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The Evaluation of Energy Efficiency and its Decoupling from Economic Growth under the Carbon Peak Target

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Abstract

The Global Malmquist-Luenberger index was used to measure the energy efficiency of 11 provinces and regions in eastern China from 2010 to 2019, the Tapio decoupling model was constructed to analyze the decoupling relationship between economic growth and energy consumption and energy use efficiency, and the prediction results of the carbon peak time of each province in the existing literature were combined to put forward suggestions for the provinces that were not ideal for the decoupling. The results show that: (1) The total average energy efficiency of the 11 eastern regions of China during the period from 2010 to 2019 was 0.911, showing an overall upward trend, while the energy efficiency changes in each region were different; (2) The decoupling of economic growth, energy consumption and energy efficiency in Hebei and Hainan provinces was not ideal, and the decoupling in other regions was getting better; (3) There will be a large gap in the time of carbon peak in 11 regions in eastern China. Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Guangdong and Liaoning will achieve carbon peak in 2030 and before; There will be no peaks in Hebei and Hainan regions, while the peaks in Shandong and Fujian appear after 2030.

JEL classification numbers: F06.
Keywords: Carbon peak, Eastern region, Energy efficiency, Tapio decoupling model, Directional distance function, Global Malmquist-Luenberger index (GML).

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1. Introduction

The energy issue is one of the important issues in the economic and social development of the world. It is not only related to the quality of people's lives and the quality of ecological environment development, but also related to national economic security and strategic security. China is currently the world's largest energy consumer (Jin, 2020). According to the BP World Statistical Yearbook, China's energy consumption accounted for 23% of the global energy consumption in 2016 (Wu et al., 2019). In recent years, although the proportion of renewable energy is increasing, coal consumption still occupies a dominant position. Coal consumption accounts for more than 50% of the total coal in the world (Jiang et al., 2021), and carbon emission is the first in the world, and environmental problems are prominent (Yang et al., 2021), which has aroused the great attention of the Chinese government. He mentioned in his important speech delivered at the General Debate of the 75th session of the United Nations General Assembly that China's carbon dioxide emissions strive to peak before 2030 and achieve carbon neutrality before 2060. To achieve this double carbon goal, various provinces and autonomous regions in China are developing various emission reduction measures (Liu et al., 2022), and to achieve the emission reduction effect, improving energy efficiency is an essential tool.

Given the important position and role of energy efficiency, many scholars at home and abroad have conducted research on it, mainly including the measurement of energy efficiency, the influencing factors of energy efficiency, and the relationship between energy efficiency and economic growth. The measurement of energy efficiency mostly uses the DEA (data envelopment analysis) method. In early research, when establishing measurement indicators, only expected output was considered, and unexpected output was not (Wei and Shen, 2007). However, production processes are generally accompanied by unexpected production such as carbon dioxide and sulfur dioxide, so considering unexpected output is more consistent with actual production conditions (Zhang, 2015; Meng and Shao, 2020; Wang et al., 2021; Fazıl, 2018). Research on the impact of energy efficiency mainly focuses on industrial structure (Liu et al., 2018; Zhou et al., 2016; Wei and Shen, 2008; Liu et al., 2022; Shi, 2002), industrial agglomeration (Pan et al., 2017), technological progress (Li and Zhou, 2006; Yu, 2017), factor market distortions (Zhou et al., 2018; Lin and Du, 2013), market segmentation (Wei and Zheng, 2017), and the degree of openness to the outside world (Li and Wu, 2018). Some scholars have also studied the impact of formal environmental regulations (regulations formulated by the government to improve environmental quality) and informal environmental regulations (social groups monitor corporate behavior through consultation and advice to reduce pollution emissions) on energy efficiency(Mu et al., 2022). There are many studies on economic growth and energy efficiency, most of which consider multiple sources of energy (Yilmaz and Mariu, 2019; Zakari et al., 2022; Chen et al., 2013). However, there are also studies on the relationship between single energy efficiency and economic growth, such as Che et al. (2015)

and others who have studied the decoupling relationship between coal utilization efficiency and economic growth in China. The study found that China's coal efficiency is low and there is large room for improvement, and the average value of coal utilization efficiency from high to low is in the eastern region, northeast region Central and Western Regions (Che et al., 2015); Lin Boqiang studied the relationship between electricity consumption and China's economy and found that state-owned property rights reform can improve energy efficiency to a certain extent (Lin, 2003). From the research scale, we have studied the relationship between economic growth and energy efficiency in countries along the Belt and Road (Yue et al., 2019), the Pearl River Delta (Ye et al., 2017), Shanxi Province (Li and Qing, 2010), European Union countries (Marques et al., 2019) and other regions. The eastern region is the pioneer of China's urbanization and economic development. In 2012, the GDP of the eastern region accounted for 57.02% of the domestic GDP, and energy consumption accounted for 50.87% of the national total, Studying the relationship between economic growth and energy efficiency can provide a reference for the development of other regions. Liu Huimin (Liu, 2016) studied the decoupling relationship between economic growth and energy consumption in eastern China, and the results showed that absolute and stable decoupling does not exist. Although China is in a weak decoupling state in most years, on a long-term scale, There is a dynamic and iterative process of "connecting decoupling-recoupling-decoupling "between economic growth and energy consumption; Zhou et al. (2016) analyzed the decoupling relationship between economic growth and energy carbon emissions in the eastern region of China, and found that most provinces in the eastern region of China exhibit a weak decoupling state between economic growth and carbon emissions, while only four provinces, Beijing, Shanghai, Tianjin, and Fujian, exhibit a strong decoupling state (Zhou et al., 2016), However, there are few literatures that combine the decoupling relationship between energy consumption and economic growth and the decoupling relationship between energy efficiency and economic growth. Therefore, this article will study the decoupling relationship between economic growth, energy consumption, and energy efficiency in the context of carbon peaking, providing a reference for China to achieve carbon peaking and carbon neutral goals.

2. Economic growth and energy intensity in Eastern China

2.1 Economic growth

This article uses GDP per capita to represent the level of economic development and draws the economic growth trend chart of eleven provinces in Eastern China from 2010 to 2019, as shown in Figure 1. It can be seen that Beijing's economic development is the best and its growth rate is also the fastest. Although the economy of Hainan is growing every year, the growth rate is not significant and the level of economic development is the lowest. Liaoning's GDP per capita decreased in 2016 and then slowly increased. Overall, the economic growth of the eleven regions shows an upward trend.

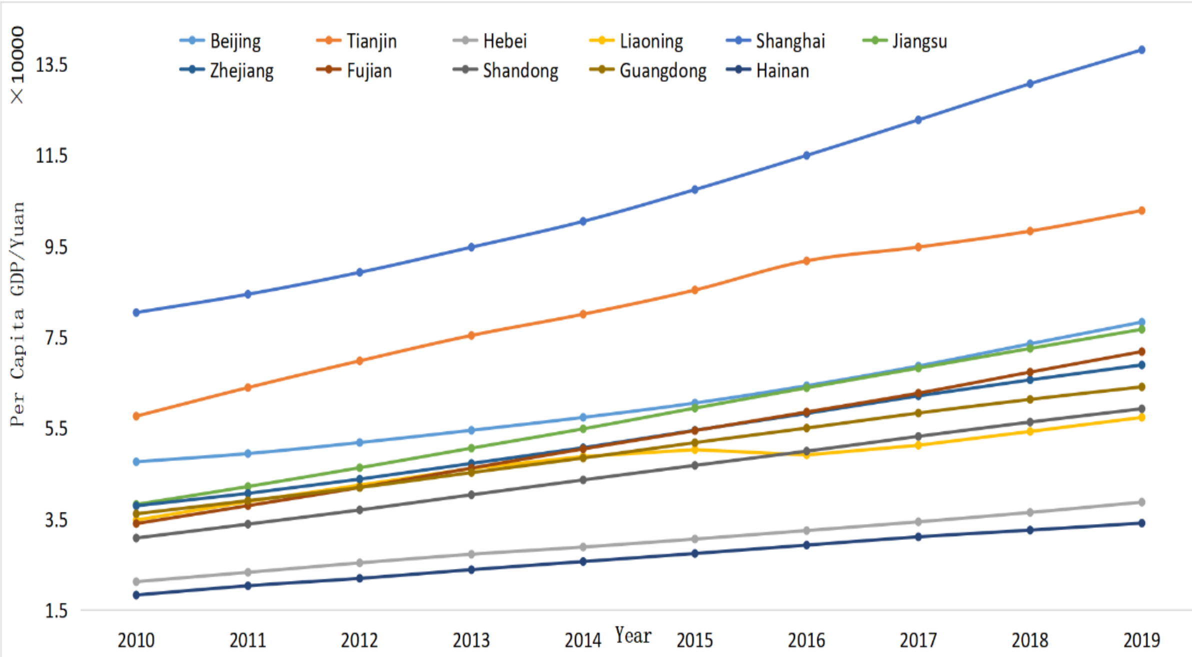


Figure 1: Economic growth trend of eastern China from 2010 to 2019

2.2 Energy intensity

This paper uses energy intensity to preliminarily estimate the energy utilization efficiency of various regions in Eastern China. The energy intensity is expressed in terms of the total energy consumption per year per actual GDP of each province and region, and a time series diagram of the energy intensity of each region is plotted, as shown in Figure 2. It can be seen that energy intensity in Hainan Province increased significantly from 2010 to 2011, and then began to decline slowly, with a downward trend in other regions. Hebei's energy intensity is the highest, and it is also declining rapidly. Beijing's energy intensity is the highest overall. Overall, energy intensity in various regions declined relatively quickly from 2010 to 2013, and declined slowly after 2013.

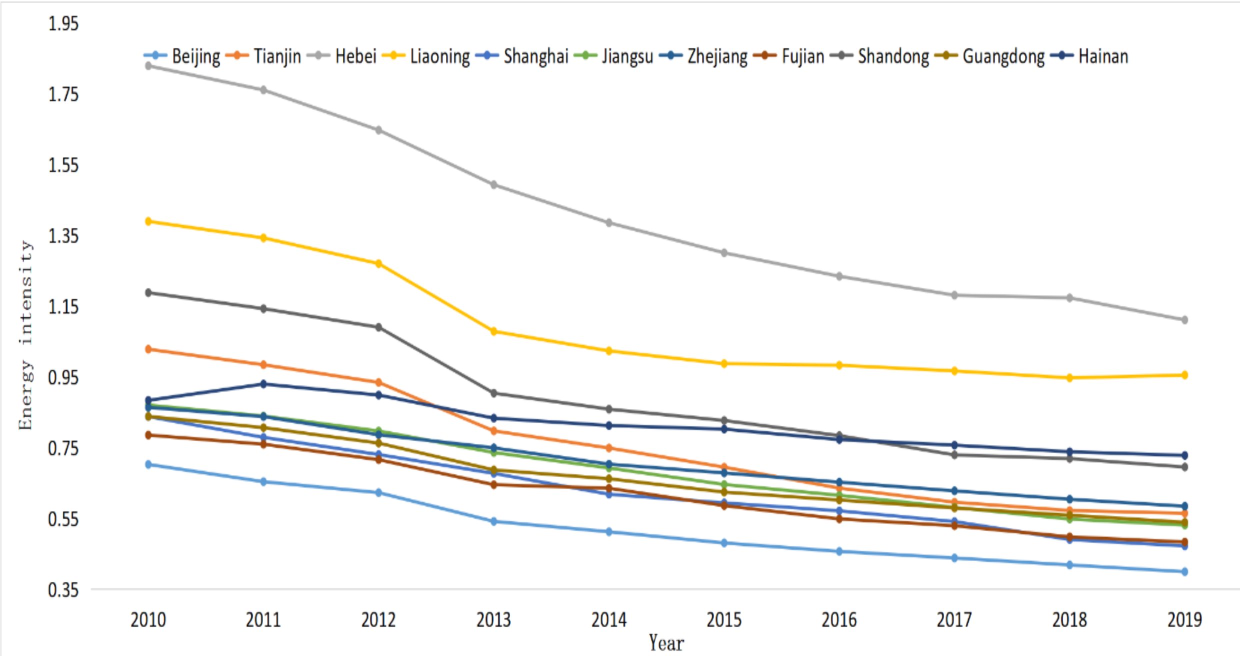


Figure 2: Energy intensity trend chart of eastern regions from 2010 to 2019

2.3 Economic growth and energy intensity

Combining Figures 1 and 2, it can be seen that economic growth and energy intensity in most regions change in opposite directions, leading to economic growth and reduced energy intensity. Beijing has the highest per capita GDP and the lowest energy intensity; Hebei has the highest energy intensity, with a per capita GDP only higher than Hainan; The overall economy of Liaoning is increasing, but its energy intensity has an upward trend, indicating an increasing trend in energy consumption per unit of GDP. Energy intensity simply examines energy efficiency from the perspective of energy consumption per unit of GDP, without considering other aspects, which is too one-sided. In order to further study energy utilization efficiency, this article uses the DDF model and GML index in DEA to calculate total factor energy efficiency and its influencing factors. Finally, it uses the Tapio decoupling model to study the decoupling relationship between economic growth, energy consumption, and energy efficiency.

3. Research methods and data sources

3.1 Measurement of energy efficiency

The directional distance function (DDF) can distinguish between good and bad outputs in the model, which is one of the reasons why it can be widely used. In actual production, the generation of expected output is often accompanied by the generation of undesired outputs, such as carbon dioxide emissions, so incorporating non-expected outputs into the input-output efficiency evaluation system will not only improve the accuracy of energy efficiency measurement, but also be close to the reality. Assuming that X represents input, Y represents good output, and B represents bad output, then the output vector is divided into good output vector g_y and bad output vector g_b, and the input vector is x_k. There are n decision units (DMUs), each decision unit has m inputs $x = (x_1, x_2, x_3 \cdots x_m) \in R_m^+$, yielding i expected outputs $y=(y_1, y_2, y_3 \cdots y_i) \in R_i^+$,and z undersired outputs $b = (b_{1,} b_{2,} b_3 \cdots b_z) \in R_z^+$; If the direction vector is $g = (g_y, -g_b)$and the undesired output is strongly disposable, then the directionality distance function model is:

$$\begin{array}{l} Max\beta \\ \left\{ \begin{array}{l} s.t. X\lambda + \beta g_x \le x_k \\ Y\lambda - \beta g_y \ge y_k \\ B\lambda - \beta g_b \le b_k \\ \sum \lambda = 1 \\ \lambda \ge 0 \end{array} \right. \end{array} \tag{1}$$

In formula (1), β is a measure of the degree of inefficiency and includes both input and output measurements. Therefore, the model belongs to a non-oriented DDF model; $\sum \lambda = 1$ represents the weight coefficient vector relative to the evaluated unit in the effective decision-making unit portfolio, which is variable return to scale (VRS). it represents the input, expected output, and unexpected output of the k-th DMU, respectively.

The GML index was proposed by Oh (2010) in 2010 to measure changes in productivity and the rate of change of its influencing factors. This index solves the potential infeasibility of the ML index. Based on the directional distance function, the GML index of the t+1 period with the t period as the base period is as follows:

$$GML_{t+1}^{t}(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}) = \frac{1 + D^G(x^t, y^t, b^t)}{1 + D^G(x^{t+1}, y^{t+1}, b^{t+1})} =$$

$$\frac{1 + D^t(x^t, y^t, b^t)}{1 + D^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})} \times \left[\frac{1 + D^G(x^t, y^t, b^t)}{1 + D^t(x^t, y^t, b^t)} \times \frac{1 + D^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})}{1 + D^G(x^{t+1}, y^{t+1}, b^{t+1})} \right]$$

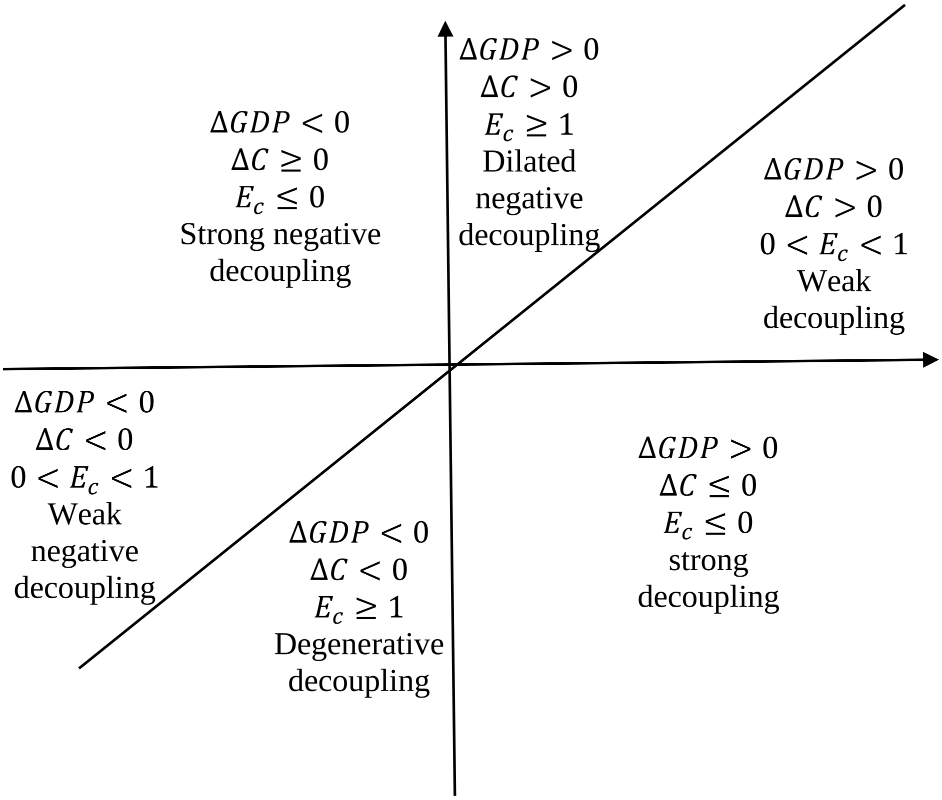
$$= EC_{t+1}^{t} \times TC_{t+1}^{t} \tag{2}$$

In formula (2), $\mathbf{D^t}(\mathbf{x^t}, \mathbf{y^t}, \mathbf{b^t})$ is the directional distance function for the t period and $\mathbf{D^G}(\mathbf{x^t}, \mathbf{y^t}, \mathbf{b^t})$ is the global directional distance function. the GML index can be broken down into EC and TC, where EC represents a change in technical efficiency or catch-up efficiency, and TC represents a change in technology. $\mathbf{GML_{t+1}^t}$refers to the change in total factor productivity from period t to period t+1. If the index is greater than 1, it indicates an increase in productivity, and it is less than 1.it also indicates a decrease in productivity; $\mathbf{EC_{t+1}^t}$ Indicates the degree of convergence to the production frontier from the t period to the t+1 period. This index is greater than 1, indicating that technical efficiency has improved and contributed to total factor productivity growth; $\mathbf{TC_{t+1}^{t}}$ represents the outward expansion of the production frontier or the change rate of technological level from the t period to the t+1 period. This index is also greater than 1, indicating technological progress and contributing to the improvement of total factor productivity.

3.2 Decoupling theory and model

Decoupling was first applied in the field of physics, meaning that the interrelationships between two or more physical variables that had a response relationship no longer existed. Later, it was widely used in other fields (Li et al., 2008). For example, the Organization for Economic Cooperation and Development (OECD) applied decoupling theory to the field of agricultural policy, exploring the relationship between policy and trade and market equilibrium. Later, The World Bank then applied this theory to the field of resources and environment. using it to analyze the decoupling relationship between economic growth, resource consumption, and environmental pollution (Gai et al., 2013). Since then, the decoupling theory has been applied more and more widely. For example, Tapio has used the decoupling theory to study the decoupling relationship between GDP, traffic volume, and carbon dioxide generated during transportation (Tapio, 2005). Song Wei and others have studied the decoupling relationship between farmland occupation and economic growth (Chen et al., 2009). Currently, there are two main types of decoupling indicators that are widely used: the decoupling factor proposed by OECD and the decoupling elasticity coefficient proposed by Tapio. Due to the high sensitivity of the decoupling factor to the selection of base period and end period, there may be some deviation in calculation. The decoupling elasticity coefficient comprehensively considers the changes in total and relative quantities, improving the accuracy of decoupling analysis results (Yasmeen, 2021). Therefore, this article selects Tapio's decoupling elasticity coefficient to study the decoupling between economic growth, energy consumption, and energy efficiency, with reference to Peng Jiawen et al. (Peng et al., 2011), The decoupling model is established based on the classification criteria shown in Table 2.

Table 1: Decoupling analysis model of economic growth, energy consumption and energy efficiency



Where ΔC represents the change in energy consumption or energy efficiency; ΔGDP represents the change in regional GDP.

$$\text{GDP elasticity of energy consumption}(E_{cc}) = \frac{\Delta \text{ energy consumption} / \text{Energy consumption in the base period}}{\Delta GDP / \text{Base period GDP}} \tag{3}$$

$$\text{GDP elasticity for energy efficiency}(E_{ce}) = \frac{\Delta \text{ energy efficiency} / \text{Base period energy efficiency}}{\Delta GDP / \text{Base period GDP}} \tag{4}$$

Decoupling can be divided into weak decoupling, strong decoupling, recessive decoupling, weak negative decoupling, strong negative decoupling, and expansionary negative decoupling. The strong decoupling of energy consumption from economic growth and the expansionary negative decoupling of energy efficiency from economic growth are the most ideal decoupling states. Only by achieving these two types of decoupling can the quality of economic development was improved, and the carbon peak and carbon neutral goals be achieved more quickly. The specific decoupling situation of this article will be explained in the empirical results below.

3.3 Data source and indicator selection

This article takes the panel data of eastern China from 2010 to 2019 as a sample and the data mainly comes from the National Bureau of Statistics of China, China Statistical Yearbook, China Energy Statistical Yearbook, and CEADS database. The main indicators used in this article are as follows:
Total factor energy efficiency measurement indicators:
1) Input indicators
(1) Labor indicators. Expressed as the sum of the number of urban units, private enterprises, and self-employed individuals in each province (unit: 10000 people).
(2) Energy consumption. Expressed by the total annual energy consumption of each region (unit: 10000 tons of standard coal).
(3) Capital stock. This article refers to Zhang Jun's approach to capital stock and calculates it using the perpetual inventory method (unit: 100 million yuan).

$$K_{it} = K_{it-1}(1-\delta_{it}) + I_{it} \quad (5)$$

In formula (5), K_{it} is the current capital stock; δ_{it} is the depreciation rate; K_{it-1} is the capital stock of the previous period; I_{it} is the actual investment amount of the current.
2) Output indicators
(1) Expected output: This article selects the actual GDP of each province, city, and autonomous region (unit: 100 million yuan) as the output indicator. to eliminate the impact of price factors, the nominal GDP of the original data is uniformly converted into actual GDP (2000=100) based on the GDP index. (2) Unexpected output: total carbon dioxide emissions by region (unit: million tons).

Table 2: Descriptive statistical analysis of energy efficiency inputs and outputs

	Input o110utput indicators	Observation	Average value	Standard deviation	Minimum	Maximum
Input indicators	Capital stock		65875.3	40409.26	3728.995	174406.6
	workforce	110	2099.995	1561.01	172.8	7115.1
Output indicators	Total energy consumption	110	19097.5	11438.62	1358.507	41390
	Provincial real GDP	110	24875.02	15481.98	1536.949	63260.76
	CO2 emissions	110	407.6269	279.2441	28.92593	937.1169

4. Results and Analysis

4.1 Energy efficiency

4.1.1 Trends in energy efficiency

This paper uses MAXDEA software to calculate the energy efficiency of 11 provinces, cities, autonomous regions, and the whole of eastern China from 2010 to 2019 and draws their annual average trend charts using Excel. As shown in Figure 2, the overall average energy efficiency of these 11 regions during the sample period is 0.911, and its overall trend is improving. However, specifically, energy efficiency decreased during 2010-2011, and growth was very slow during 2011-2016, and the growth rate accelerated after 2016. Among these regions, the energy efficiency fluctuations in Tianjin, Fujian, and Liaoning are relatively large. Among them, the energy efficiency of Tianjin in 2010 decreased from 120 to 0.8826 in 2014 and has been increasing all the way since 2014. The energy efficiency in 2018 and 2019 is both 1; Overall, Fujian's energy efficiency declined, from 1 in 2010 to 0.858 in 2011, and then began to rise and fall. In 2019, the energy efficiency was 0.8827, with a trend of continuing to rise; In 2014, the energy efficiency of Liaoning fell to the lowest point (0.6993), which is also the lowest point of energy efficiency in these provinces and regions. After that, it began to rise, especially after 2016, the energy efficiency curve became steeper, indicating that the growth rate of energy efficiency after 2016 was becoming faster and faster. Among these provinces, Guangdong, Beijing, Shanghai, and Shandong have relatively high energy efficiency, with Guangdong having a slight decrease in energy efficiency in 2014, while the energy efficiency in other periods is 1; In 2019, energy efficiency in Shandong decreased somewhat (0.921), and there is a trend of continued decline; Although there are fluctuations in energy efficiency in Beijing and Shanghai, the range is not significant; Hebei Province's energy efficiency dropped to the lowest level in 2016, In 2019, there is a continuous downward trend, and the overall energy efficiency of the province is in the middle level; The overall energy efficiency of Hainan Province also shows a downward trend; It can be seen that energy efficiency in Jiangsu Province has been increasing in other periods except for the decrease in energy efficiency in 2013; The energy efficiency trend curve in Zhejiang is perfect, with no downward phase and rising all the way.

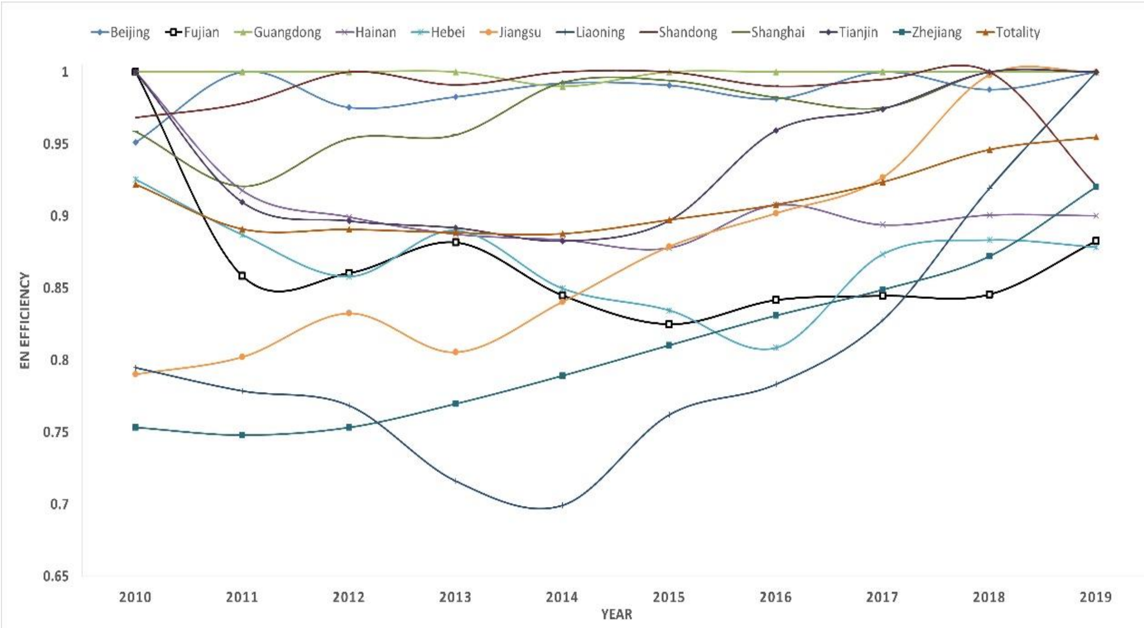


Figure 3: Energy efficiency trend chart

4.1.2 GML index and its decomposition

To specifically study the influencing factors of energy efficiency, this paper uses the GML index to calculate the total factor energy efficiency and decompose it into the technical efficiency index EC and the technical progress index TC, and GML=EC*TC. If the index is greater than 1, it indicates an improvement in energy efficiency, technological efficiency, and technological progress. Conversely, if the index is less than 1, energy efficiency decreases, technical efficiency decreases, and technology regresses. From Table 1, it can be seen that the overall energy efficiency has increased by 4.8%, which is consistent with the trend in Figure 3. However, its technical efficiency has increased by 2.1%, and its technical progress has been 2.4%, both contributing to the improvement of energy efficiency are basically the same. The increase in energy efficiency in Jiangsu, Liaoning, and Zhejiang is similar, with the increase in energy efficiency in Jiangsu and Liaoning mainly driven by the catch-up effect, while the increase in energy efficiency in Zhejiang Province is mainly due to technological progress. We can see that the GML of Fujian, Hainan, Hebei, and Shandong is less than 1, which means that their energy utilization efficiency has decreased, with the TC of Fujian being equal to 1. We can know that the decrease in energy efficiency is caused by the decrease in technical efficiency; Hainan is the opposite of Fujian, with EC equal to 1 and TC less than 1. Therefore, the decline in energy efficiency in Hainan is due to technological decline. The pulling effect of technological progress on energy efficiency in Shandong has not offset the inhibitory effect of declining technological efficiency on energy efficiency, so energy efficiency in Shandong has decreased; Similarly, the decline in energy efficiency in Hebei is both a cause of the decline in technological efficiency and a result of technological retrogression. There has been no change in energy efficiency in Guangdong and Tianjin. The improvement in energy efficiency in Beijing and Shanghai is due to technological progress.

Table 3: Cumulative change values from 2010 to 2019

Provence	GML	EC	TC
Beijing	1.051	1.000	1.051
Fujian	0.883	0.883	1.000
Guangdong	1.000	1.000	1.000
Hainan	0.900	1.000	0.900
Hebei	0.949	0.972	0.977
Jiangsu	1.266	1.156	1.095
Liaoning	1.258	1.222	1.030
Shandong	0.951	0.933	1.020
Shanghai	1.043	1.000	1.043
Tianjin	1.000	1.000	1.000
Zhejiang	1.222	1.064	1.148
overall	1.048	1.021	1.024

4.2 Analysis of decoupling between economic growth, energy consumption, and energy efficiency

To better explore the decoupling relationship between economic growth, energy consumption, and energy efficiency, this article analyzes the decoupling status of each province on an annual basis based on the energy efficiency trend chart in Figure 3. Based on the Tapio decoupling elasticity model, the GDP elasticity of energy consumption and the GDP elasticity of energy utilization efficiency are calculated and combined with the decoupling analysis model in Table 2, the annual decoupling status of each region can be obtained. The specific results are shown in Tables 4 and 5.

From 2010 to 2011, economic growth and energy consumption in the eastern provinces and regions were concentrated in a weak decoupling state (10/11), with 7 regions experiencing a strong decoupling state between economic growth and energy efficiency, indicating that the growth rate of energy consumption in these 7 regions was slower than that of economic growth, while energy efficiency was gradually declining with economic growth; The energy efficiency of three regions is improving with economic growth, which is a good state of development. The growth rate of energy consumption in Hainan Province is faster than that of economic growth, and its energy efficiency is declining, indicating that this region is experiencing extensive economic growth.

From 2011 to 2012, energy consumption and economic growth in 11 provinces were all in a weak decoupling state, with 5 regions having a weak decoupling relationship between economic growth and energy efficiency; The strong decoupling between energy efficiency and economic growth in six regions indicates that the GDP of these six regions has increased and energy efficiency has decreased;

The decoupling of economic growth from energy consumption and energy efficiency in 2012-2015 mainly focused on weak decoupling and strong decoupling, indicating that energy consumption in the eastern region is increasing and energy efficiency is declining. In addition, during 2014-2015, the energy efficiency and economic growth of Liaoning Province were in an expansionary negative decoupling state, that is, the growth rate of energy efficiency was faster than the economic growth rate, which is an ideal decoupling.

In 2015-2016, energy consumption in 9 provinces and regions also increased with economic growth, with 4 provinces in a weak decoupling state of energy efficiency from economic growth, and 5 regions in a strong decoupling state. While energy consumption in Tianjin is decreasing with economic growth, energy efficiency is improving with economic growth. Liaoning's economic growth and energy consumption show a recessive decoupling relationship, that is, both GDP and energy consumption are declining, and the speed of energy consumption decline is greater than the speed of GDP decline. However, its economic growth and energy efficiency are in a strong negative decoupling state, that is, the economy has experienced a recession, and energy efficiency is improving, indicating that Liaoning Province is taking GDP decline as a price to achieve low-carbon development.

The distribution of 2016-2017 is similar to that of 2012-2015. The relationship between economic growth, energy consumption, and energy utilization efficiency is mainly concentrated in weak decoupling and strong decoupling relationships, respectively. Among them, nine provinces and regions have a weak decoupling relationship between economic growth and energy consumption, and five of them have a weak decoupling relationship between energy efficiency and economic growth, indicating that both energy consumption and energy efficiency increase with economic growth, There are three regions where energy efficiency decreases with economic growth, while another region (Liaoning) has an expansionary negative decoupling between energy efficiency and economic growth.

In 2017-2018, the growth rate of energy consumption in 9 provinces was slower than the economic growth rate, and the energy efficiency of 4 regions increased with the increase of GDP, while the energy efficiency of 3 regions decreased with the increase of GDP, while the energy efficiency of the remaining two regions showed an expansionary negative decoupling relationship with GDP, that is, both GDP and energy efficiency were increasing, and the energy efficiency increased faster than the growth rate of GDP. In two urban areas (Tianjin and Shanghai), energy consumption has decreased and energy efficiency is increasing.

In 2018-2019, there were 10 regions where the relationship between energy consumption and economic growth was weak decoupling, 5 of which had weak decoupling between energy efficiency and economic growth, and 5 had strong decoupling. In another region (Liaoning), both energy consumption and energy

utilization efficiency have increased faster than economic growth.
To sum up, during the period 2010-2019, economic growth and energy consumption in most areas of eastern China were in a weak decoupling state, and they were in a strong decoupling and weak decoupling state from energy efficiency.

Table 4: Analysis results of decoupling economic growth and energy consumption in eastern China from 2010 to 2019

Provence	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Weak decoupling	Beijing, Hebei, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Liaoning (10)	Hainan, Hebei, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Liaoning, Beijing (11)	Jiangsu, Zhejiang, Fujian, Hainan (4)	Beijing, Tianjin, Zhejiang, Fujian, Shandong, Guangdong, Liaoning, Hainan, Jiangsu (9)	Beijing, Hebei, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan (10)
Strong decoupling			Beijing, Hebei, Tianjin, Shanghai, Shandong, Guangdong, Liaoning (7)	Hebei, Shanghai (2)	Liaoning (1)
Strong negative decoupling					
Dilated negative decoupling	Hainan (1)				
	2015-2016	2016-2017	2017-2018	2018-2019	
Weak decoupling	Beijing, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan (9)	Beijing, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Hainan, Liaoning (9)	Beijing, Hebei, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, Liaoning (9)	Beijing, Hebei, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan (10)	
Strong decoupling	Tianjin (1)	Tianjin, Shandong (2)	Tianjin, Shanghai (2)		
Strong negative decoupling					
Dilated negative decoupling				Liaoning (1)	
Degenerative decoupling	Liaoning (1)				

Table 5: Analysis results of decoupling annual economic growth and energy efficiency in eastern China from 2010 to 2019

	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Weak decoupling	Beijing, Shandong, Jiangsu, Guangdong (4)	Jiangsu, Zhejiang, Shanghai, Fujian, Shandong, Guangdong (6)	Beijing, Shanghai, Zhejiang, Fujian, Hebei, Guangdong (6)	Jiangsu, Zhejiang, Shanghai, Shandong, Beijing (5)	Tianjin, Shanghai, Guangdong, Jiangsu, Zhejiang, Shandong (6)
Strong decoupling	Tianjin, Hebei, Liaoning, Shanghai, Fujian, Hainan, Zhejiang (7)	Hainan, Tianjin, Hebei, Liaoning, Beijing (5)	Tianjin, Liaoning, Jiangsu, Shandong, Hainan (5)	Fujian, Guangdong, Hainan, Tianjin, Hebei, Liaoning (6)	Hainan, Beijing, Fujian, Hebei (4)
Strong negative decoupling					
Dilated negative decoupling					Liaoning (1)
Weak negative decoupling					
	2015-2016	2016-2017	2017-2018	2018-2019	
Weak decoupling	Tianjin, Fujian, Jiangsu, Zhejiang, Hainan, Guangdong (6)	Beijing, Hebei, Tianjin, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong (8)	Zhejiang, Shandong, Shanghai, Hainan, Tianjin, Fujian, Guangdong (7)	Beijing, Hebei, Fujian, Jiangsu, Zhejiang, Tianjin, Shanghai, Guangdong (8)	
Strong decoupling	Shanghai, Shandong, Beijing, Hebei (4)	Shanghai, Hainan (2)	Beijing, Hebei (2)	Shandong, Hainan (2)	
Strong negative decoupling	Liaoning (1)				
Dilated negative decoupling		Liaoning (1)	Liaoning, Jiangsu (2)	Liaoning (1)	
Weak negative decoupling					

To more intuitively understand the decoupling of economic growth from energy consumption and energy efficiency in each province during the sample period, Table 4 and Table 5 are integrated, as shown in Table 6. In the table, Tcc represents the decoupling of economic growth from energy consumption, and Tce represents the decoupling of economic growth from energy efficiency. We can see that most provinces' Tcc and Tce are mainly weak decoupling and strong decoupling. For example, during the period 2010-2019 in Beijing, most years' Tcc and Tce are mainly weak decoupling, that is, economic growth, increased energy consumption, and improved energy efficiency. However, the increase in energy consumption and energy efficiency is not as significant as economic growth, such as in Tianjin, Shanghai, Zhejiang, Fujian and Jiangsu. The decoupling situation in Shandong and Guangdong is similar to that in Beijing. There are 7 years in which Tcc in Hebei is in a weak decoupling state, while 6 years in which Tce is in a strong decoupling state, indicating that energy consumption is increasing with economic growth and energy efficiency is decreasing with economic growth, which is an undesirable state. We can see that the decoupling of Liaoning Province is more diverse than that of other provinces. Its energy consumption and economic growth are mainly in a weak decoupling relationship, while energy efficiency and economic growth are mainly in a state of expansionary negative decoupling and strong decoupling. The decoupling situation in Hainan Province and Hebei Province is similar, with 8 years of weak decoupling and 7 years of strong decoupling in the sample period.

Table 6: Comprehensive results of decoupling economic growth from energy consumption and energy efficiency in eastern provinces and regions of China from 2010 to 2019

	Beijing	Tianjin	Hebei	Liaoning	Shanghai	Jiangsu
T_{cc}	Weak decoupling (7), Strong decoupling (2)	Weak decoupling (5), Strong decoupling (4)	Weak decoupling (7), Strong decoupling (2)	Weak decoupling (5), Strong decoupling (2), Recessionary decoupling (1), Dilated negative decoupling (1)	Weak decoupling (6), Strong decoupling (3)	Weak decoupling (9)
T_{ce}	Weak decoupling (5), Strong decoupling (4)	Weak decoupling (5), Strong decoupling (4)	Weak decoupling (3), Strong decoupling (6)	Dilated negative decoupling (4), Strong decoupling (4), Strong negative decoupling (1)	Weak decoupling (6), Strong decoupling (3)	Weak decoupling (7), Strong decoupling (1), Dilated negative decoupling (1)
	Zhejiang	Fujian	Shandong	Guangdong	Hainan	
T_{cc}	Weak decoupling (9)	Weak decoupling (9)	Weak decoupling (7), Strong decoupling (2)	Weak decoupling (8), Strong decoupling (1)	Weak decoupling (8), Dilated negative decoupling (1)	
T_{ce}	Weak decoupling (8), Strong decoupling (1)	Weak decoupling (6), Strong decoupling (3)	Weak decoupling (6), Strong decoupling (3)	Weak decoupling (8), Strong decoupling (1)	Weak decoupling (2), Strong decoupling (7)	

In summary, the overall decoupling situation in the eastern region has not reached a completely ideal state, and the economic growth and energy consumption in most regions are still in a weak decoupling state, without achieving a strong decoupling; Energy efficiency and economic growth are far from expansionary negative decoupling and tend to be weak and strong decoupling. It can be seen that in order to achieve the ideal decoupling of economic growth from energy consumption and energy efficiency, various regions should adopt targeted policies and measures in their subsequent development, achieve low-carbon economic development, and achieve carbon peak and carbon neutral goals as soon as possible.

4.3 Carbon emission prediction

Based on the above calculation of energy efficiency in various regions of eastern China and the decoupling study of economic growth, energy consumption, and energy efficiency, this article uses the prediction data of Pan Dong et al. (Pan et al., 2021) on the baseline scenario of carbon dioxide emissions in eastern China to understand the carbon peak time in various regions and the results are shown in Figure 4.

We can see that Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Guangdong, and Liaoning achieved carbon peaks by 2030 and before. Among them, Beijing, Tianjin, and Shanghai have relatively low cumulative carbon emissions, while Jiangsu, Liaoning, Zhejiang, and Guangdong have relatively high cumulative carbon emissions. Therefore, these four provinces should pay attention to reducing carbon dioxide emissions while achieving their carbon peak goals; There are no peaks in Hebei and Hainan regions, and carbon emissions have been increasing from 2020 to 2040 and Hebei's cumulative carbon emissions are high. In the next development, the province should focus on reducing emissions and improving energy efficiency; The peaks in Shandong and Fujian occurred after 2030.

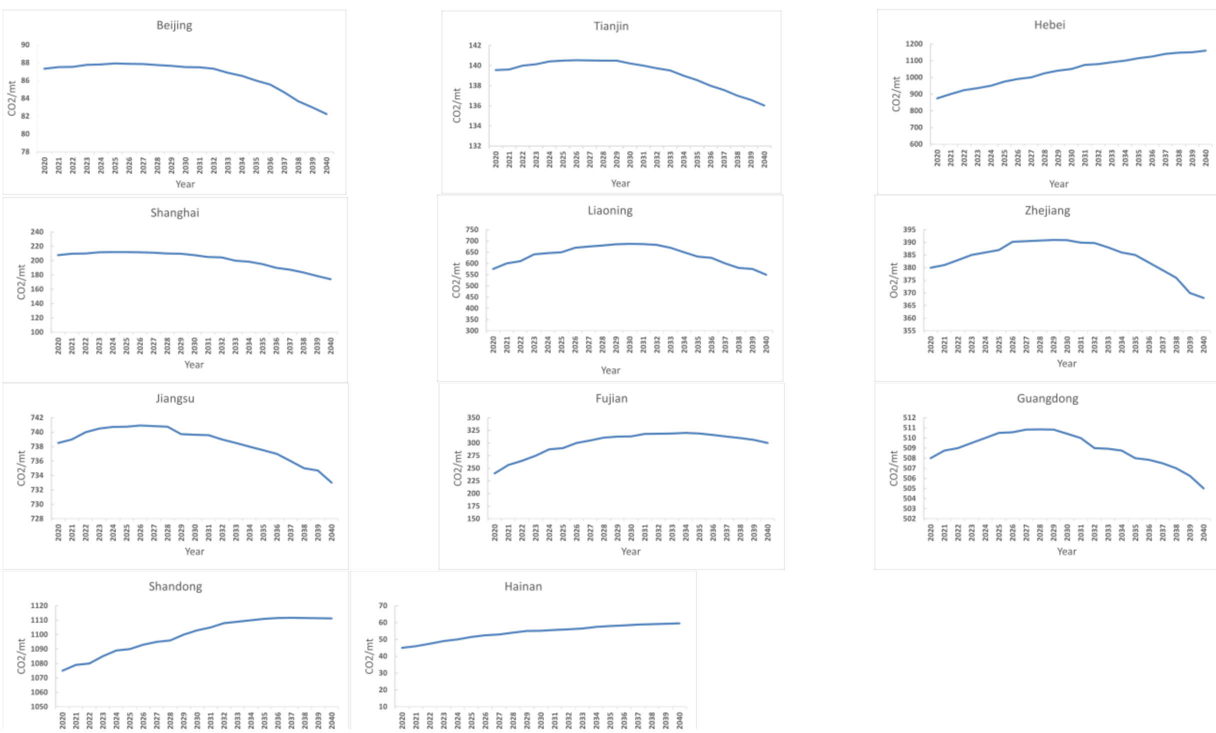


Figure 4: Prediction of carbon peak time

In summary, there is a significant gap in the carbon peak time in 11 regions in eastern China, and not all regions can achieve the carbon peak goal by 2030. This is mainly because each province has different energy consumption and energy efficiency. Therefore, China should fully consider the actual situation in the eastern region when formulating carbon peak strategies, and should focus on provinces with high cumulative carbon emissions and achieving the carbon peak goal after 2030.

5. Main conclusions

(1) The total average energy efficiency of 11 regions in eastern China during the period 2010-2019 was 0.911, showing an overall upward trend, while the changes in energy efficiency vary from region to region. According to the cumulative GML index and its decomposition results, we can see that the overall energy efficiency has increased by 4.8%. The energy efficiency of Beijing, Jiangsu, Liaoning, Shanghai, and Zhejiang provinces has increased, while the energy efficiency of Shandong, Hainan, Fujian, and Hebei provinces has decreased. Shandong and Fujian are caused by the decline in technological efficiency. Therefore, these two provinces should adjust and optimize the energy consumption structure and resource allocation, adjust the scale of enterprises, strengthen the training of professionals, and improve management levels, so that technological efficiency can play a positive role in improving energy efficiency. The decline in energy efficiency in Hainan Province is due to technological retrogression, so the province needs to strengthen investment in scientific research and promote scientific and technological progress. The technological retrogression and decline in technological efficiency in Hebei Province have jointly led to a decline in energy efficiency in the province. Therefore, the province needs to work together in terms of resource allocation and management level. The energy efficiency of Guangdong and Tianjin has not changed.

(2) During the period 2010-2019 in Beijing, economic growth, energy consumption, and energy efficiency were in a weak decoupling state in most years, that is, economic growth, increased energy consumption, and improved energy efficiency. However, the increase in energy consumption and energy efficiency was not as significant as economic growth. The decoupling situation in Tianjin, Shanghai, Zhejiang, Fujian, Jiangsu, Shandong, and Guangdong was similar to that in Beijing; In most years, the economic growth of Hebei and Hainan provinces has a weak decoupling relationship with energy consumption and a strong decoupling relationship with energy efficiency. That is, economic growth leads to increased energy consumption and decreased energy efficiency, which is detrimental to achieving a decoupling between economic growth and energy consumption. These two provinces should pay attention to improving their technological level and increasing investment in clean energy such as hydropower and wind power, to improve energy efficiency and reduce energy consumption, Realize weak decoupling or even expansionary negative decoupling between energy efficiency and economic growth as soon as possible, and achieve strong decoupling between

energy consumption and economic growth; The energy consumption and economic growth in Liaoning Province are mainly in a weak decoupling state, with a strong decoupling relationship between energy efficiency and economic growth before 2014 and an expansionary negative decoupling relationship after 2014, which means that the development of Liaoning Province is improving.

(3) There is a large gap in the carbon peak time in 11 regions in eastern China. Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Guangdong, and Liaoning achieved carbon peaks by 2030 and before, while Hebei and Hainan regions did not have peaks, while Shandong and Fujian peak after 2030. Therefore, provinces and regions that cannot meet the carbon peak goals on time should deeply promote the energy revolution: First, accelerate the clean and low-carbon transformation of the energy production and consumption system; Strengthen the energy security system and capacity building; Third, improve the reliability and modernization level of the energy industry chain.

(4) The three results are basically consistent: changes in energy efficiency across provinces, decoupling of economic growth from energy consumption and efficiency and prediction of carbon peak times. "Provinces with declining energy efficiency, and unsatisfactory decoupling of economic growth from energy consumption and energy efficiency all have carbon peaks after 2030 or have not yet reached peak levels. These provinces should focus on improving energy efficiency and reducing carbon in their economic development. The country should also take into account the actual situation of each province when setting peak targets for each province."

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