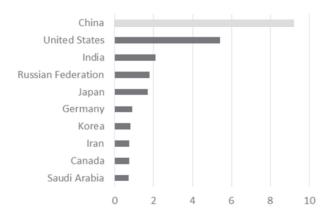


Fig. 1. Top 10 countries with the highest carbon emissions as announced by the IEA.

with the improvement of the economic development level. Therefore, the kind of path and policy adopted to achieve the carbon peak and intensity target is an issue that China urgently needs to solve. If the chosen path and the implemented policies are appropriate, then achieving the goal of carbon peak and intensity will not only impose rigid constraints on China's economic and social development, but will also promote China's economic development to a low-carbon transition. On the contrary, it may have a serious negative impact on China's economic and social development, and even lead to a hard landing of the economy. In order to achieve these goals, it is crucial to analyze the various positive and negative drivers that result in increasing CO₂ emissions. Through this approach, the effectiveness of policy implementation can be enhanced by benefiting from analyzing drivers. That is, to achieve the targets of climate change mitigation, incorporating policies will benefit from collecting information about the effects of various influencing factors.

On the one hand, the use of various measurement methods to analyze the key factors affecting emissions in different countries and regions has become the subject of many studies in recent years. Many studies utilize the grand causality test to explore whether there is a causal relationship among energy use, CO2 emissions, and economic development [5-7]. For example, Zhou et al. used the Granger causality test and found that there is a bidirectional causal relationship between China's CO₂ emissions and economic structure and between CO₂ emissions and energy consumption structures, and there is a unidirectional causal link between CO₂ emissions and GPD, between CO, emissions and urbanization, and between CO, emissions and trade [8]. Although causality analysis is conducive to providing key insights for implementing climate change mitigation policies, it does not quantify the role of many causal factors on carbon emissions [9]. Therefore, under the background of active emissions reduction, in order to be able to identify and quantify explicitly the more key factors for CO, emissions reduction, this paper adopts the logarithmic mean divisia index (LMDI) decomposition method, which will be particularly helpful for policy makers designing the path of future low-carbon development and sustainable development and determine the direction of implemented measures. The LMDI decomposition method boasts many advantages. For instance, LMDI is relatively concise and flexible compared to the Computable General Equilibrium (CGE) analysis method [10]. In contrast with the other decomposition method, SDA [11-12], based on environmental-extended input-output (IO) table, LMDI requires less data. Hence, LMDI is at an emerging use in different horizontal and vertical layers. In the horizontally aligned sectors, LMDI is applied to measure the quantitative relationship between energy consumption embodied in carbon emissions and various influencing factors across the transport sector [13-15], industrial sector [16-18], construction sector [19-20], power sector [21-22], mining sector [23], and residents' lives [24]; in the vertical level, LMDI decomposition method is employed to national and regional scopes such as China, Beijing [25], the Pearl River Delta [26] and the like. It also exists in further studies that combine the national and regional conditions systematically. For example, Jiang et al. used the LMDI method to analyze the driving forces of carbon emissions in the Chinese provinces, and applied the hierarchical clustering method to classify regions with regard to the uniform drivers, and gave detailed emission reduction strategies for different categories [27]. Xu et al. used the LMDI method to compare China's regional contribution to CO₂ emissions from 1995-2012 [28].

On the other hand, due to the constraints of time period and geographical position, the empirical findings of influencing factors have been varied. Wang et al. used inter-provincial data to analyze CO, emissions and considered that economic development is an important contributing factor and that technological progress has an inhibitory effect on the growth of CO₂ emissions [29]. Similarly, Shao et al. believed that rapid economic growth is the primary driver of increasing CO₂ [30]. Yi et al. found that technological progress is the most key limiting factor for carbon emission intensity [31]. Other factors cannot be ignored. Ohlan examined the relationship among population density, energy consumption, economic growth, trade exports and CO, emissions and identified that population density played a major role [32]. Salahuddin found that there is an inverse relationship between CO₂ emissions and financial development [33]. Shen et al. took Beijing as an example to examine the carbon emissions factors at different stages. The main driver of carbon emissions growth in 1991-2002 was economic output followed by population size, and the main inhibitory effect was the industrial structure; economic output in 2004-2020 was the most significant factor in increasing carbon emissions, followed by population size and energy structure, and the energy intensity is the main factor in curbing carbon emissions [25]. Zhang et al. utilized the LMDI model to determine that investment intensity was the main driving force for the ascendant industrial carbon emission intensity, and R&D intensity and energy intensity were the main contributors to descending carbon emission levels [18]. Urbanization level, industrialization level, industrial structure, and other social and economic indicators are also under study. However, on account of the methods, data, variables and time period, there may be a U-shaped relationship rather than purely positive or negative relationship. For example, Ozturk et al. adopted the EKC hypothesis to examine the link running from CO₂ emissions to GDP, energy consumption, urbanization, trade exports and other pollutants in Cambodia, but did not confirm the EKC assumption in this region [34]. Martinez selected a developing country area and confirmed an inverse U-shaped relationship between urbanization and CO, emissions [35].

Scenarios are detailed and reasonable inferences and descriptions for situations that may occur in the future. Its purpose is to realize the analysis of a specific problem by combining qualitative and quantitative methods on the basis of objective reality. Scenario analysis method can simulate different technical routes in an effective manner and will help us to discuss whether the future carbon emission targets can be achieved. Some studies have used scenario analysis methods to explore low-carbon development pathways. Taking Jilin Province as an example, four scenarios were set up to explore the carbon emissions peak time and peak value in this region, and carbon emissions control was carried out based on the results [36]. Heikki et al. discussed the CO₂ emissions of road freight in Finland and classified the six scenarios using cluster analysis according to different economic development conditions. The results showed that the predicted CO, emissions of all scenarios compared to 2010 would be reduced by at least 26% [37]. Wang et al. established the STRIPAT model to estimate the relationship among carbon emissions, population, per capita GDP, electricity consumption, energy consumption, and analyzed the scenarios of electric energy development and stated that the way to reduce carbon emissions should consider increasing technological capabilities and the proportion of electricity used [38].

Although some research literature already discusses whether China or the region can achieve carbon emissions reduction targets by 2020 or 2030 [36, 39-41], the existing literature seldom systematically and progressively researches whether it can achieve the targets promised by China and ignore the goal of the carbon emissions boundary. In addition, because of the huge differences in resource endowment in different regions, specific methods should be adopted to analyze concrete issues and the drivers of carbon emissions in the region ought to be revealed. This paper tackles a case of provincial significance, namely Hebei Province as the research object. First of all, taking the perspective of energy consumption, this research calculates the carbon emissions from 2001 to 2015. Secondly, we demonstrate a real application of the LMDI method to examine the carbon drivers in Hebei Province in the last years. Finally, an extended IPAT model is established and combined with scenario analysis to forecast the achievement of carbon emissions targets in different scenarios, that is, the carbon emission intensity in 2020 and 2030 were respectively 40-45% (Target 1) and 60-65% (Target 2) lower than 2005, achieving emission peaks (Target 3) and carbon emissions boundary (Target 4) by 2030. Then, through comparative analysis of the carbon emissions control model, the optimal development scenarios for meeting low-carbon targets are determined, which is more suitable for Hebei's economic development. The research ideas and methods of this article can be reference for carbon emission prediction in other regions.

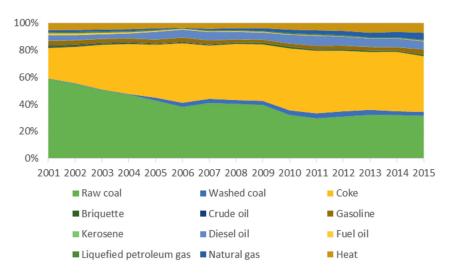


Fig. 2. Specific structure of energy utilization in 2001-2015.

Material and Methods

Research Area and Data Sources

Hebei Province is located in the north of China and borders the Bohai Sea in the east, surrounded by Beijing and Tianjin (also known as the Beijing-Tianjin-Hebei area). Since the 21st century, the large-scale development and transformation of energy resources have promoted the rapid economic growth of Hebei Province. At the same time, it has also led to a continuous increase in energy consumption. Fig. 2 shows the specific energy consumption structure. In 2015, total primary energy consumption in Hebei Province was 336 million tons of standard coal, an increase of 64% from 2001. In primary energy consumption, coal and its derivatives consumption has always dominated, from 91.84% in 2001 to 87% in 2015. In the industrial structure, the secondary industry is the most significant contributor to energy consumption in Hebei Province. The energy consumption of six energy-intensive sub-sectors (coal mining, petroleum processing and coking, chemicals, non-metals, ferrous metals, electricity and thermal power) reached 185 million standard coal, accounting for about 80% of energy consumption by the second industry sector in 2015. In terms of energy efficiency, the unit GDP energy consumption in 2015 reached 0.999 tons of standard coal per 10,000 yuan, equivalent to 1.41 times the national average in the corresponding period. Therefore, how to actively explore the path of energy savings and emissions reduction and develop a "low-carbon and recycling" economy has become a serious problem in Hebei Province.

The data for calculating the carbon emissions of Hebei Province and the influencing factors are listed, respectively, in the Energy Balance Sheet of the China Energy Statistical Yearbook in 2001-2015 and the Hebei Province Economic Yearbook in 2001-2015. In the calculation of carbon emissions in Hebei Province, different types of energy are uniformly converted to standard coal.

Estimated Carbon Emissions

Because carbon emission data cannot be obtained directly, carbon emission information is acquired through calculation. This article starts with energy consumption and applies the most widely used calculation method

Table 1. Factors of various energy sources.

Energy Types	Raw coal	Washed coal	Coke	Briquette	Crude oil	Gasoline	Kerosene
SCE conversion factor (tSCE/t)	0.7143	0.9	0.9713	0.6	1.4286	1.4714	1.4714
CO ₂ emission factor (10 ⁴ tC/10 ⁴ tSCE)	0.7559	0.7559	0.855	0.7559	0.5857	0.5538	0.5714
Energy Types	Diesel oil	Fuel oil	Natural Gas	Heat	Electricity	Liquefied petroleum gas	
SCE conversion factor (tSCE/t)	1.4571	1.4286	1.33	34.12	-	1.7143	
CO ₂ emission factor (10 ⁴ tC/10 ⁴ tSCE)	0.5921	0.6185	0.4483	0.67	0.272	0.5042	

of carbon emission. The IPCC developed and revised the "IPCC Guidelines for National Greenhouse Gas Inventories" in 1996 and 2006, providing research institutions and scholars with calculation methods and default data for various energy-related carbon emission factors. This study used Formula (1) to estimate $\rm CO_2$ emissions in Hebei Province:

$$C = \sum_{i=1}^{n} E_i \times c_i \times f_i$$
 (1)

...where C is the total carbon emissions from energy consumption; E_i is the terminal consumption of the ith energy; and c_i is the conversion coefficient of ith energy into standard coal. f_i is the carbon emission factor of the ith energy. Table 1 presents the standard coal conversion coefficient and CO_2 emission factors for different energy types.

LMDI Decomposition Method

The LMDI factorization method was proposed by Ang in 1998 and can be defined as decomposing the equation into its components [42]. The IPAT model is the starting point for LMDI and decomposes the impact of the environment into population, wealth, and technology effects. Since the IPAT model has good scalability, factors can be increased based on actual conditions. This paper decomposes the total carbon emissions from energy consumption in Hebei Province into six parts, including economic scale, population size, industrial structure, energy consumption structure, energy efficiency, and carbon intensity. According to the expanded Kaya identity, the carbon emissions in Hebei Province are decomposed as follows:

$$C = \sum_{i} C_{ij} = \sum_{j} \frac{C_{ij}}{E_{ij}} \times \frac{E_{ij}}{E_{j}} \times \frac{E_{j}}{G_{j}} \times \frac{G_{j}}{G} \times \frac{G}{P} \times P$$

$$= \sum_{j} \sum_{j} U \times M \times I \times S \times Q \times P$$
(3)

...where i denotes energy types and j denotes different types of industries. In Formula (2), C_{ij} denotes the carbon emissions of the ith energy of the jth industry and E_{ij} denotes the consumption of the ith energy of the jth industry. E_{j} denotes energy consumption of the j industry; G_{j} denotes the economic output of the j industry; G_{j} denotes the GDP; and P_{j} denotes population size. In Formula (3), U_{j} is the ratio of carbon emissions to energy consumption, which represents the impact of carbon emission coefficient on carbon emissions; M_{j} is the proportion of energy consumed by the ith energy in industry and represents the energy consumption per unit of GPD_{j} , also called energy intensity, which represents the index of energy use efficiency and the impact of

technological progress on carbon emissions; S indicates the industrial structure; Q is the per capita GDP, and represents the economic scale; and P indicates population size.

Due to the carbon emissions coefficient corresponding to different types of energy sources that do not change in the short term, U does not affect total CO₂ emissions. Therefore, the amount of carbon emissions changes from t to 0 can be expressed as:

$$\Delta C = C_t - C_0 = \Delta C_{M_effect} + \Delta C_{I_effect} + \Delta C_{S_effect} + \Delta C_{Q_effect} + \Delta C_{P_effect}$$

...where ΔC_{M_effect} represents the energy consumption structure effect; ΔC_{1_effect} represents the technological progress effect, ΔC_{S_effect} represents the industrial structure effect, ΔC_{Q_effect} represents the economic scale effect, and ΔC_{P_effect} represents the population scale effect. The effect expression of each carbon emissions coefficient is established as:

$$\Delta C_{M_{-}effect} = \begin{cases} 0 & ifE_{ij}^{0} \times E_{ij}^{t} = 0 \\ L(C_{ij}^{t}, C_{ij}^{0})In\frac{M_{i}^{t}}{M_{i}^{0}} & ifE_{ij}^{0} \times E_{ij}^{t} \neq 0 \end{cases} \tag{5}$$

$$\Delta C_{l_effect} = \begin{cases} 0 & \text{if } E_{ij}^0 \times E_{ij}^t = 0 \\ L(C_{ij}^t, C_{ij}^0) ln \frac{l_i^t}{l_i^0} & \text{if } E_{ij}^0 \times E_{ij}^t \neq 0 \end{cases}$$
(6)

$$\Delta C_{s_effect} = \begin{cases} 0 & \text{if } E_{ij}^{0} \times E_{ij}^{t} = 0 \\ L(C_{ij}^{t}, C_{ij}^{0}) ln \frac{S_{i}^{t}}{S_{i}^{0}} & \text{if } E_{ij}^{0} \times E_{ij}^{t} \neq 0 \end{cases}$$
(7)

$$\Delta C_{G_{-effect}} = \begin{cases} 0 & if E_{ij}^{0} \times E_{ij}^{t} = 0 \\ L(C_{ij}^{t}, C_{ij}^{0}) In \frac{G_{i}^{t}}{G_{i}^{0}} & if E_{ij}^{0} \times E_{ij}^{t} \neq 0 \end{cases}$$
(8)

$$\Delta C_{P_effect} = \begin{cases} 0 & if E_{ij}^0 \times E_{ij}^t = 0 \\ L(C_{ij}^t, C_{ij}^0) ln \frac{P_i^t}{P_i^0} & if E_{ij}^0 \times E_{ij}^t \neq 0 \end{cases}$$

$$(9)$$

$$L(x,y) = \frac{(x-y)}{(\ln x - \ln y)}$$
(10)

If C_0 represents the carbon emissions of the base year, d represents the energy intensity growth rate; m represents the energy consumption structure adjustment rate; s represents the industrial structure adjustment rate; q represents the economic growth rate; p represents the population growth rate, then the total amount of carbon emissions in year t is as follows:

$$C_{t} = C_{0} [(1+d)\times(1+m)\times(1+s)\times(1+q)\times(1+p)]^{t}$$
 (11)

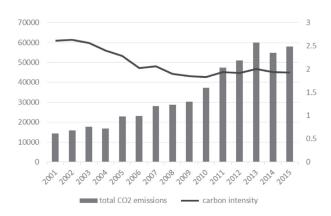


Fig. 3. Total CO_2 emissions and carbon intensity from 2001 to 2015 in the research region.

Results and Discussion

Carbon Emission Results and Comparison

Carbon emissions from 2001 to 2015 in Hebei Province are calculated according to Formula (1). Carbon emission intensity is defined as the carbon emissions per unit of GDP. The changes in carbon emissions and carbon intensity during 2001-2015 are shown in Fig. 3.

Hebei Province's carbon emissions were rising from 2001 to 2015. During the study period, total carbon emissions increased by 4.03 times, and the annual growth rate was 9.7%. Only carbon emissions in 2014 decreased by 8% compared to 2013. In 2013, China opened several cities such as Beijing and Guangzhou to conduct carbon emissions trading pilots. As a major emitter, Hebei Province was undoubtedly under pressure to accept this measure. However, China's carbon emissions trading market is not yet mature and in an exploratory phase, which has not yet been implemented nationwide. In 2015, the carbon emissions in Hebei Province rebounded.

From the perspective of the proportion of various industries, the data show that the growth rate of CO₂ emissions driven by the development of the secondary industry is always the largest, accounting for 61-78%

during the study period. However, because the historical position cannot be changed within a short time, the secondary industry is the main contributor to CO₂ emissions. Followed by secondary industry, tertiary industry occupied 20.5-36% during this period. The tertiary industry involves transportation, wholesale, retail and other service industries. With the growth of GPD and the improvement of people's living standards, the overall CO₂ emissions from tertiary industry are on the rise. Primary industry had the lowest CO₂ emissions. Agriculture, animal husbandry, and fisheries consume less energy resources compared to the sub-sectors of secondary and tertiary industries.

From the perspective of carbon emission intensity, the overall curve is in a declining state and it has a fluctuating shape in 2010-2013. In 2015, it decreased by 27% on the basis of 2001 with an average annual drop of 2%. Compared with certain developed provinces and cities in the country, the carbon emission intensity in Hebei Province has a lower declining rate such as 5.5% [39] in Beijing and 6.21% [43] in Zhejiang. This means that the assignment of reducing carbon emissions intensity in Hebei Province is arduous, and a comprehensive and systematic adjustment strategy must be established to confront the challenges of the country's commitment.

Decomposition Analysis

In order to analyze the cyclical changes in carbon emissions in the study area, this paper divides the 2001-2015 period into three phases: 2001-2005 (Tenth Five-Year Plan), 2006-2010 (11th FYP), and 201-2015 (12th FYP), which is similar to the previous document [3, 29-31]. Among the three research stages divided by this study, the decomposition results of economic scale effect, industrial structure effect, the population scale effect, technological progress effect, and energy consumption structure effect are shown in Table 2 and Fig. 4. The decomposition of the total carbon emissions over the past 2001-2015 years is expressed in Fig 5.

Table 2. LDMI decomposition results in 2001-2015. Unit: 10,000 tons.

Year	Contribution	ΔC_{M_effect}	ΔC_{I_effect}	ΔC_{S_effect}	$\Delta C_{Q_{effect}}$	$\Delta C_{P_{effect}}$	Summary
2001-2005	Value	-1395.37	-1306.28	362.93	10355.14	406.93	8423.36
	Proportion	-16.57%	-15.51%	4.31%	122.93%	4.83%	100.00%
2006-2011	Value	9659.57	-2834.43	227.93	15241.36	1238.56	23532.98
	Proportion	41.05%	-12.04%	0.97%	64.77%	5.26%	100.00%
2011-2015	Value	7348.52	-4925.78	-2018.04	8878.26	1307.65	10590.61
	Proportion	69.39%	-46.51%	-19.05%	83.83%	12.35%	100.00%
2001-2015	Value	15612.72	-9066.49	-1427.18	34474.76	2953.15	42546.94
	Proportion	36.70%	-21.31%	3.35%	81.03%	6.94%	100.00%

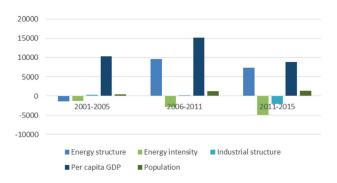


Fig. 4. Proportion of each influencing factor from 2001 to 2015.

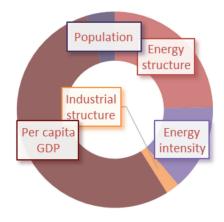


Fig. 5. Ratio of five influential factors in 2001-2015.

From Table 2 and Fig. 4 we can see that the economic scale is the main driver of carbon emissions. This conclusion is in line with the above literature [25, 29-30]. In the 10th, 11th, and 12th FYPs, economic growth contributed 122.93%, 64.77%, 83.83% to the carbon emissions respectively, and the cumulative effect reached 344.7376 million tons, accounting for 81.03% of the growing carbon emissions from 2001 to 2015. This indicates that during the study period, economic growth mainly relied on the increase of carbon emissions, and the development of economic scale did not remove from the growth of carbon emissions. Accordingly, it is critical to search for economic development modes that reduce energy dependence to a certain extent and balance quality and speed [44]. Moreover, China accessed at the WTO after the 21st century. Hebei Province, as the industrial undertaking space of the Beijing-Tianjin-Ji area, plays an important role in industry and construction. A large number of energy-consuming enterprises are put into production to push forward energy consumption, and Hebei Province enters a period of accelerated industrialization. Furthermore, owing to major changes in the environment at home and abroad, in 2012 economic development in China entered a "new normal" economy and maintained rapid growth at medium and high speed [39]. Thus, the economic growth rate under the "new normal" would slow down. In comparison with the 10th FYP, the contribution of economic size to carbon emissions would decrease in the 12th FYP, but it still may be the main force of carbon emissions growth.

In terms of energy consumption structure, except for the 10th FYP, during the 11th and 12th FYPs the effect was positive with a contribution of 41.5% and 69.39% respectively. In 2001-2015, the accumulated contribution was 36.7% as shown in Fig. 5. The energy consumption structure held the second largest amount of drivers. According to the IPCC carbon emission coefficient data presented in Table 1, among the carbon emissions caused by fossil energy consumption, coal is the largest contributor, followed by oil and natural gas. Fig. 2 also illustrates the status quo of the energy consumption structure characterized by coal. Although the country proposed ameliorating the energy supply, improving a drastic consumption revolution, pushing the clean use of coal and establishing a diversified energy system, Hebei Province adopted measures to replace the consumption of coal with the use of natural gas in order to respond to national policies. This had a certain contribution to reduce carbon emissions, but it is not optimistic to optimize the internal structure of energy use within a short time [45-46]. Therefore, the energy consumption structure would not have an inhibitory effect in the Hebei region in the short term.

From the perspective of demographic effects, the promotion effect during the study period was 4.83%, 5.26%, and 12.53%, respectively. In 2001-2015, a total of 29.19 million tons CO₂ was contributed. Its incremental effect is less than the economic scale and energy structure effects. The results show that the increase in population size in the study area had led to an increase in CO₂ emissions from beginning to end. In general, the development of the regional economy is positively related to population growth [47]. According to the Hebei Bureau of Statistics, the population of Hebei Province increased from 66.99 million to 74.24 million in 2001-2015 with an annual growth rate of 10.8%. On the one hand, the increasing population size has led to a higher demand for various products, transport services and living energy, which has brought out an increase in carbon emissions [48]. On the other hand, due to the continuous urbanization in Hebei Province, a large number of non-urban populations were absorbed into secondary and tertiary industries, and the increase in energy consumption in Hebei Province also facilitated the growth of carbon emissions.

From an industrial structure point of view, Fig. 4 shows that in 2001-2005 and 2006-2010, the industrial structure devoted to CO₂ emissions in Hebei Province, but it was less mass than the economic scale effect, energy consumption structure effect, and population effect. During the 12th FYP, CO₂ emissions were suppressed through industrial restructuring. Different situations have emerged in the three phases. According to the Hebei Economic Yearbook, the proportion of the secondary industry in Hebei Province had been rising from 48.9% in 2001 to 52.5% in 2010. The two phases

contributed 4.3% and 0.97% respectively. During the 12th FYP, Hebei Province actively adjusted the proportion of the secondary industry and gradually developed into the tertiary industry, making the output ratio of the secondary industry to the total region GDP drop from 53.54% to 48.27%. The tertiary industry accounted for 34.6% at the beginning and rose to 39.66%. This indicated that the proportion of the secondary industry had declined and the tertiary industry had flourished. That is, the upgrading of industrial structure can reduce CO₂ emissions because the tertiary industry (light industry) generates lower CO₂ emissions than heavy industry [29]. Thence, during the 12th FYP and later, Hebei Province should respond to the national policy and follow the trend of the "new normal" economy, raise access standards for high-energy-consuming industries, eliminate large amounts of backward production capacity, and vigorously develop emergent industries and service industries to stimulate economic growth and curb CO, emissions.

From the point of view of technological progress (energy use efficiency), the three phases set in this paper are in a state of inhibiting CO, emissions, which contributed 15.51%, 12.04%, and 46.51%, respectively. Technological progress was the major contributor to the suppression of CO, emissions. This is consistent with both our initial expectation and the previous studies [29, 31]. On the one hand, although technological progress had an important inhibitory effect on CO, emission, technological advances in carbon emission intensity had been proved to be relatively slow, and the potential impact on the suppression of CO, emissions may be offset by the rapid increase in energy consumption [49]. On the other hand, technological advances and the improvement of energy efficiency have no doubt about the role of reduction. Hebei Province continues to introduce innovative technology as a support. With the incessant transformation and upgrading of the industrial structure, the inhibitory effect of energy intensity on carbon emissions would be further enhanced. In addition, promoting the application of innovative concepts in the future, such as eco-design, clean production, energy auditing and green building, would also be conducive to change the status of CO₂ emissions

In this section, the contribution value and rate of various drivers for the CO₂ emissions in Hebei Province from 2001 to 2015 were explored. In the next part, the scenario setting will be based on past drivers and the possible future development trend.

Scenario Settings and Parameter Settings

Scenario settings need to consider various factors comprehensively and reasonably. According to the LMDI model parameters set in this paper, to predict the future total carbon emissions and carbon emission intensity of Hebei Province, the future economic development speed, population size, energy utilization

efficiency, industrial structure, and energy consumption structure need to be set. Section 3 mentioned that the major positive driver of carbon emissions in Hebei Province from 2001 to 2015 was economic output, and technological progress was the main inhibitor. Three scenarios were designed based on this result and possible future trends: inertial emission reduction (IER) scenarios, relative emission reduction (RER) scenarios, and absolute emission reduction (AER) scenarios.

IER: Under these circumstances, based on the current state of social development in the traditional way, Hebei Province would still take economic development as the main target, and energy technology progress and consumption structure would be evolved in accordance with the historical development trend of the past. The government has taken measures to maintain the existing energy conservation and emission reduction policies and no longer formulates another mandatory strict energy policy. During the research phase, the regional GDP had grown at an average rate of 11.9%, which is higher than the national average development rate. Therefore, under the IER scenario, the GDP growth rate is placed at 11.5%. The population growth rate, energy intensity, energy structure adjustment rate, and the growth rate of the industrial structure will be chosen as the average level of the 12th FYP, which are 0.5%, -2.7%, -3%, and -1.7% respectively.

RER: In this context, economic development would not be the main target with the weakening dependence on energy consumption. The GDP growth rate is lower than that of the IER scenario, gradually decreasing from 9.5%. Due to the universal two-child policy, the annual growth rate of the population would reach 1%, then the growth rate of per capita GDP starts to decline from 8.4%. In addition, the "China Energy Outlook 2030" report pointed out that the primary energy consumption structure would continue to be optimized. The proportion of coal consumption would decline by a large margin, which accounts for 60% and 49% in 2020 and 2030, respectively. And with the rapid development of clean energy, non-fossil energy in 2020, 2030 would drop to 15%, 22% [50]. In order to achieve the objective of "China Energy Outlook 2030", the energy structure setup shows a phased change. The growth rate of 2016-2020 is similar to that of the IER scenario, which is -3%, and the speed is accelerated to -3.4% in 2021-2030. In addition, the proportion of the secondary industry in Hebei Province experienced a trend of increasing first and then declining. From 48.88% in 2001 to 54.3% in 2008, it peaked and fell back to 48.27% in 2015. At the same time, the proportion of the tertiary industry performs a growing trend. The average rate of decline in the proportion of the secondary industry from 2016 to 2020 is set to be higher than that of the IER scenario, which is 1.8%, and the speed in the period of 2021-2030 is 1.7%. The 13th Five-Year Energy Development Plan of Hebei Province claimed that by 2020 the energy consumption per unit of GDP would be reduced by 19% compared to 2015, which would reach 0.46 tons of standard coal per million. Therefore, during the 13th Five-Year Plan period, the energy intensity is set to decline by 4% per year, and it is decelerated to 3.5% in 2021-2030. Therefore, in the context of IER, RER is in a certain condition that the economic development rate is reduced, the proportion of clean energy is appropriately increased on the basis of the original energy structure and the industrial structure is further adjusted appropriately, which reflect to some extent that the people and the company's awareness of energy conservation have improved significantly.

AER: From 2016 to 2030, economic development may decouple from the growth of CO, emissions, which means that GDP growth may not depend on the increase of CO, emissions. The Hebei provincial government may establish a carbon emissions market for trading. Under this background, enterprises will increase their investment in scientific research and be forced to use a large proportion of clean energy. The concept of low-carbon lifestyle and consumption is wellreceived. Under this scenario, the GDP growth rate for 2016-2020 is equal to the RER. It is set to 6.5% from 2020 to 2030, which is the bottom line of the national economic development rate [51]. The parameters of the industrial structure and population size are identical to those of the RER scenario. So as to further reduce the proportion of coal consumption and improve the energy consumption structure, higher than the energy structure setting target of "China Energy Outlook 2030", the decline rate of coal accounting for 2021-2030 is set at 3.5%. In the ARE, the technology for conversion to low carbon from 2021 to 2030 is further upgraded, and the rate of decline in energy intensity is set at 3.7%. Thus, the AER scenario is based on the RER scenario and the main positive drivers of carbon emissions are strengthened in the low-carbon direction.

Table 3. Achievements of Target 1 and Target 2 in 2020 and 2030.

Year	Scenario	Carbon emission intensity (ton/10 thousand Yuan)	Falling degree
	IER	1.36	38.99%
2020	RER	1.25	45.14%
	AER	1.24	44.82%
2030	IER	0.67	70.61%
	RER	0.52	77.11%
	AER	0.50	77.81%

Simulation Results and Discussion

According to the setting of different parameters in this paper and the possible scenarios in the future, the carbon emission intensity in 2020 and 2030 are calculated as shown in Table 3. The total amount of carbon emissions in 2016-2030 are presented in Fig. 6.

Under the IER scenario, the rapid growth of carbon emissions is motivated by the development of traditional extensive economic development. Per capita GDP in 2020 and 2030 will reach 2.3 times and 3.17 times of 2015 respectively. The energy intensity gradually decreases to 0.87 times and 0.67 times of 2015, and the proportion of coal consumption declines by 16% and 37%. The economic growth under the RER scenario is slower than that in the IRE scenario and shows a decreasing trend. Therefore, in 2020 and 2030, the GDP per capita will be 1.86 times and 1.7 times in 2015 respectively. In addition, by 2020 and 2030, energy intensity will rapidly drop by 20% and 44%, respectively. The industrial structure of Hebei Province is expected to be upgraded, and the output ratio of

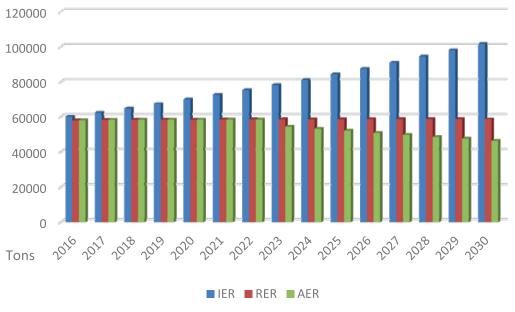


Fig 6. Carbon emissions trend in 2016-2030 in three situations.

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Year	2016	2017	2018	2019	2020	2021	2022	2023
IER	60237.07	62536.28	64923.25	67401.32	69973.98	72644.84	75417.64	78296.28
RER	58098.41	58158.59	58202.87	58231.21	58243.6	58361.3	58463.2	58549.2
AER	58098.41	58158.59	58202.87	58231.21	58243.6	58263.3	58273.3	54390.23
Year	2024	2025	2026	2027	2028	2029	2030	
IER	81284.79	84387.37	87608.38	90952.33	94423.92	98028.01	101769.7	
RER	58619.23	58673.23	58711.15	58732.95	58738.62	58728.14	58701.52	
AER	53163.28	51964.02	50791.8	49646.03	48526.1	47431.44	46361.47	

the secondary industry has dropped to 44% and 35% respectively. Compared with the RER scenarios, the economic growth rate of the absolute emission reduction scenarios from 2020 to 2030 will drop significantly. As a result, by 2030 the regional per capita GDP will be 2.66 times that of 2015, but it will be 20% lower than the RER scenario. In addition, the carbon emissions under the relative emission reduction scenarios in 2030 will be 1.26 times the AER scenario values.

Varied parameter settings for the three scenarios result in different carbon emissions and peak times. The prediction value and trend of carbon emissions are shown in Fig. 6 and Table 4. For Target 1, both RER and AER can be reduced by 40-45% on the basis of carbon emission intensity in 2005. In the IER scenario, owing to the high setting of the economic development speed parameter, the minimum standard is not reached. For Target 2, in 2030 the three programs are respectively reduced by 70.61%, 77.11%, and 77.81% based on the carbon emissions intensity in 2005. Consequently, the three scenarios set in the Hebei region can easily reach Paris Agreement commitment. For peak value and time performance, carbon emissions would not peak before 2030 and have been rising in IER. In RER, carbon emissions would peak in 2028 with a peak value of 58738.62 million tons, and the AER scenario would peak in 2022. Compared with the RER scenarios, AER plans have set higher requirements. During the period of 2021-2030, the government would adopt a mandatory emissions reduction policy and the sharp decline in the rate of economic development would lead to a peak of six years in advance. However, any low-carbon development plan should consider the carbon emissions boundary. The Paris agreement pointed out that by 2050 the global temperature rise should be controlled within 2 degrees, preferably within 1.5 degrees. Hoekstra et al. estimated that the carbon emission boundary is about 25×109 t/a in the article [52], and the global population would increase from 7 billion to close to 10 billion by 2050, and the per capita carbon emissions should be controlled below 2.5t/a. After calculation, the per capita carbon emissions of the three scenarios are 12.7 t/a, 6.8 t/a, and 5.4 t/a – all far exceeding the per capita carbon emissions boundary. It is proved that in the

period from 2030 to 2050, the potential for reducing carbon emissions in Hebei Province will still be great.

In order to study China's Hebei Province more realistically, the analysis of this paper extends to 2030 and predicts the realization of the government's highest standards of carbon emissions targets. Moreover, the parameters of the model set in this paper will be conducive to considering more policy factors, such as the second-child release policy and energy consumption structure adjustment goals. Under the IER scenario, carbon intensity in 2020 was 38.99% lower than that in 2005, which does not fulfill the emission reduction targets promised by the Chinese government at the UN Climate Change Conference. In addition, its per capita carbon emissions exceeded the carbon emission boundary by 4.08 times. Thereby, this situation does not represent an ideal development scenario. Compared with other scenarios, the AER scenario is based on the rapid decline of economic growth rate from 2020 to 2030, which will usher in peak value in 2022 with the lowest total carbon emissions and carbon emissions intensity in 2030. However, the per capita GDP growth rate is less than 6%, making the per capita GDP of Hebei Province under the AER scenario of 2030 as RMB 106,700, which is much lower than the contemporary per capita GDP of the most advanced countries (4×10⁴ dollar). Besides, China implements a market economy control mechanism that combines the visible hand (government) with the invisible hand (market). The regulation and control of the government in macroeconomics is indispensable. Although the 14th FYP (2021-2025) and the 15th FYP (2026-2030) have not yet been formulated, under the AER scenario, per capita GDP growth of 6% per year may not be able to accomplish the government's targets. Consequently, the absolute emission reduction scenario may not be suitable for the development stage of Hebei Province during the period of 2021-2030. For RER scenarios, the per capita GDP in 2030 is more than RMB 130,000, which will be the closest to the per capita income of the current developed countries. There is no need to curb carbon emissions at the expense of economic development. In addition, the plan would complete Target 1, Target 2, and Target 3, but the carbon boundary is still well above the set standards.

Therefore, the future plans for energy conservation and emissions reduction should take into account the various boundaries of carbon emissions, such as the per capita boundary and the horizontal boundary of urbanization [43]. Accordingly, relative emission reduction scenarios will not hinder the process of modernization and urbanization and may become the closest low-carbon development model at this stage.

International experience suggests that the use of market mechanisms, in particular the establishment of a carbon emissions trading system, not only has a positive effect on the reduction of greenhouse gas emissions, but also can gradually increase the efficiency of energy utilization and continuously optimize the economic structure. In China, emissions trading has also proved to be a cost-effective method that can help achieve emissions reduction targets at lower economic costs [53]. Fig. 2 indicates that Hebei Province has a decreasing trend compared to 2013 in 2014, demonstrating that carbon emissions trading not only promotes energy conservation and emission reductions in pilot provinces and cities, but may also cause invisible pressure in other regions. Under the principle of historical egalitarianism, Hebei Province should bear more emission allowance [54]. According to a study of Guangdong's carbon emissions trading scheme, compared with non-emission trading scenarios, more sectors involved in emissions trading programs can reduce GDP loss and increase economic output [55]. This provides strong evidence that the promotion of the trading system in Hebei Province and even throughout the country may be an appropriate economic mode of reducing emissions and mitigating climate change.

Conclusions

Based on the carbon emissions data of Hebei Province from 2001 to 2015, this paper applies the LMDI method to decompose the carbon emissions data into economic scale effect, population scale effect, energy consumption structure effect, industrial structure effect and technological progress effect. In light of the contribution of various factors to emissions and possible future low-carbon transitions, inertia emission reduction scenarios, relative emission reduction scenarios, and absolute emission reduction scenarios have been set, and carbon emissions have been simulated in three scenarios to explore the achievement of the targets for 2020 and 2030 in Hebei Province. Research indicates:

- (1) During the study period, total carbon emissions in Hebei Province showed an overall upward trend, increasing by 4.08 times. Only 2014 decreased by 8% compared to 2013. The growth rate of CO_2 emissions from energy consumption in the secondary industry hold always the largest amount, accounting for 61-78% in 2001-2015.
- (2) Economic development is the foremost driving factor to increase carbon emissions in Hebei Province,

followed by energy consumption structure and population. The reduction of energy intensity (technical progress) is the main contributor to the continuous reduction of carbon emissions. The industrial structure promoted the emission of CO_2 during the 10^{th} FYP and the 11^{th} FYP, while during the 12^{th} FYP it suppressed CO_2 emissions and experienced the first promotion and post-inhibition effects, indicating that Hebei's industrial structure has been gradually optimized to the direction of low-carbon industries.

- (3) Scenario analysis results show that inertial emission reduction scenarios would not be able to complete the 40-45% reduction in carbon intensity in 2020 based on 2005, and carbon emission peaks would not be reached by 2030; relative emission reduction scenarios and absolute emission reduction scenarios can achieve the aims of Copenhagen emission reduction, and the Paris agreement can accomplish the task of peaking before 2030. Moreover, under the three scenarios, the carbon emission boundary far exceeds the per capita standard. There will be a great potential for reducing emissions in Hebei Province at the stage of 2031-2050.
- (4) Compared with the absolute emission reduction scenario, the design of relative emission reduction scenarios is more reasonable and closer to the low-carbon development path, because the early arrival of carbon emission peaks cannot be at the expense of economic development. However, in the period of 2021-2030, Hebei Province must consider the carbon emission boundary and make efforts to reduce the per capita carbon emission value. In the future, Hebei Province may introduce a carbon emissions trading system that promotes the competition of enterprises to complete the corresponding quotas, and strives to close the relative emission reduction programs, thus prompting the transformation of low-carbon development.

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Conflict of Interest

The authors declare no conflict of interest.

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