Empirical Decomposition and Forecast of Carbon Neutrality for High-End Equipment Manufacturing Industries

Hang Lu, Ehsan Elahi* and Zhenya Sun

School of Economics, Shandong University of Technology (SDUT), Zibo, China

The Chinese government focuses on the high-end equipment manufacturing industry to achieve a target of carbon neutrality. This study takes China's Bohai Rim as a case study. First, the Tapio decoupling model was used to analyze the carbon emission status of the high-end equipment manufacturing industry in the Bohai Rim. Second, LMDI was used to determine the main factors of carbon emission. Similarly, the Monte Carlo simulation predicted the time of carbon neutrality. The results found that the relationship between carbon emission and the development of the high-end equipment manufacturing industry is that of strong decoupling, but there is still a risk of "recoupling." The scale effect is the primary driving force for carbon emission reduction in the equipment manufacturing industry, followed by a structural effect and a carbon emission intensity effect. In the baseline scenario, low-carbon scenario, and technological breakthrough scenario, carbon neutrality will be achieved before 2060. The results of the study suggest that China should improve energy utilization efficiency and encourage green innovation.

Keywords: high-end equipment manufacturing industry, carbon neutrality, empirical decomposition, scenario simulation, China's Bohai Rim

1 INTRODUCTION

In 2020, China proposed to achieve carbon neutrality by 2060. The goal of this proposal indicates that carbon emission reduction and carbon neutrality will be China's development themes for a long time. The high-end equipment manufacturing industry is a technology-intensive strategic emerging industry. It is located in the high-end link of the manufacturing industry. It has the characteristics of high added value, good growth, and a strong driving force. It acts as the engine of China's economic growth (Fan and Du, 2018). Although the high-end equipment manufacturing industry has a lower carbon emission level than other manufacturing industries, it still emits 10% of the carbon dioxide from the manufacturing industry. Therefore, reducing carbon emission to achieve carbon neutrality is the top priority.

China's Bohai Rim includes five provinces and cities, namely, Beijing, Tianjin, Hebei, Liaoning, and Shandong. It is one of the most important economic circles in China's coastal areas and the second largest place for high-end equipment manufacturing in China (Tong et al., 2019). In recent years, the development of the high-end equipment manufacturing industry in the Bohai Rim has made great progress. On the basis of maintaining traditional advantages, heavy high-tech industries are emerging. In addition, the Bohai Rim is also one of the largest carbon emission areas in China. Therefore, how to reduce the carbon emission of the high-end equipment manufacturing industry in

the Bohai Rim not only contributes to achieving carbon neutrality goals, but also can provide experience and reference for high-end equipment manufacturing in other countries of the world to achieve carbon neutrality, and provide theoretical support for the environmental protection of the world.

Since the reform and opening up, the scale-expanding economic growth mode has made China the second-largest economy in the world. At the same time, China has also become the country with the largest total carbon emissions. With the gradual deterioration of climate issues such as global warming, reducing carbon dioxide emissions has become the consensus of all countries in the world, but the right to carbon emission represents a country's right to development to a certain extent (Elahi et al., 2020; Elahi et al., 2021a). Therefore, how to achieve economic growth while reducing carbon emission and environmental pollution is an important topic of academic research (Sheng et al., 2019; Odhiambo et al., 2020; Peng et al., 2021a; Peng et al., 2021b; Zhong et al., 2021).

To study carbon emission, it is necessary to identify the main influencing factors of carbon emissions, and on this basis, put forward relevant suggestions for carbon emission reduction (Peng et al., 2018; Peng et al., 2020; Zhang et al., 2020; Zhong et al., 2020; Gu et al., 2020a; Wu et al., 2021; Zhao et al., 2021). First, the continuous advancement of new urbanization has an important impact on China's carbon emissions (Gu et al., 2019; Gu et al., 2020b; Zhao et al., 2020; Wang et al., 2021). The adoption of management strategies is important to reduce environmental emissions and human health damages (Elahi et al., 2021b; Elahi et al., 2022a; Elahi et al., 2022b). Although the development of urbanization has increased the level of regional carbon emissions, urbanization can also promote carbon emission reduction by enhancing human capital accumulation and cleaner production technology. Therefore, strengthening the role of urbanization in the accumulation of human capital and the promotion of cleaner production technologies is the key method to solve the "high carbon lock-in" in the process of urbanization (Zhang et al., 2016). Second, the impact of carbon emission on economic development obeys the law of rising first and then decreasing. The key to carbon emission reduction lies in reaching the peak in advance and reducing the peak height. The adjustment of the industrial structure has reduced the regional carbon emission, which is conducive to peaking carbon dioxide emissions (Yuan et al., 2016). Financial efficiency can also affect carbon emissions. If sectors with lower carbon emissions can maximize corporate profits for financial institutions, the improvement of financial efficiency can reduce regional carbon emissions (Jing et al., 2021). Technological progress also plays a key role in the process of carbon emissions. Optimal use of resources is helpful for cleaner production and reduction of health damages (Elahi et al., 2019a; Elahi et al., 2019b; Elahi et al., 2019c). It affects energy costs, reduces energy prices, creates income effects and substitution effects of energy consumption, improves energy structure, increases the proportion of clean energy use, and ultimately reduces regional carbon emissions (Yang et al., 2019). Financial and advisory services are important to disseminate technology in the society (Elahi et al., 2018). The spatial agglomeration of the economy can affect carbon emission too. Its impact shows a significant negative relationship. At the same time, stricter environmental regulation policies and deeper regional integration development caused by economic agglomeration will also indirectly promote carbon emission reduction (Ren et al., 2020).

As an uncertainty analysis method, Monte Carlo simulation has the characteristics of comprehensiveness and flexibility, so it is widely used in the analysis of uncertain events (Shao et al., 2017). Carbon emission is regarded as a standard uncertainty event, so the use of Monte Carlo simulation can give full play to predict the future carbon emission level, thus providing an effective path for exploring carbon neutrality.

In the present article, we used the Tapio decoupling model to analyze the present status of carbon emission in the Bohai Rim. The LMDI method is used to decompose the influencing factors of carbon emission in China's high-end equipment manufacturing industry. Similarly, Monte Carlo simulation is conducted to analyze the evolution trend of carbon emission to predict the carbon neutrality of the high-end equipment manufacturing industry.

2 MATERIALS AND METHODS

2.1 Data Sources
Based on the research purpose, the data from five provinces and cities in the Bohai Rim from 2009 to 2019 were collected. Particularly, the data were collected from the China Statistical Yearbook (2010–2020), China Energy Statistical Yearbook (2010–2020), China Environmental Statistical Yearbook (2011–2020), and the statistical yearbooks of the five provinces and cities in the Bohai Rim. Some missing data were supplemented by the average value method.

2.2 Analytical Framework
2.2.1 Carbon Emission Measurement Model
Because of the lack of clear classification standards for China's high-end equipment manufacturing industry, this article refers to the "National Economic Industry Classification and Code" (GB/T 4754-2017), "Strategic Emerging Industries" (trial), and " High-tech Industry Statistical Classification Catalogue," combined with relevant literature (Huang and Zhang, 2015) and divides the high-end equipment manufacturing industry including General Equipment Manufacturing (C34), Special Equipment Manufacturing (C35), Automobile Manufacturing (C36), Railways, Ships, Aerospace and Other Transportation Equipment Manufacturing (C37), Electrical Machinery and Equipment Manufacturing (C38), Computer, Communications and Other Electronic Equipment Manufacturing (C39), and Instrumentation Manufacturing (C40).

Based on the method adopted by the Intergovernmental Panel on Climate Change (IPCC), this study uses energy consumption data from the provincial statistical yearbooks, and the models were constructed as follows:

$$CE = \sum_{i=1}^{n} A_i \times N_i \times CC_i \times O_i \times B, \qquad (1)$$

where CE is the total carbon emission of high-end equipment manufacturing in the Bohai Rim, i is the kinds of fossil energy, A_i

TABLE 1 | Decoupling situation.

Decoupling level		ΔC/C and ΔG/G	DE
Decoupling	Strong	$\Delta C/C < 0$; $\Delta G/G > 0$	$DE < 0$
	Weak	$\Delta C/C > 0$; $\Delta G/G > 0$	$0 < DE < 0.8$
	Very weak	$\Delta C/C < 0$; $\Delta G/G < 0$	$DE > 1.2$
Connection	Growth	$\Delta C/C > 0$; $\Delta G/G > 0$	$0.8 < DE < 1.2$
	Weak	$\Delta C/C < 0$; $\Delta G/G < 0$	$0.8 < DE < 1.2$
Negative decoupling	Weak	$\Delta C/C < 0$; $\Delta G/G < 0$	$0 < DE < 0.8$
	Strong	$\Delta C/C > 0$; $\Delta G/G < 0$	$DE < 0$
	Very weak	$\Delta C/C > 0$; $\Delta G/G > 0$	$DE > 1.2$

is the energy consumption, N_i is the low-energy calorific value, CC_i is the carbon emission factor provided by IPCC, O_i is the carbon oxidation factor, and B is the mass ratio of carbon dioxide molecules to carbon (3.667).

2.2.2 Tapio Decoupling Model

The Tapio decoupling model has been widely used in various fields (Petri, 2005). Since the Tapio model can accurately determine the decoupling state of a region at a certain time, this study uses the Tapio model to study the relationship between the development of high-end equipment manufacturing and carbon emission in the Bohai Rim, and the decoupling model is given as

$$DE = \frac{\Delta C/C}{\Delta G/G}, \tag{2}$$

where DE is the decoupling elasticity value, ΔC is the difference between the carbon emission of the present period and the carbon emission of the previous period, C is the carbon emission of the present period, ΔG is the difference between the total output value of the high-end equipment manufacturing industry in the Bohai Rim and the previous period, and G is the present gross output value. According to the division of the decoupling elasticity value by scholars (Liu, 2016), the relationship between high-end equipment manufacturing and carbon emission is divided into three types: connection, decoupling, and negative decoupling. The details are given in **Table 1**. Among them, a strong decoupling state means that the development of the high-end equipment manufacturing industry in the Bohai Rim is not based on energy consumption and carbon emission, and there is no direct relationship between industrial development and carbon emission. Weak decoupling and very weak decoupling indicate that as the industry develops, the negative impact of carbon emission will also increase, but the growth rate is smaller than that of economic development. The connection and negative decoupling states are both non-ideal states of carbon emission and industrial economic development.

2.2.3 LMDI Decomposition Model

This study uses the LMDI model to analyze carbon emission factors (Fu et al., 2021). The model is given as

$$C = \sum_i C_i = \sum_i Y \frac{Y_i}{Y} \frac{C_i}{Y_i} = \sum_i CS_iT_i, \tag{3}$$

where C is the total carbon emission of high-end equipment manufacturing in the Bohai Rim, C_i is the carbon emission of various sub-sectors in the high-end equipment manufacturing industry, Y is the output value of the high-end equipment manufacturing industry in the Bohai Rim, Y_i is the output value of each sub-sector of the high-end equipment manufacturing industry, $S_i = Y_i / Y$ is the proportion of i industry output value in total output value, and $T_i = C_i / Y_i$ is i industry unit output value energy consumption.

Assuming 0 as the base period to the t period, the change in carbon emission can be estimated using the given function:

$$\Delta C = C^t - C^0 = \sum_i C_i^t S_i^t T_i^t - \sum_i C_i^0 S_i^0 T_i^0 = \Delta C_Y + \Delta C_S + \Delta C_T, \tag{4}$$

where ΔC_Y is the scale effect of carbon emission, indicating the difference in carbon emission due to changes in the output value of high-end equipment manufacturing; ΔC_S is the structural effect of carbon emission, indicating changes in carbon emission due to structural changes in various sub-sectors of the high-end equipment manufacturing industry; and ΔC_T is the intensity of carbon emission which indicates the change in total carbon emission due to changes in the intensity of carbon emission.

On the basis of the LMDI model, we continued using the additive decomposition model to decompose the carbon emission of high-end equipment manufacturing in the Bohai Rim, and the model is given as

$$\Delta C_Y = \sum_i L\left(C_i^0, C_i^t\right) \ln \frac{Y_i^t}{Y_i^0}, \tag{5}$$

$$\Delta C_S = \sum_i L\left(C_i^0, C_i^t\right) \ln \frac{S_i^t}{S_i^0}, \tag{6}$$

$$\Delta C_T = \sum_i L\left(C_i^0, C_i^t\right) \ln \frac{T_i^t}{T_i^0}, \tag{7}$$

$$L\left(C_i^0, C_i^t\right) = \begin{cases} \dfrac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} & \left(C_i^t \neq C_i^0\right) \\ C_i^t & \left(C_i^t = C_i^0\right) \end{cases}. \tag{8}$$

2.2.4. Monte Carlo Simulation

Monte Carlo simulation is used to predict the carbon neutrality of the high-end equipment manufacturing industry in the Bohai Rim. Since the most likely variation interval and median value of a variable are known, but the shape of its probability distribution is unknown, it is assumed that each variable is a triangular distribution. Then, we used Crystal Ball to simulate each factor in the baseline scenario, low-carbon scenario, and technological breakthrough scenario to predict the specific time of carbon neutrality in the high-end equipment manufacturing industry in the Bohai Rim. The number of simulations is 500,000 times. The annual average change rate is set and refers to various policies.

TABLE 2 | Carbon emission of high-end equipment manufacturing in the Bohai Rim (10 kilo-tons).

Province	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Beijing	656	715	780	856	835	803	786	815	801	738	696
Tainjin	151	136	135	229	305	241	194	135	29	28	27
Hebei	899	1,130	1,313	920	939	935	882	908	876	838	792
Liaoning	1,217	1,459	1,576	1,696	1,850	716	610	429	267	149	109
Shandong	3,590	4,544	5,739	4,356	4,535	4,313	4,124	3,442	2,953	2,704	2,476
Bohai Rim	6,513	7,984	9,543	8,057	8,464	7,008	6,596	5,729	4,926	4,457	4,100

FIGURE 1 | Decoupling situation.
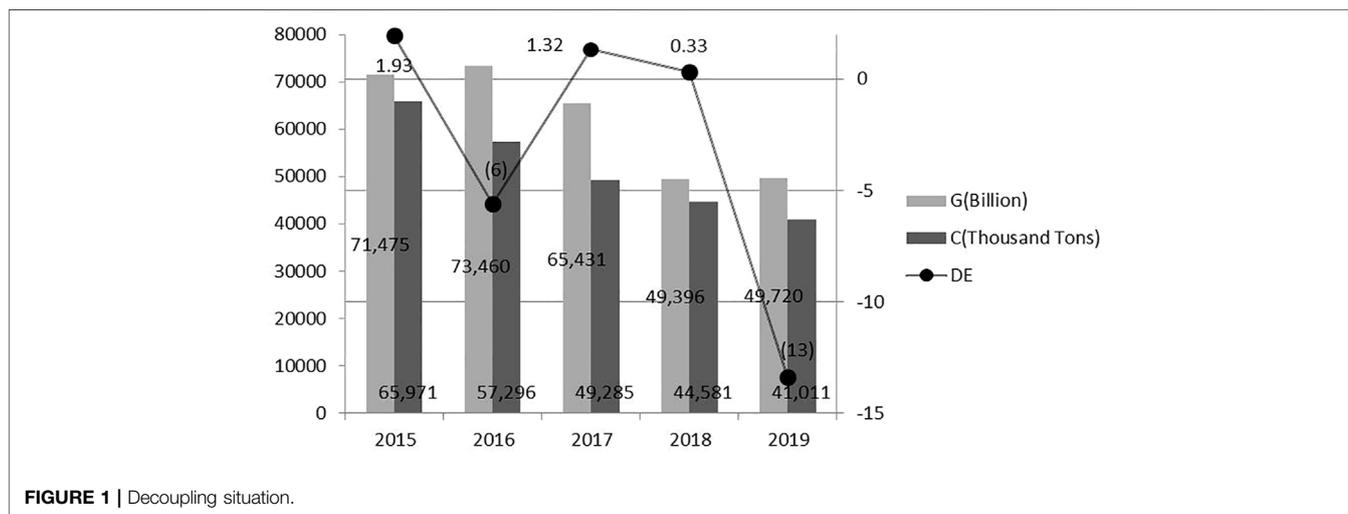
3 RESULTS AND DISCUSSION

3.1 Carbon Emission Status Analysis

According to the carbon emission measurement model, the carbon emission of high-end equipment manufacturing in the Bohai Rim was calculated (**Table 2**). From 2009 to 2019, the carbon emission of the high-end equipment manufacturing industry in the Bohai Rim showed an increasing trend and then reduced in the later stage. The peak of carbon emission occurred in 2011 with a total carbon emission of 95.43 million tons. From 2011 to 2019, the total carbon emission of the high-end equipment manufacturing industry in the Bohai Rim gradually decreased, with an average annual growth rate of 14.8%. From the perspective of provinces and cities, the carbon emission of the high-end equipment manufacturing industry generally presents the pattern of Shandong > Hebei > Beijing > Liaoning > Tianjin. Shandong Province contributed 60% of the total carbon emission of the high-end equipment manufacturing industry in the Bohai Rim.

3.2 Carbon Emission Decoupling Model Analysis

According to the Tapio decoupling model, this study analyzes the carbon emission decoupling effect of the high-end equipment manufacturing industry in the Bohai Rim in the past 5 years. It can be seen from **Figure 1** that since 2015, the output value (G), total carbon emission (C), and decoupling elasticity value (DE) of the

high-end equipment manufacturing industry showed a decreasing trend. There was an adjustment from the weak decoupling state in 2015 to the strong decoupling state in 2019, but the decoupling state of regional carbon emission is not stable.

The carbon emission decoupling status of the high-end equipment manufacturing industry in various provinces and cities is shown in **Table 3**. It is found that by 2019, except for Shandong Province, other provinces and cities in the Bohai Rim will have reached a strong decoupling state of industrial development and carbon emission. Among them, Beijing has maintained a strong decoupling relationship between carbon emission and the development of the high-end equipment manufacturing industry in recent years. It is an advantageous area of decoupling effects in the Bohai Rim, which can provide a reference for the low-carbon development of other provinces and cities. Tianjin, Hebei, Liaoning, and Shandong have basically maintained a decoupling state; they have also crossed weak decoupling, and very weak decoupling indicates that the decoupling relationship between carbon emission and the development of high-end equipment manufacturing is not stable.

3.3 Decomposition of Carbon Emission Factors
3.3.1 Decomposition of Carbon Emission Factors in the Bohai Rim
From 2015 to 2019, the carbon emission of high-end equipment manufacturing in the Bohai Rim decreased by 28.95 million tons

TABLE 3 | Decoupling situation of the Bohai Rim.

Province	2015	2016	2017	2018	2019
Beijing	Very weak decoupling	Weak decoupling	Strong decoupling	Strong decoupling	Strong decoupling
Tainjin	Strong decoupling	Very weak decoupling	Very weak decoupling	Strong decoupling	Strong decoupling
Hebei	Strong decoupling	Weak decoupling	Weak negative decoupling	Weak negative decoupling	Strong decoupling
Liaoning	Weak negative decoupling	Weak connection	Very weak decoupling	Very weak decoupling	Strong decoupling
Shandong	Strong decoupling	Strong decoupling	Very weak decoupling	Weak negative decoupling	Weak negative decoupling
Bohai Rim	Very weak decoupling	Strong decoupling	Very weak decoupling	Weak decoupling	Strong decoupling

TABLE 4 | Decomposition of carbon emission factors in the Bohai Rim.

Bohai Rim	Changes in carbon emissions (10 kilo-tons)					
	2015	2016	2017	2018	2019	Total
ΔC	−333	−937	−800	−474	−351	−2,895
ΔCY	−252 (75.7%)	−19 (2.0%)	−291 (36.4%)	−1222 (257.8)	−395 (112.5%)	−2,179 (75.3)
ΔCS	195 (58.5%)	78 (−8.3%)	−258 (32.3%)	638 (134.6%)	170 (−48.4%)	−453 (15.6%)
ΔCT	−275 (82.6%)	−996 (106.3%)	−251 (31.4%)	1386 (−292.4%)	−127 (36.2%)	−263 (9.1%)

The values in parentheses indicate the contribution rate of each influencing factor.

of coal (**Table 4**). Among them, the carbon emission reduction caused by the scale effect of carbon emission was 21.79 million tons of coal, and the contribution rate to carbon emission reduction was 75.3%. The structural adjustment of the high-end equipment manufacturing industry reduced the carbon emission of 4.53 million tons of standard coal and contributed 15.6% to the carbon emission reduction. Changes in the intensity of carbon emission resulted in a reduction in carbon emission of 2.63 million tons of coal with a contribution rate of 9.1%.

From 2015 to 2019, the scale of the high-end equipment manufacturing industry in the Bohai Rim dropped from 7,147.5 to 4,971.9 billion yuan, and the total carbon emission also declined. It can be seen that the Bohai Rim has made significant progress in energy conservation and emission reduction in recent years. However, most of the reduction in carbon emission from high-end equipment manufacturing in the Bohai Rim region is due to the reduction in the output value, and such carbon emission reduction methods are unsustainable. Reduction of carbon emission intensity does not play an important role in the carbon emission reduction process of high-end equipment manufacturing in the Bohai Rim region. Therefore, improving the technical level and reducing the carbon emission intensity is an important way to reduce carbon emissions in the high-end equipment manufacturing industry in the Bohai Rim in the future.

3.3.2 Decomposition of Carbon Emission Factors in Provinces and Cities
3.3.2.1 Scale Effects
From 2015 to 2019, the scale effect of carbon emission has made positive contributions to carbon emission reduction except in Beijing. However, the contribution of the scale effect to carbon emission reduction is premised on the decline in the output value of the high-end equipment manufacturing industry. Among them, Shandong Province has the largest carbon emission

reduction rate of 14.78 million tons. At the same time, the output value of its high-end equipment manufacturing industry has also declined the most, from a total output value of 3,480.5 billion yuan in 2015 to 1,746.4 billion yuan in 2019 (see **Table 5**

3.3.2.2 Structural Effect
From 2015 to 2019, there is regional heterogeneity in the change of carbon emissions caused by the structural effect. The adjustment of industrial structures in Beijing, Tianjin, and Hebei has increased the total amount of carbon emission. The adjustment of industrial structures in Liaoning and Shandong has promoted the reduction of carbon emissions. It is because from 2015 to 2019, the proportion of automobile manufacturing, computer communication, and other electronic equipment manufacturing in Beijing, Tianjin, and Hebei has increased. However, other sub-industries changed less, resulting in a carbon emission rise. For Shandong and Liaoning, the proportion of general equipment manufacturing, special equipment manufacturing and electrical machinery, and equipment manufacturing has dropped significantly, and consequently, the total carbon emissions have declined (**Table 6**).

3.3.2.3 Carbon Emission Intensity Effect
The reduction of carbon emission intensity in Beijing and Tianjin has promoted the decline of the total carbon emission with a contribution of 220.31% and 90.75% (**Table 7**). The reason for this phenomenon is that Beijing and Tianjin promulgate policies to improve energy efficiency. At the same time, the two cities took advantage of regional technological innovation to gradually build a green, low-carbon, and renewable energy system. However, the intensity of the carbon emission effect led Hebei, Liaoning, and Shandong to an increase in carbon emissions in the high-end equipment manufacturing industry. The contribution of carbon emission intensity in the past 5 years is −25.47%, −2.14%, and

TABLE 5 | Scale effect of carbon emission in provinces and cities.

ΔCY	2015	2016	2017	2018	2019	Total
Beijing	37.49 (214.97%)	36.58 (125.04%)	38.94 (272.72%)	26.01 (41.10%)	29.85 (71.44%)	93.89 (87.30%)
Tainjin	2.78 (5.90%)	9.91 (16.66%)	30.13 (28.60%)	2.34 (200.33%)	1.60 (228.55%)	42.10 (19.68%)
Hebei	30.49 (58.05%)	32.14 (126.95%)	107.20 (344.26%)	−88.54 (230.54%)	120.03 (258.14%)	314.11 (219.29%)
Liaoning	253.71 (237.35%)	205.57 (113.59%)	21.50 (13.34%)	20.85 (17.59%)	21.69 (54.47%)	438.61 (72.20%)
Shandong	72.69 (66.96%)	127.69 (17.00%)	214.37 (43.89%)	1182.8 (468.97%)	281.2 (126.29%)	1478 (81.07)

The values in parentheses indicate the contribution rate of each influencing factor.

TABLE 6 | Structural effect of carbon emissions in provinces and cities.

ΔC_S	2015	2016	2017	2018	2019	Total
Beijing	29.98 (171.90%)	33.45 (114.35%)	−27.38 (191.71%)	−10.09 (15.95%)	9.55 (22.85%)	35.51 (33.01%)
Tainjin	25.04 (53.10%)	6.66 (11.19%)	13.84 (13.14%)	0.50 (43.14%)	3.94 (562.15%)	22.30 (10.43%)
Hebei	80.96 (154.16%)	47.18 (186.36%)	−65.48 (210.30)	−108.30 (282.00%)	180.035 (387.18%)	134.40 (93.82%)
Liaoning	−22.20 (20.77%)	−106.75 (58.98%)	−85.82 (53.23%)	−49.05 (41.38)	82.00 (205.91%)	−181.82 (29.93%)
Shandong	80.27 (73.95%)	97.23 (12.94%)	−65.92 (13.50%)	−471.00 (186.74%)	−105.52 (47.39%)	464.93 (25.50%)

The values in parentheses indicate the contribution rate of each influencing factor.

TABLE 7 | Carbon emission intensity effect in provinces and cities.

ΔC_T	2015	2016	2017	2018	2019	Total
Beijing	−9.93 (56.93%)	−40.77 (139.38%)	−25.85 (181.00%)	−79.22 (125.15%)	−81.185 (194.29%)	−236.96 (220.31%)
Tainjin	−69.41 (147.20%)	56.26 (94.53%)	−61.37 (58.26%)	−4.01 (343.48%)	−3.04 (433.60%)	−194.1 (90.75%)
Hebei	−102.99 (196.11%)	−54.00 (213.30%)	141.54 (454.55%)	158.43 (412.54%)	−106.50 (229.04%)	36.48 (25.47%)
Liaoning	169.01 (158.11%)	131.34 (72.57%)	−96.91 (60.11%)	−90.34 (76.21%)	−100.13 (251.44%)	12.97 (2.14%)
Shandong	−261.51 (240.91%)	−976.07 (129.94%)	−208.19 (42.62%)	1401.61 (555.71%)	164.05 (73.67%)	119.89 (6.58%)

Note: The values in parentheses indicate the contribution rate of each influencing factor.

−6.58%. It caused an increase in the level of regional carbon emissions. The possible reason is that Hebei, Liaoning, and Shandong did not pay attention to improving energy utilization efficiency, and more emphasis was on adjusting the energy structure and promoting the development of clean energy, which may lead to an increase in the carbon emission intensity of high-end equipment manufacturing.

Beijing and Tianjin have obvious advantages in carbon emission reduction in the high-end equipment manufacturing industry. It is worth learning from other regions. The carbon emission reduction of high-end equipment manufacturing industries in Hebei, Liaoning, and Shandong mainly depends on the scale effect. The intensity of carbon emission has not played an important role in the process of carbon emission.

3.4 Carbon Neutrality Forecast for the High-End Equipment Manufacturing in the Bohai Rim

3.4.1 Scenario Setting

Based on the development of China's clean energy industry, the future development scenarios are set as the base scenario, the low-carbon scenario, and the technological breakthrough scenario.

3.4.1.1 Base Scenario

The base scenario refers to the high-end equipment manufacturing industry in the Bohai Rim that adheres to the present development model and carbon emission policy. Assuming that the current economic environment and technological level remain unchanged, the government will no longer issue stricter carbon emission policies. The carbon emission indicators are predicted based on the development trend in recent years. In terms of clean energy (CE), the country still adheres to the present development policy and the total output of clean energy is predicted based on the output data of recent years. At the same time, this study refers to various policies (Lin and Liu, 2010). The median value of the annual average change rate of carbon emission intensity is set to −3.43%, and then, the minimum and maximum annual average rate of change is adjusted on the basis of the median value. The potential change rate of each influencing factor under the base scenario is given in **Table 8**.

3.4.1.2 Low-Carbon Scenario

Under the low-carbon scenario, the high-end equipment manufacturing industry in the Bohai Rim has changed the traditional development model, and the industrial-scale expansion is no longer at the expense of the environment. The

TABLE 8 | Potential change rate of each influencing factor under the base scenario.

	2020–2030 (%)			2031–2040 (%)			2041–2050 (%)		
	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
ΔCY	4.5%	5.5%	6.5%	3.5%	4.5%	5.5%	2.5%	3.5%	4.5%
ΔCS	−2.9%	−2.9%	−1.9%	−2.9%	−1.9%	−0.9%	−1.9%	−0.9%	−0.09%
ΔCT	−3.83%	−3.43%	−3.03%	−2.83%	−2.43%	−2.03%	−1.83%	1.43%	−1.03%
CE	9.2%	10.7%	12.4%	8.2%	9.7%	11.4%	7.2%	8.7%	10.4%

TABLE 9 | Potential change rate of each influencing factor under the low-carbon scenario.

	2020–2030 (%)			2031–2040 (%)			2041–2050 (%)		
	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
ΔCY	4.5%	5.5%	6.5%	3.5%	4.5%	5.5%	2.5%	3.5%	4.5%
ΔCS	3.9%	−2.9%	−1.9%	−2.9%	−1.9%	−0.9%	−1.9%	−0.9%	−0.09%
ΔCT	−4.83%	−4.43%	−4.03%	−3.83%	−3.43%	3.03%	−2.83%	−2.43%	−2.03%
CE	10.2%	11.7%	13.4%	9.2%	10.7%	12.4%	8.2%	9.7%	11.4%

government has issued relevant policies to improve energy efficiency and reduce the intensity of carbon emissions. At the same time, the proportion of clean energy consumption in the energy consumption structure has increased, the level of energy-saving technologies has been improved, and the rate of decline in total carbon emissions has accelerated. As for the production of clean energy, the government will introduce policies to promote the development of new energy and clean energy, and the total output of clean energy production has increased. In addition, the effectiveness of policy implementation and the uncertainty of the economic environment are fully considered. The potential change rate of each influencing factor under the low-carbon scenario is given in **Table 9**.

3.4.1.3 Technological Breakthrough Scenario

With the increasingly strict carbon emission policy in China, the technological innovation activities of energy saving and emission reduction are becoming increasingly active. Technological innovation has become a necessary way to achieve carbon neutrality. On the one hand, through technological innovation, it is possible to find the potential for structural adjustment and optimization of various sub-industries of the high-end equipment manufacturing industry. On the other hand, the optimization of production processes brought by technological innovation has reduced the carbon emission intensity of various industries. At the same time, the improvement of clean energy production technology not only guarantees the safety problems in the process of clean energy production but also promotes the increase of the total amount of clean energy production. The specific change rate is shown in **Table 10**.

3.4.2 Simulation Method—Carbon Neutrality Forecast
3.4.2.1 Base Scenario

Under the base scenario, by 2049, the total carbon emission of the high-end equipment manufacturing industry in the Bohai Rim will be about 5.09 million tons. Compared with 2019, the

reduction of carbon emission is 35.92 million tons and the annual carbon emission reduction is 1.1588 million tons. At the same time, the total carbon emission will decrease by about 4.52 million tons caused by the use of clean energy. Overall, the probability of achieving carbon neutrality in the high-end equipment manufacturing industry in the Bohai Rim in 2049 is 40.38%. By 2050, total carbon emissions will continue to decrease, clean energy production will continue to rise, and the probability of reaching the carbon neutrality target will increase to 81.70%. In 2051, the probability of achieving carbon neutrality in the high-end equipment manufacturing industry in the Bohai Rim will expand to 97.69%. The possibility of achieving carbon neutrality is extremely high, which is about 9 years earlier than the target. Among the influencing factors, the carbon emission intensity effect has the largest contribution to carbon neutrality. A total of 57.5394 million tons of carbon dioxide were reduced with a contribution rate of 145.93%.

3.4.2.2 Low-Carbon Scenario

Under the low-carbon scenario, compared with the baseline scenario, the carbon emissions of high-end equipment manufacturing in the Bohai Rim region are further reduced. By 2044, the total carbon emissions will be about 7.76 million tons and the carbon emissions from the use of clean energy will be about 4.10 million tons. At that time, the probability of attaining the carbon neutrality target will be about 4.35%. In 2045, the total carbon emissions will be about 5.77 million tons, while the total carbon emissions reduced by the use of clean energy will reach 4.49 million tons, and the probability of carbon neutrality will be about 49.12%. In 2046, the total amount of carbon emissions will be reduced to 3.71 million tons, while the total amount of carbon dioxide emissions reduced by the use of clean energy will reach 4.93 million tons, and the probability of achieving carbon neutrality will be 93.22%. Among the various influencing factors, the reduction of carbon emission intensity is still the biggest contributor to the realization of carbon neutrality, with a

TABLE 10 | Potential change rate of each influencing factor under the technological breakthrough scenario.

	2020–2030 (%)			2031–2040 (%)			2041–2050 (%)		
	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
ΔCY	4.5%	5.5%	6.5%	3.5%	4.5%	5.5%	2.5%	3.5%	4.5%
ΔCS	4.9%	−3.9%	−2.9%	−3.9%	−2.9%	−1.9%	−2.9%	−1.9%	−0.9%
ΔCT	−5.83%	−5.43%	−5.03%	−4.83%	−4.43%	−4.03%	−3.83%	−3.43%	−3.03%
CE	11.2%	12.7%	14.4%	10.2%	11.7%	13.4%	9.2%	10.7%	12.4%

total carbon emission reduction of 54.75 million tons and a contribution rate of 146.78%.

3.4.2.3 Technological Breakthrough Scenario

Under the technological breakthrough scenario, because of the improvement of the production technology of the high-end equipment manufacturing industry in the Bohai Rim region and the progress of the production technology of clean energy, the realization time of carbon neutrality will be further shortened. In 2040, the probability of achieving carbon emissions is 0.039%. In 2041, the probability of achieving carbon neutrality rises to 33.50%, and it can be found that the probability of achieving carbon neutrality is still low. However, by 2042, the probability of carbon neutrality in the Bohai Rim region will increase to 97.84%, and there is great hope for achieving carbon neutrality. The technological breakthrough scenario achieves the carbon neutrality goal 4 years earlier than the low-carbon scenario and 9 years earlier than the baseline scenario, indicating that technological progress has a significant role in promoting carbon neutrality in the high-end equipment manufacturing industry in the Bohai Rim. At the same time, technological breakthroughs continued to increase the contribution of the carbon emission intensity effect, reducing carbon emissions by a total of 47.52 million tons with a contribution rate of 161.63%.

4 CONCLUSION, POLICY IMPLICATIONS, AND FUTURE RESEARCH

4.1 Conclusion and Policy Implications

In the present study, the Tapio model was used to analyze the carbon emission of high-end equipment manufacturing in the Bohai Rim (including five provinces: Beijing, Tianjin, Hebei, Liaoning, and Shandong) from 2015 to 2019. The LMDI model was used to decompose the influencing factors of carbon emissions. On this basis, combined with various policy indicators, the Monte Carlo simulation method was used to predict carbon neutrality. The main conclusions of this study are given as follows.

First, in 2019, the development of high-end equipment manufacturing and carbon emissions in the Bohai Rim region showed an ideal state of strong decoupling, but this ideal state is not stable and there is a risk of "recoupling." From the perspective of the provinces and cities around the Bohai Sea, the carbon decoupling situation in Beijing and Tianjin is relatively good, and the ideal state of strong decoupling can be maintained. The next two provinces are Hebei and Liaoning, which have achieved

strong decoupling in 2019. The carbon decoupling situation in Shandong Province is relatively poor, and it has been in a non-ideal state of negative decoupling in recent years.

Second, the result of the LMDI model finds that the scale effect is the main contributor to carbon emission reduction in the high-end equipment manufacturing industry in the Bohai Rim. The contribution rate is 75.3%. The second is the structural effect and the carbon emission intensity effect, with contribution rates of 15.6% and 9.1%, respectively. From the perspective of each province and city, except Beijing and Tianjin which use the reduction of carbon emission intensity as the main force for carbon emission reduction, the other three provinces use the scale effect as the main contributor to carbon emission reduction but such carbon reduction is unsustainable.

Third, under different scenarios, there are significant differences in the evolution path of carbon neutrality in the high-end equipment manufacturing industry in the Bohai Rim. Under the baseline scenario, the low-carbon scenario, and the technological breakthrough scenario, the carbon neutrality target is expected to be achieved ahead of schedule, and the carbon neutrality time estimated by the Monte Carlo simulation is 2051, 2046, and 2042, respectively. In each scenario, the contribution rate of carbon emission intensity to carbon neutrality is the largest and gradually increases, which are 145.93%, 146.78%, and 161.63%, respectively.

China should improve energy utilization efficiency and strengthen incentives for green innovation in high-end equipment manufacturing enterprises. The carbon emission reduction of the high-end equipment manufacturing industry in the Bohai Rim mainly depends on the scale effect, and the carbon emission intensity still has great potential to promote carbon emission reduction. Therefore, reduce the waste of energy in processing, conversion, transportation, distribution, and other terminal utilizations. Then the use of new technologies such as cloud computing and big data to establish a smart energy management system is of great importance to the high-end equipment manufacturing enterprises in the Bohai Rim. In addition, the government should guide enterprises to increase investment in energy conservation and provide enterprises with tax relief and policy subsidies to urge them to take the social responsibility for the realization of the carbon neutrality goal.

4.2 Future Research

This article gathered data from high-end equipment manufacturing in China's Bohai Rim to research its carbon emission status and predict the time to attain the carbon neutrality goal. However, the many influencing factors

affecting carbon emission and the analysis methods for carbon neutrality prediction need to be further explored. Moreover, micro-level data on carbon emissions should be considered to make a detailed and comprehensive analysis.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

HL was responsible for the collection and arrangement of relevant literature, data analysis and article writing. EE made comments on the choice of the article title and revised the article, and ZS collected data needed for the article.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.926365/full#supplementary-material

REFERENCES

Elahi, E., Khalid, Z., Weijun, C., and Zhang, H. (2020). The Public Policy of Agricultural Land Allotment to Agrarians and its Impact on Crop Productivity in Punjab Province of Pakistan. *Land Use Policy* 90, 104–324. doi:10.1016/j.landusepol.2019.104324

Elahi, E., Zhang, H., Lirong, X., Khalid, Z., and Xu, H. (2021b). Understanding Cognitive and Socio-Psychological Factors Determining Farmers' Intentions to Use Improved Grassland: Implications of Land Use Policy for Sustainable Pasture Production. *Land Use Policy* 102, 105–250. doi:10.1016/j.landusepol.2020.105250

Elahi, E., Abid, M., Zhang, L., Ul Haq, S., and Sahito, J. G. M. (2018). Agricultural Advisory and Financial Services; Farm Level Access, Outreach and Impact in a Mixed Cropping District of Punjab, Pakistan. *Land use policy* 71, 249–260. doi:10.1016/j.landusepol.2017.12.006

Elahi, E., Khalid, Z., Tauni, M. Z., Zhang, H., and Lirong, X. (2021a). Extreme Weather Events Risk to Crop-Production and the Adaptation of Innovative Management Strategies to Mitigate the Risk: A Retrospective Survey of Rural Punjab, Pakistan. *Technovation* 117, 102255. doi:10.1016/j.technovation.2021.102255

Elahi, E., Khalid, Z., and Zhang, Z. (2022a). Understanding Farmers' Intention and Willingness to Install Renewable Energy Technology: A Solution to Reduce the Environmental Emissions of Agriculture. *Appl. Energy* 309, 118459. doi:10.1016/j.apenergy.2021.118459

Elahi, E., Weijun, C., Jha, S. K., and Zhang, H. (2019a). Estimation of Realistic Renewable and Non-renewable Energy Use Targets for Livestock Production Systems Utilising an Artificial Neural Network Method: A Step towards Livestock Sustainability. *Energy* 183, 191–204. doi:10.1016/j.energy.2019.06.084

Elahi, E., Weijun, C., Zhang, H., and Abid, M. (2019b). Use of Artificial Neural Networks to Rescue Agrochemical-Based Health Hazards: a Resource Optimisation Method for Cleaner Crop Production. *J. Clean. Prod.* 238, 117900. doi:10.1016/j.jclepro.2019.117900

Elahi, E., Weijun, C., Zhang, H., and Nazeer, M. (2019c). Agricultural Intensification and Damages to Human Health in Relation to Agrochemicals: Application of Artificial Intelligence. *Land Use Policy* 83, 461–474. doi:10.1016/j.landusepol.2019.02.023

Elahi, E., Zhang, Z., Khalid, Z., and Xu, H. (2022b). Application of an Artificial Neural Network to Optimise Energy-and Cost-Saving Strategy for Commercial Poultry Farms. *Energy* 244, 123169. doi:10.1016/j.energy.2022.123169

Fan, D. C., and Du, M. Y. (2018). Research on Technology Innovation Resource Allocation Efficiency and its Influencing Factors in High-End Equipment Manufacturing Industries---Based on the Empirical Analysis of the Two-stage StoNED-Tobit Model. *Chin. J. Manag. Sci.* 26, 13–24. doi:10.16381/j.cnki.issn1003-207x.2018.01.002

Fu, H., Li, G. P., and Zhu, T. (2021). Carbon Emission of China's Manufacturing Industry:Industry Differences and Decomposition of Driving Factors. *Reform* 4, 38–52.

Gu, H., Bian, F., and Elahi, E. (2020a). Effect of Air Pollution on Female Labor Supply: An Empirical Analysis Based on Data of Labor Force Dynamic Survey of China. *Soc. Work Public Health* 35, 187–196. doi:10.1080/19371918.2020.1764433

Gu, H., Cao, Y., Elahi, E., and Jha, S. K. (2019). Human Health Damages Related to Air Pollution in China. *Environ. Sci. Pollut. Res. Int.* 26, 13115–13125. doi:10.1007/s11356-019-04708-y

Gu, H., Yan, W., Elahi, E., and Cao, Y. (2020b). Air Pollution Risks Human Mental Health: An Implication of Two-Stages Least Squares Estimation of Interaction Effects. *Environ. Sci. Pollut. Res.* 27, 2036–2043. doi:10.1007/s11356-019-06612-x

Huang, H. X., and Zhang, Z. H. (2015). Research on Science and Technology Resource Allocation Efficiency in Chinese Emerging Strategic Industries Based on DEA Model. *China Soft Sci.* 4, 150–159.

Jing, Y. J. L. X. F., and Wang, Y. Y. (2021). Government Research on the Path to Regulating Carbon Emissions---Based on a Financial Efficiency Perspective. *China Soft Sci.* 5, 135–144.

Lin, B. Q., and Liu, X. Y. (2010). China' s Carbon Dioxide Emissions under the Urbanization Process :Influence Factors and Abatement Policies. *Econ. Res. J.* 45, 66–78.

Liu, H. M. (2016). Can Economic Growth Decouple With Energy Consumption: A Temporal and Spatial Study of Eastern China. *China Popul. Resour. Environ.* 26, 157–163.

Odhiambo, M. R. O., Abbas, A., Wang, X., and Elahi, E. (2020). Thermo-Environmental Assessment of A Heated Venlo-Type Greenhouse in the Yangtze River Delta Region. *Sustainability* 12, 10412. doi:10.3390/su122410412

Peng, B., Yan, W., Elahi, E., and Wan, A. (2021a). Does the Green Credit Policy Affect the Scale of Corporate Debt Financing? Evidence From Listed Companies in Heavy Pollution Industries in China. *Environ. Sci. Pollut. Res.* 29 1–13. doi:10.1007/s11356-021-15587-7

Peng, B., Zhao, Y., Elahi, E., and Wan, A. (2021b). Investment in Environmental Protection, Green Innovation, and Solid Waste Governance Capacity: Empirical Evidence Based on Panel Data From China. *J. Environ. Plan. Manag.* 65, 1–24. doi:10.1080/09640568.2021.2017866

Peng, B., Tu, Y., Elahi, E., and Wei, G. (2018). Extended Producer Responsibility and Corporate Performance: Effects of Environmental Regulation and Environmental Strategy. *J. Environ. Manag.* 218, 181–189. doi:10.1016/j.jenvman.2018.04.068

Peng, B., Zheng, C., Wei, G., and Elahi, E. (2020). The Cultivation Mechanism of Green Technology Innovation in Manufacturing Industry: From The Perspective of Ecological Niche. *J. Clean. Prod.* 252, 119711. doi:10.1016/j.jclepro.2019.119711

Petri, T. (2005). Towards A Theory of Decoupling: Degrees of Decoupling in the EU and the Case of Road Traffic in Finland Between 1970 And 2001. *Transp. Policy* 12, 137–151.

Ren, X. S., Liu, J. Y., and Zhao, G. H. (2020). The Impact and Transmission Mechanism of Economic Agglomeration on Carbon Intensity. *China Popul. Resour. Environ.* 30, 95–106. doi:10.1016/j.tranpol.2005.01.001

Shao, S., Zhang, X., and Zhao, X. R. (2017). Empirical Decomposition and Peaking Pathway of Carbon Dioxide Emissions of China's Manufacturing Sector Generalized Divisia Index Method and Dynamic Scenario Analysis. *China Ind. Econ.* 4, 44–63. doi:10.19581/j.cnki.ciejournal.2017.03.003

Sheng, X., Peng, B., Elahi, E., and Wei, G. (2019). Regional Convergence of Energy-Environmental Efficiency: From The Perspective of Environmental Constraints. *Environ. Sci. Pollut. Res.* 26, 25467–25475. doi:10.1007/s11356-019-05749-z

Tong, J. X., Xu, Q., and Li, Y. (2019). Evaluation and Measurement of Technical Efficiency of the Equipment Manufacturing Industry on China's Five Spatial Layouts. *Forum Sci. Technol. China* 4, 84–92. doi:10.13580/j.cnki.fstc.2019.04.011

Wang, F., Cai, W., and Elahi, E. (2021). Do Green Finance and Environmental Regulation Play a Crucial Role in the Reduction of CO_2 Emissions? An Empirical Analysis of 126 Chinese Cities. *Sustainability* 13, 13014. doi:10.3390/su132313014

Wu, B., Peng, B., Wei, W., and Ehsan, E. (2021). A Comparative Analysis on the International Discourse Power Evaluation of Global Climate Governance. *Environ. Dev. Sustain.* 23, 1–22. doi:10.1007/s10668-020-01180-4

Yang, L. S., Zhu, J. P., and Jia, Z. J. (2019). Influencing Factors and Current Challenges of CO_2 Emission Reduction in China: A Perspective Based on Technological Progress. *Econ. Res. J.* 54, 118–132.

Yuan, Y., Xi, Q. M., Sun, T. S., and Li, G. P. (2016). The Impact of the Industrial Structure on Regional Carbon Emission:Empirical Evidence Across Countries. *Geogr. Res.* 35, 82–94. doi:10.1002/sres.2444

Zhang, H., Yang, J., Ren, X., Wu, Q., Zhou, D., and Elahi, E. (2020). How to Accommodate Curtailed Wind Power: A Comparative Analysis Between The US, Germany, India And China. *Energy Strategy Rev.* 32, 100538. doi:10.1016/j.esr.2020.100538

Zhang, T. F., Yang, J., and Sun, P. F. (2016). The Impacts and Channels of Urbanization on Carbon Dioxide Emissions in China. *China Popul. Resour. Environ.* 26, 47–57.

Zhao, X., Peng, B., Elahi, E., Zheng, C., and Wan, A. (2020). Optimization of Chinese Coal-Fired Power Plants For Cleaner Production Using Bayesian Network. *J. Clean. Prod.* 273, 122837. doi:10.1016/j.jclepro.2020.122837

Zhao, Y., Peng, B., Elahi, E., and Wan, A. (2021). Does the Extended Producer Responsibility System Promote the Green Technological Innovation of Enterprises? An Empirical Study Based on The Difference-In-Differences Model. *J. Clean. Prod.* 319, 128631. doi:10.1016/j.jclepro.2021.128631

Zhong, Z., Peng, B., and Elahi, E. (2021). Spatial and Temporal Pattern Evolution and Influencing Factors of Energy-Environmental Efficiency: A Case Study of Yangtze River Urban Agglomeration in China. *Energy & Environ.* 32, 242–261. doi:10.1177/0958305x20923114

Zhong, Z., Peng, B., Xu, L., Andrews, A., and Elahi, E. (2020). Analysis of Regional Energy Economic Efficiency and Its Influencing Factors: A Case Study of Yangtze River Urban Agglomeration. *Sustain. Energy Technol. Assessments* 41, 100784. doi:10.1016/j.seta.2020.100784