Decoupling trend and emission reduction potential of CO$_2$ emissions from China’s petrochemical industry

Duanxiang Peng$^1$ · Jizheng Yi$^1$ · Aibin Chen$^1$ · Huanyu Chen$^1$ · Jieqiong Yang$^2$

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Abstract
This paper aims to study the decoupling status and emission reduction potential of China’s petrochemical industry from 1996 to 2019. Firstly, the IPCC method is used to calculate the CO$_2$ emissions of the petrochemical industry in China, then the logarithmic mean Divisia index (LMDI) method is used to identify the influencing factors of CO$_2$ emissions, then the decoupling index is constructed to analyze the dependence of economic development on CO$_2$ emissions, and finally the emission reduction potential model is established by using the influencing factors to reflect the CO$_2$ emission reduction potential of the petrochemical industry. The results reveal that (1) the CO$_2$ emissions can be divided into two stages of slow decline (1996–2000), (2015–2019), and one stage of rapid growth (2000–2015). (2) The energy intensity effect is the most effective factor to restrain CO$_2$ emission, the economic growth effect is the key factor to promote CO$_2$ emission. (3) From 1996 to 2019, there was a weak decoupling relationship between CO$_2$ emission of petrochemical industry and economic development. Strong decoupling only occurred in 1996–2000 and 2015–2019. The CO$_2$ emissions show only three decoupling score: I, II, and III. (4) CO$_2$ mitigation occurred in four sub periods: 1996–2000, 2005–2010, 2010–2015, and 2015–2019. Therefore, the government should establish an energy-saving and environment-friendly industrial production system, intensify the use of clean energy, and optimize the labor force structure. It not only effectively strengthens the decoupling between the petrochemical industry and economic development, but also provides an empirical example for the carbon emission reduction and economic sustainable development of the petrochemical industry in other countries in the world.

Keywords CO$_2$ emissions · LMDI · Mitigation potential · Decoupling state · Petrochemical industry

Introduction
Global climate change is a key issue related to the political, economic, social and ecological sustainable development of governments. Greenhouse gas emission (GHG) is an important factor affecting global warming. According to the 2009 International Energy Agency (IEA) report, in 2007, China’s total CO$_2$ emissions exceeded that of the USA, ranking first in the world. In 2017, China’s CO$_2$ emissions accounted for 30% of the world’s total (Li et al. 2019). To effectively control CO$_2$ emissions, the Chinese government is actively taking measures to establish a particularly strict path of sustainable development to reduce carbon emissions (Chen et al. 2016). At the end of 2009, China announced at the UN climate change conference held in Copenhagen that the carbon emissions per unit of GDP in 2020 will be reduced by 40–45% compared with 2005. At the Paris climate conference in 2015, it was promised to further reduce this index by 60–65% by 2030 (Mi et al. 2017). In 2019, COVID-19 became a global pandemic, affecting the economic development of China and the world. It plays a great role in global carbon emission reduction in the short term, but it may also bring new challenges to carbon emission reduction in the long term (Wang and Zhang 2021; Wang et al. 2022a, b; Wang and Su 2020a). At present, fossil fuels still account for the largest proportion in China’s energy structure, while the industrial sector consumes 70% of fossil fuels. Therefore,
achieving carbon emission reduction targets for energy intensive industries can effectively reduce carbon emissions. China’s petrochemical industry is an important pillar industry of the national economy. With large economic aggregate and high industrial correlation, it is closely related to economic development and people’s life. It occupies an important position in China’s industrial economic system. Since the reform and opening up, China’s petrochemical industry has made great progress. It has become an important part of China’s economy. However, what cannot be ignored is the environmental pollution caused by development. As an energy intensive industry in China, petrochemical industry produces huge carbon emissions with high energy consumption. 6

So far, the CO₂ emission of petrochemical industry has attracted the attention of many scholars. For example, in the world, some scholars have conducted scenario analysis on the energy transformation of the chemical industry (Als-hammari 2021; Li et al. 2021a, b). It was found that carbon capture and solar energy technology can provide a technology combination to achieve the deep carbon emission reduction target of Saudi Arabia’s chemical industry in 2030. As for how to achieve zero emissions in the chemical industry, Saygin and Gielen (2021) studied the way to achieve zero CO₂ emissions in the global chemical and petrochemical industry. They analyzed the complexity of carbon accounting caused by fossil fuels, and evaluated the technical and economic potential of 20 zero carbon solutions. Raza et al. (2021) analyzed the degree of substitution between energy and non energy inputs in Pakistan’s chemical sector. It was found that the three indicators of capital energy, capital labor and labor energy consumption can be substituted for each other. Akyürek (2020) studied the influencing factors of total energy consumption growth of 10 manufacturing industries in Türkiye from 2005 to 2014. The results showed that the activity effects of 7 manufacturing industries including chemical industry contributed significantly to energy consumption, while the structure and intensity effects were not significant. Talaei et al. (2018) used a bottom-up energy modeling framework to study the CO₂ emission reduction potential of the chemical industry. The study found that by 2030 and 2050, the cumulative carbon emissions of chemical workers will be 7.1 million tons and 29.7 million tons respectively, but more than 75% of the emission reduction can be realized at a negative cost. As for China, Meng and Sager (2017) studied the CO₂ emissions related to the energy consumption of China’s petrochemical industry in 2012. It was found that the total energy consumption and CO₂ emissions accounted for 32% and 18% of the total CO₂ emissions generated by China’s industries, respectively. Lin and Long (2014) analyzed the influencing factors of fossil energy consumption in China’s chemical industry and found that labor productivity and energy intensity have an important impact on fossil fuel demand. In terms of prediction and Simulation of carbon peak, Lu et al. (2020) simulated the driving factors and forward-looking prediction of carbon emission peak of China’s heavy chemical industry. It was found that under the implementation of the predetermined mitigation scenario, the carbon emissions of the heavy chemical industry and its corresponding sub industries can reach the peak. During the simulation period in 2035, the carbon emissions of the energy processing industry, the steel industry, and the building materials industry account for a larger proportion of the cumulative carbon emissions of the chemical industry.

Exploring the influencing factors of CO₂ emission in various industries has become a hot issue studied by scholars at home and abroad. At present, there are mainly three factor decomposition methods: IDA (index decision analysis), SDA (structural decision analysis) and (production theoretical decomposition analysis) PDA. This PDA method is mainly through the effective combination of production theory, directional distance function and environmental DEA technology. The advantage of PDA is that it can accurately describe the impact of technical factors on carbon strength. However, the PDA method is only applicable to the form of multiplication and decomposition, and it needs to solve the problems such as the optimal solution of linear programming. For example, Wang et al. (2022a, b), Li et al. (2022a, b, c), Yang et al. (2022). The SDA method is mainly based on the input–output table, which can distinguish the technology effect and the final demand effect, and can evaluate the direct effect and the indirect effect at the same time. The disadvantage is that the input–output table is usually updated every five years, and the decomposition process is not unique, which is not conducive to time series analysis and trend comparison. Research examples include Wang et al. (2020a, b), Chen et al. (2019), and Wu et al. (2020). On the contrary, the advantage of IDA method is that it requires less data, only industry or regional data. Its decomposition model is simple, and the addition decomposition form and multiplication decomposition form can be applied at the same time. It can also handle zero values, so it has been widely used. For example, Zha et al. (2019), Balezentis (2020). The LMDI decomposition method belongs to a branch of IDA method. Compared with PDA and SDA decomposition methods, the LMDI method not only requires less data, but also can achieve complete decomposition without residue, effectively avoiding the problem of pseudo regression. It can effectively analyze the overall indicators and maintain the high consistency among various decomposition indicators. Therefore, this method has become an application method for this paper and other researches to achieve the decomposition of carbon emission factors. For example, Alajmi (2021) revealed the influencing factors of CO₂ emissions.
from nine industries in Saudi Arabia from 1990 to 2016 through LMDI method. The analysis showed that energy effect was the main factor to increase greenhouse gas emissions, and the impact of activities and population also led to the increase of CO$_2$ emissions, while the impact of activities, energy and population in the power sector was greater than that in the transport sector. Isik et al. (2020) found that there are three main factors that promote the increase of CO$_2$ emissions from Turkey’s transportation industry from 2000 to 2017, namely, economic development effect, population effect and emission intensity effect. Fatima et al. (2019) found that the income effect and labor effect were key factors in the increase of industrial CO$_2$ emissions in China from 1991 to 2016, followed by the energy structure effect. The energy intensity and carbon emission effect were the most critical factors to restrain CO$_2$ emission. Quan et al. (2020) found through LMDI method that the economic growth effect is the most important factor to promote the growth of carbon emissions of China’s logistics industry from 2000 to 2016, and the energy intensity effect is the key inhibitor of carbon emissions growth. For the chemical industry, Lin and Long (2016) found that energy intensity and energy structure play a restraining role, while per capita output and industrial economic scale play a promoting role. Fan et al. (2015) also found that from 2000 to 2010, the economic output effect was the leading factor to promote the growth of carbon emissions in China’s petrochemical industry, while the industrial structure effect produced a certain degree of carbon emission reduction. However, the effect of technology changes greatly, but it did not show an obvious decreasing trend. Zhang et al. (2019b) decomposed CO$_2$ emission changes in China’s coal chemical industry from 2020 to 2030. The study found that the CO$_2$ emissions increased significantly, and the economic growth effect and the energy intensity effect were the main reasons. Similarly, industrial structure is also a negative factor affecting CO2 emissions. Du et al. (2018) conducted a factor decomposition study on the change of energy CO$_2$ emissions in China’s energy intensive industries. It was found that for the chemical industry, the expansion of industrial scale from 1986 to 2013 had the greatest impact on the increase of CO$_2$, while the impact of energy structure and industrial structure on the change of CO$_2$ emissions was relatively small.

The decoupling analysis between CO$_2$ emission and economic development in various industries is another issue worthy of attention. OECD (2002) first put forward the concept of “decoupling index.” Vehmas et al. (2007) proposed six possible theoretical frameworks for de-linking and link analysis. At present, The Tapio model has become the most common method to explore the relationship between economic development and CO$_2$ emissions. For example, Zhang and Da (2015) analyzed the decoupling relationship between China’s carbon emissions and economic growth from 1996 to 2010. It was found that there was a relative decoupling effect between carbon emissions and economic growth in most years. Yang et al. (2018) used LMDI and Tapio index to analyze the decoupling state of industrial economic growth and CO$_2$ emissions. It was found that from 1996 to 2015, the decoupling state of manufacturing industry changed from strong decoupling to weak decoupling(WD), and then to strong decoupling(SD). Zhao et al. (2022) quantitatively analyzed the relationship between China’s carbon emissions and economic development from 2009 to 2019. It was found that China’s carbon emissions and economic development are basically in a weak decoupling state. Engo (2019) found through the Tapio model that there were only four decoupling states between CO$_2$ emissions and economic growth of the transport industry in Cameroon from 1990 to 2016. Raza and Lin (2020) studied the decoupling between CO$_2$ emissions from the transport sector and economic growth in Pakistan from 1984 to 2018. It was found that CO$_2$ emissions showed EC decoupling during 1984–2018. WD occurred in three periods, namely, 1999–2003, 2004–2008, and 2009–2013. Yan and Chen (2022) analyzed the decoupling between the economic development of the construction industry and CO$_2$ emissions from 2009 to 2019. The results showed that the economic development level of most provinces was positively correlated with their CO$_2$ emissions, and the main driving factor of decoupling was indirect carbon intensity. Liu and Feng (2020) studied the CO$_2$ emissions of China’s economic expansion, and found that the decline in energy intensity led to the WD state in 2010–2016, and the per capita service output always inhibited the progress of the decoupling process. Wang and Feng (2021) studied the decoupling between economic expansion and CO$_2$ emissions of 29 non-ferrous metal industries in China. It was found that weak decoupling was dominant in 2004–2017, and the progress of energy saving technology was the main contributor to promote the decoupling process. Yang et al. (2021a) found that technological progress in energy conservation and production efficiency also played a major role in promoting global decoupling, and the optimization of energy structure also played a positive role in promoting the decoupling process. Wang et al. (2020a) found that carbon emissions of China’s iron and steel (IS) industry are mostly weakly decoupled from economic growth based on the Tapio model. Tang et al. (2014) used the Tapio decoupling model to find that from 1990 to 2012, there were two decoupling states of CO$_2$ emissions from China’s tourism industry: negative decoupling and WD, and tourism traffic was the main factor leading to CO$_2$ emissions in tourism industry. Yang et al. (2018) also analyzed the decoupling status of China’s industrial economic growth and CO$_2$ emissions through LMDI method and Tapio model, and found
that the decoupling status of the manufacturing industry presents a U-shaped trend, which is first SD, then WD, and finally SD. Zhao et al. (2017) analyzed the decoupling effect of China’s five major industries’ economic growth and CO₂ emissions from 1992 to 2012, and found that there was a WD from 1992 to 2012, and there was also a WD between the five major industries. Among them, the industrial sector played a major role in China’s decoupling status, and the construction sector played the smallest role.

In the above literature review, some studies mainly focus on decomposing the intuitive factors of CO₂ emissions through LMDI method (Li et al. 2022a, b, c). This allows us to identify some factors that may have an impact on CO₂ emissions of the petrochemical industry. Then, the direct decoupling analysis between environmental pollution and GDP development of specific industries is studied from the perspective of production and energy consumption (Wang and Su 2020b). It provides valuable experience for decoupling analysis of industrial economic development and CO₂ emissions. However, they neglect to establish decoupling indicators from the perspective of influencing factors and rarely analyze the trend of carbon emission mitigation potential of the petrochemical industry.

This paper uses the LMDI method to identify the influencing factors of CO₂ emissions in China’s petrochemical industry, which not only confirms the analysis of the influencing factors of CO₂ emissions in the existing literature (Li et al. 2021a, b), such as the promotion of economic growth factors on carbon emissions. Based on the above factors, a decoupling index is also constructed to reflect the decoupling degree between economic growth and CO₂ emissions, which fills the gap in the existing literature in establishing decoupling indicators from the perspective of influencing factors. Finally, a theoretical mitigation model is established by using the above influencing factors to reflect the CO₂ emission reduction potential of China’s petrochemical industry. This provides case experience for studying the CO₂ emission reduction potential of other industries (Li et al. 2022a, b, c). The exploration of carbon emission reduction potential not only reflects the effect of carbon emission reduction in the past, but also has an important impact on the formulation of carbon emission reduction policies in the petrochemical industry in the future. The research time of this paper is from 1996 to 2019. The whole period is divided into five sub periods: 1996–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2019. In addition, these studies also provide policy makers with suggestions to reduce carbon emissions. The method and data details are given in the “Methodology” and “Data sources” sections respectively. The “Result analysis and discussions” section is the result analysis and discussion, and the “Conclusion and policy implication” section is the conclusions and policy recommendations.

Methodology

Calculation of CO₂ emissions

At present, the calculation of carbon emissions mainly includes input–output method, life cycle method, and IPCC method. The IPCC method estimates CO₂ emissions according to energy consumption and CO₂ emission coefficient (Wang and Feng 2018; Yang et al. 2021b), which is applicable to the estimation of carbon emissions caused by direct energy consumption in various industries and regions. Based on 12 kinds of energy data and the formula provided by the 2006 IPCC guidelines for National Greenhouse Gas Inventories, this paper estimates the energy related CO₂ emissions of China’s petrochemical industry:

\[ C^i = \sum_i E_i \times Q_i \times C_i \times A_i \times 44/12 \]  \hspace{1cm} (1)

In formula (1): \( C^i \) is the total carbon emission; \( E_i \) is the \( i \)-th energy consumption; \( Q_i \) is the average low calorific value (kJ/kg); \( C_i \) is the carbon content per unit calorific value(t/TJ); \( A_i \) is the carbon oxidation rate; 44/12 is the conversion coefficient between carbon and CO₂. Relevant indicators of various energy sources are shown in Table 1.

LMDI decomposition model

In this paper, The LMDI method is used to construct the CO₂ emission decomposition model of China’s petrochemical industry. Different from previous studies, this paper uses per capita economic output instead of GDP, which can better represent the economic activities and economic development of the industry. In addition, the industry scale factor is added, and the number of employees can better reflect the industrialization degree of an industry. The annual CO₂ emission \( C^i \) of petrochemical industry can be expressed as formula (2):

\[ C^i = \frac{C^i}{E_i} \times \frac{E}{E} \times \frac{G}{P} \times P = CI \times ES \times EI \times IA \times IS \]  \hspace{1cm} (2)

In formula (2), \( E_i \) represents the annual fossil energy consumption of the petrochemical industry, \( E \) represents the annual energy consumption of the petrochemical industry, \( G \) represents the annual added value of the petrochemical industry, and \( P \) represents the annual employees of the petrochemical industry. CI (carbon intensity): represents the quality of industrial energy use, and refers to the carbon emission generated by unit energy consumption. ES (energy structure): expressed as energy structure, which measures the proportion of fossil energy in total energy consumption. EI (energy...
Table 1: Emission factors for all types of energy

| Fuels                  | Average low heat (KJ/Kg) | Carbon content per unit calorific value (t/TJ) | Carbon dioxide rate (%) |
|------------------------|--------------------------|-----------------------------------------------|------------------------|
| Raw Coal               | 20,908                   | 26.37                                         | 94                     |
| Coke                   | 28,435                   | 29.50                                         | 93                     |
| Crude oil              | 41,816                   | 20.10                                         | 98                     |
| Gasoline               | 43,070                   | 18.90                                         | 98                     |
| Kerosene               | 43,070                   | 19.50                                         | 98                     |
| Diesel                 | 42,652                   | 20.20                                         | 98                     |
| Natural gas            | 38,931                   | 15.30                                         | 99                     |
| Fuel oil               | 41,816                   | 20.10                                         | 98                     |
| Cleaned Coal           | 26,344                   | 25.41                                         | 98                     |
| Other Washed Coal      | 8363                     | 25.80                                         | 98                     |
| Liquefied Petroleum Gases | 50,179           | 17.20                                         | 98                     |
| Refinery Gas           | 46,055                   | 18.20                                         | 99                     |

Intensity): refers to the amount of energy consumed per unit of industrial added value. IA (Per capita economic output): it is defined as the industrial output of each worker. IS (industry scale): represents the number of employees in the industry.

Using LMDI, the change of CO₂ emission is decomposed into five factors: carbon intensity, per capita output, energy structure, industry scale and energy intensity. Equation (3) for measuring changes in carbon emissions from t to the base periods (the base period subscript is 0):

\[ \Delta C_{tot} = C^t - C^0 = \Delta C_{CI} + \Delta C_{ES} + \Delta C_{EI} + \Delta C_{IA} + \Delta C_{IS} \]  

(3)

In formula (3), \( \Delta C_{CI} \) represents the carbon intensity effect. \( \Delta C_{ES} \) represents the energy structure effect. \( \Delta C_{EI} \) represents the energy intensity effect. \( \Delta C_{IA} \) represents the per capita economic output effect. \( \Delta C_{IS} \) represents industry scale effect. Each effect has its own estimation formula:

\[ \Delta C_{CI} = L(C^0, C^t) \cdot \ln(H^t / H^0) \]  

(4)

\[ \Delta C_{ES} = L(C^0, C^t) \cdot \ln(E^t / E^0) \]  

(5)

\[ \Delta C_{EI} = L(C^0, C^t) \cdot \ln(ES^t / ES^0) \]  

(6)

\[ \Delta C_{IA} = L(C^0, C^t) \cdot \ln(IA^t / IA^0) \]  

(7)

\[ \Delta C_{IS} = L(C^0, C^t) \cdot \ln(IS^t / IS^0) \]  

(8)

where \( L(C^0, C^t) = \frac{C^t - C^0}{\ln(C^t / C^0)} \) is called logarithmic mean weight.

Decoupling indicator

Measures to reduce CO₂ emissions include the carbon intensity effect, the energy structure effect, the industry scale effect, and the energy intensity effect. The decoupling indicator for petrochemical industry, \( D^t \), represents the ratio of the sum of all factors that can reduce CO₂ emissions to CO₂ increases. Therefore, \( D^t \) in the calculation period \([0, t]\) can use the following formula:

\[ D^t = \frac{\Delta F^t}{\Delta C_{IA}^t} \]  

(9)

Among them,

\[ \Delta F^t = \Delta C_{CI} + \Delta C_{ES} + \Delta C_{EI} + \Delta C_{IS} \]  

(10)

According to the decoupling criteria in references Tapio (2005) and Zhang et al. (2019a, b), as shown in Table 2, 8 decoupling states can be represented by 5 scores. By decoupling degree, using score to correspond to each decoupling state can better show the evolution trend of decoupling state of a region or industry. If \( \Delta C_{IA}^t > 0 \), the decoupling score gradually decreases by 1 as the decoupling state decreases. In this paper, the score corresponding to SD (strong decoupling) is set to 4, which means that the inhibitory effect of four factors on CO₂ emission is greater than the driving effect of economic growth, that is, the total CO₂ emission decreases at the same time of economic growth. If \( \Delta C_{IA}^t < 0 \), the decoupling score gradually decreases 1 with the decrease of decoupling status. When RD (Recessive decoupling) occurs, the reduction of CO₂ emission is greater than that of GDP. Therefore, set the score corresponding to RD to 3. Therefore, the score of the corresponding SND (strong negative decoupling) is set to 0.
Table 2 Measures of decoupling index

| Δ F* | ΔC* | D* | Decoupling state | Score | Grade |
|------|------|----|-----------------|-------|-------|
| > 0  | > 0  | D* ≥ 0 | Expensive negative decoupling (END) | 1 | IV |
| < 0  | > 0  | 0 > D* ≥ -0.4 | Expensive coupling (EC) | 2 | III |
| < 0  | > 0  | -0.4 > D* ≥ -1 | Weak decoupling (WD) | 3 | II |
| > 0  | > 0  | -1 > D* | Strong decoupling (SD) | 4 | I |
| > 0  | < 0  | D* ≤ 0 | Strong negative decoupling (SND) | 0 | V |
| < 0  | < 0  | 0.4 ≥ D* > 0 | Weak negative decoupling (WND) | 1 | IV |
| < 0  | < 0  | 1 > D* > 0.4 | Recessive coupling (RC) | 2 | III |
| < 0  | < 0  | D* > 0 | Recessive decoupling (RD) | 3 | II |

**CO2 emission reduction potential model**

In order to measure the CO2 emission reduction potential of the petrochemical industry, a CO2 emission reduction potential model is established according to the influencing factors. The CO2 emission of petrochemical industry driven by per capita economic output effect (ΔC*IA) is expressed as theoretical added value. Therefore, the mitigation rate of CO2 (MRC*) of the petrochemical industry during [0, t] can be expressed as:

\[
MRC^t = \frac{-\Delta F^t}{C_0 + \Delta C^t_{IA}} \times 100
\]  

It should be noted that if Δ F* < 0 and MRC* > 0, it means that the CO2 emission of petrochemical industry has been alleviated in time. When MRC* is larger, it means that the mitigation rate of CO2 is higher; If Δ F* > 0 and MRC* < 0, it means that the CO2 emission of petrochemical industry has not been effectively reduced. When MRC* is smaller, it means that the mitigation rate of CO2 is lower and the problem of CO2 emission has not been improved.

**Data sources**

This research used time series statistics from 1996 to 2019. The terminal energy consumption of petrochemical industry refers to the total energy consumed by Extraction industry of Petroleum and Natural Gas, Manufacture of Raw Chemical Materials and Chemical Products, Manufacture of Rubber and Plastic Products, Manufacture of Fibers and Processing of Petroleum, Coking and Processing of Nuclear Fuel. Energy data are from CESY (China Energy Statistics Yearbook). The main energy types include coal products (raw coal, coke, washed coal, other washed coal), petroleum products (kerosene, liquefied petroleum gas, refinery gas, diesel, crude oil, fuel oil and gasoline), as well as natural gas and electricity. The industry added value and its employees are derived from CSY (China Statistical Yearbook) and CISY (China Industrial Statistics Yearbook). The industry added value is converted according to producer price index provided in CSY, and the data are calculated at constant prices in 1996.

**Result analysis and discussions**

**Analysis of CO2 emission change in China’s petrochemical industry**

Figure 1 shows that CO2 emissions from China’s petrochemical industry increased from 346.43 million tons in 1996 to 592.63 million tons in 2019. The CO2 emission curve of the petrochemical industry can be divided into three stages: two stages of slow decline (1996–2000), (2015–2019), and one stage of rapid growth (2000–2015). Figure 1 also shows that in the second stage (2000–2015), the average annual growth rate of CO2 emission of petrochemical industry is 6.81%. In 2000, the CO2 emitted by the petrochemical industry due to coal products accounted for 58.23% of the total CO2 emissions of petrochemical industry. However, this figure reached 76.68% in 2015. The proportion of oil products in CO2 emissions decreased from 30.62% in 2000 to 13.56% in 2015. The reason is that with the development of petrochemical industry, the dependence on coal has gradually increased, the proportion of coal consumption has increased linearly, and the proportion of natural gas is still stable at about 11%. In the two slow decline stages (1996–2000) and (2015–2019), the average annual decline rates of CO2 emissions of petrochemical industry were 4.39% and 4.34% respectively. The proportion of CO2 produced by coal products decreased from 70.38% in 1996 to 58.23% in 2000, and from 76.68% in 2015 to 66.40% in 2019. This is mainly because during the “9th Five-Year Plan” period, energy conservation and consumption reduction became the strategic focus of energy policy, increased the proportion of natural gas use, and increased the proportion of primary energy for power generation. During the “13th Five-Year Plan” period, the 13th five-year energy plan clearly pointed out to increase...
the proportion of natural gas use and reduce the proportion of coal consumption to less than 58%.

The highest CO₂ emission coefficient in 1996 was 2.427 t/tce, and the lowest CO₂ emission coefficient in 2019 was 2.317 t/tce, with an overall decline of only 4.75%. This shows that during this period, there has been little improvement in fuel quality and technology, and in the development and use of clean energy. Figure 2 shows that the curve of fossil energy consumption as a proportion of total energy use is divided into four stages. In the first stage from 1996 to 2002, the share of fossil energy in the petrochemical industry decreased rapidly, which can be explained as: on the one hand, the momentum of coal production was insufficient and the supply situation tended to be tight at the end of the 1990s; on the other hand, it has greatly accelerated the development and use of oil and natural gas. The second stage is from 2003 to 2006, which is the stage of moderating growth. It is mainly due to the stable growth of China’s economy and the steady rise of energy demand, while coal still plays a leading role in the energy consumption of petrochemical industry. The third stage (2007–2009) and the fourth stage (2010–2019) are slow decline stage and rapid decline stage respectively. The main reason is that in order to realize the low-carbon transformation of the industry, reduce the dependence on coal energy, and gradually increase the development and

Fig. 1 CO₂ emission of petrochemical industry and its proportion in different energy types

Fig. 2 CO₂ coefficient and fossil energy share in petrochemical industry
utilization rate of clean energy such as natural gas and electricity.

Figure 3 shows that from 1996 to 2019, the economic output increased from 344.871 billion yuan to 3863.821 billion yuan. However, the economic output curve of China’s petrochemical industry is divided into three stages: moderate growth stage (1996–2008), rapid growth stage (2009–2015), and fluctuation stage (2017–2019). Figure 3 also shows that from 1996 to 2019, the energy intensity decreased from 4.825 to 1.011 tce/10^4 yuan. The energy intensity curve is also divided into four stages: two rapid decline stages (1996–2003), (2012–2015), fluctuating decline stage (2004–2011), and stable stage (2016–2019). From 1996 to 2003, the rapid decline in energy intensity was due to the gradual decline in fossil energy consumption during the “9th Five-Year Plan” period, resulting in a gradual decline in CO2 emissions. From 2004 to 2011, although the energy intensity decreased from 2.703 to 1.714 tce per 10^4 yuan, there was an upward trend in 2007–2008 and 2009–2011. This was mainly due to the economic downturn in 2008 as a result of the global financial crisis, while output remained stable as energy consumption increased between 2009 and 2011. From 2012 to 2015, the energy intensity decreased rapidly for the second time, from 1.714 to 0.997 tce per 10^4 yuan, which can be explained that during the “12th Five-Year Plan,” China’s economy was booming, far faster than energy consumption. From 2016 to 2019, the energy intensity is close to 1, and the development tends to be stable, but it is still higher than the global average.

Figure 4 shows that the industry scale of China’s petrochemical industry mainly showed a trend of first decline, then rise and then decline from 1996 to 2019. It can be divided into four stages, including two rapid decline stages (1996–2000), (2016–2019), one rapid rise stage (2001–2010), and one stable
stage (2011–2015). In the first stage, from 1996 to 1999, the industry scale decreased from 9.463 million to 6.567 million. In the second stage, from 2001 to 2010, the industry scale increased rapidly from 6.514 million to 11.025 million, reaching the peak in recent 20 years. In the third stage, from 2011 to 2015, the scale of the industry did not increase or decrease significantly, and the industrialization process of the petrochemical industry developed steadily. In the fourth stage, from 2016 to 2019, the scale of the industry began to decline gradually, from 10.617 million to 8.319 million. This is because the state strengthened the low-carbon transformation of petrochemical and other high energy-consuming industries during the “13th Five-Year Plan” period.

**Analysis of influencing factors of carbon emissions**

In order to better analyze the effect of policy implementation, this study divides the research period from 1996 to 2019 according to China’s 5-year plan. The decomposition results are shown in Table 3 and Fig. 5. From the overall situation from 1996 to 2019, the $\Delta C_{t\text{IA}}$ was the most critical factor for the growth of carbon emissions in the chemical sector, and the contribution rate of the economic growth effect to the increase of $\text{CO}_2$ emissions was 403.36%. This is consistent with the research results of (Fan et al. 2015), mainly because the current insufficient development and use of clean energy has not reduced the dependence on fossil energy, and economic growth has led to a large number of carbon emissions. The $\Delta C_{t\text{EI}}$ was the leading force to restrain the increase of carbon emissions, with a contribution rate of $-247.60\%$, followed by the inhibition of $\Delta C_{t\text{ES}}$. The inhibition of $\Delta C_{t\text{IS}}$ was weaker than that of energy structure, reducing 62.204 million tons of $\text{CO}_2$ emissions. This result is inconsistent with the conclusion of Lin and Long (2016). Their conclusion is that the industry scale promotes the increase of carbon emissions. One possible reason is that the rapid expansion of industry scale before the “11th Five-Year Plan” leads to the increase of carbon emissions, and during the subsequent “12th Five-Year Plan” and the “13th Five-Year Plan,” the petrochemical industry gradually optimizes the labor force population, improves the quality of labor force, and turns the role of promotion into that of inhibition. The $\Delta C_{t\text{CI}}$ had little effect, reducing only 22.318 million tons of $\text{CO}_2$ emissions, with a contribution rate of only $-7.33\%$. In the future, China’s petrochemical industry should maintain the continuous decline of energy intensity, shift the focus of emission reduction to adjusting the energy structure, reducing the dependence on fossil energy.

### Table 3  Changes in carbon emissions caused by various influencing factors

| Time periods | $\Delta C_{t\text{ES}}$ | $\Delta C_{t\text{CI}}$ | $\Delta C_{t\text{EI}}$ | $\Delta C_{t\text{IA}}$ | $\Delta C_{t\text{IS}}$ | $\Delta C$ |
|--------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 1996–2000    | -1185.474              | -1465.752              | -20,232.965            | 27,241.960             | -10,060.476            | -5702.707              |
| 2000–2005    | -144.472               | 1588.603               | -4318.683              | 17,589.900             | 6027.148               | 20,742.496             |
| 2005–2010    | -1612.792              | 522.891                | -19,911.928            | 16,324.814             | 17,482.619             | 12,805.604             |
| 2010–2015    | -2125.885              | -272.315               | -21,490.713            | 42,914.385             | -3731.070              | 15,294.403             |
| 2015–2019    | -5437.866              | -3338.333              | -10,504.963            | 22,870.440             | -16,262.874            | -12,673.595             |
| 1996–2019    | -8535.748              | -2231.838              | -75,435.103            | 122,889.302            | -6220.412              | 30,466.201             |

### Fig. 5  Contributions of all factors to changes in $\text{CO}_2$ emissions

![Contributions of all factors to changes in CO2 emissions](image-url)
vigorously develop clean energy and reduce its dependence on coal.

From the perspective of several 5-year plans, the $\Delta C_{IA}$ showed the only leading force to increase carbon emissions during the five-year plans. During the “9th Five-Year Plan” and the “13th Five-Year Plan,” the CO$_2$ emissions of China’s petrochemical industry decreased, while the contribution rate of economic growth effect to the increase of CO$_2$ emissions reached 477.70% and 180.46%. On the contrary, the $\Delta C_{EI}$ was always the most important factor to reduce carbon emissions, with a cumulative reduction of 754.351 million tons. Both the $\Delta C_{CI}$ and $\Delta C_{IS}$ had played a positive role in the increase of CO$_2$ emissions during the “10th Five-Year Plan” and “11th Five-Year Plan,” with a cumulative increase of 211.149 million tons and 235.098 million tons respectively. The inhibitory effect of $\Delta C_{ES}$ on CO$_2$ emission was the smallest during the “10th Five Year Plan” period, with a reduction of only 0.144 million tons and a contribution rate of −0.70%. The trend change of some indicators described in the “Analysis of CO2 emission change in China’s petrochemical industry” section is the reason for the change of the above influencing factors.

**Decoupling analysis**

During 1996–2019, there were three decoupling states between CO$_2$ emissions of China’s petrochemical industry and economic development. As shown in Table 4, from 1996 to 2019, the CO$_2$ emission of petrochemical industry showed a WD state with economic growth, and the decoupling index was −0.752, indicating that the emission reduction effects of the four factors compensated for part of CO$_2$ brought by economic output. This is mainly due to the increase in the proportion of non-fossil energy, the improvement of energy efficiency caused by energy technology innovation in recent years and the decrease of carbon emission coefficient. WD also occurred during 2005–2010 and 2010–2015. Figure 6 shows that this is mainly because the decline of energy intensity has increased the inhibition of CO$_2$ emission during the “11th Five-Year Plan.” While the energy intensity is in the

| Time periods   | Δ F^t | $\Delta C_{IA}$ | $D^t$ | Decoupling state | Score | Grade |
|---------------|-------|----------------|-------|------------------|-------|-------|
| 1996–2000     | 32,944.667 | 27,241.960   | −1.209 | SD               | 4     | I     |
| 2000–2005     | 3152.596  | 17,589.900   | 0.179  | EC               | 2     | III   |
| 2005–2010     | 3519.210  | 16,324.814   | −0.216 | WD               | 3     | II    |
| 2010–2015     | 27,619.982 | 42,914.385   | −0.644 | WD               | 3     | II    |
| 2015–2019     | 35,544.036 | 22,870.440   | −1.554 | SD               | 4     | I     |
| 1996–2019     | 86,497.801 | 116,964.002  | −0.752 | WD               | 3     | II    |

**Table 4 Decoupling results of CO$_2$ emissions from China’s petrochemical industry**

**Fig. 6 The change of effect value of four factors**
stage of rapid decline during the “12th Five-Year Plan,” the reduction of industry scale has also inhibited CO$_2$ emission. CO$_2$ emissions from China’s petrochemical industry showed a SD state during 1996–2000 and 2015–2019, with decoupling indexes of $-1.209$ and $-1.554$, respectively. The carbon emissions decreased while economic growth. As can be seen from Fig. 7, if the decoupling index is smaller, it indicates that the decoupling state is better, and the corresponding score is larger. For example, during 1996–2000 and 2015–2019, the score was 4. On the contrary, if the decoupling index is larger, it indicates that the decoupling state is worse, and the corresponding score is smaller. Therefore, during 2000–2005, the score was 2. This is mainly because, first, during the “9th Five-Year Plan” period, fossil energy supply fell short of demand, energy conservation realized the transformation of growth mode and the improvement of economic benefits, and CO$_2$ emissions also decreased. Second, it can be seen from Fig. 6 that during the “13th Five-Year Plan” period, low-carbon energy structure became the primary goal and the process of low-carbon energy was further accelerated. Natural gas and non-fossil fuels were the main sources of energy development, and the gradual economic slowdown had also led to a decrease in the increase of CO$_2$. During the period of the “10th Five-year Plan,” the CO$_2$ emission of China’s petrochemical industry showed EC state, and the decoupling index was 0.179. The increase in employees reflects the acceleration of the industrialization process in the petrochemical industry, and the expansion of the industry scale is the reason for the emergence of EC during 2000–2005.

In general, the decoupling index established based on the influencing factors reflects the decoupling state of the petrochemical industry and explains the reasons for its state at the same time. At present, we find that the petrochemical industry is in WD state during the whole research period. Different from other studies (Yan and Chen 2022; Zhao et al. 2017), SD appeared during the “13th Five-Year Plan.” This reflects that with the implementation of China’s carbon emission reduction policies and measures for the petrochemical industry, the decoupling efforts in reducing carbon emissions and economic growth have achieved results.

Table 4 also lists three decoupling levels that occurred during all Five-Year Plans and between 1996 and 2019: I, II, and III. From the overall research process, the decoupling of CO$_2$ emissions in China’s petrochemical industry showed a U-shaped trend, from the “9th Five-Year Plan” period for the grade I, to the “10th Five-year Plan” of the grade II, to the “11th Five-Year Plan” of the grade II, to the “12th Five-Year Plan” of the grade II, and finally to the “13th Five-Year Plan” of the grade I. The degree of decoupling changed from good to worse and then gradually improved. For the whole period from 1996 to 2019, the decoupling grade is II.

### Analysis of mitigation potential

Table 5 lists the mitigation rate of CO$_2$ emissions from China’s petrochemical industry in all five-year plans (1996–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2019). Carbon mitigation occurs in four periods: 1996–2000, 2005–2010, 2010–2015, and 2015–2019. Figure 8 shows that the mitigation rate of CO$_2$ emission from petrochemical industry shows a V-shaped trend, which decreases first and then increases gradually. During 1996–2000, the CO$_2$ emission reduction rate was 53.235%. The main factor to reduce CO$_2$ emission was the energy intensity effect ($\Delta C^\text{EI}$), followed by the industry scale effect ($\Delta C^\text{IS}$). The mitigation rate of carbon emissions from 2005 to 2010 was only 5.331%, because although energy technology innovation led to the improvement of energy efficiency and the proportion of non-fossil energy, the expansion of industry scale caused a large number of CO$_2$ emissions. From 2010 to 2015, the CO$_2$ emission mitigation rate of the petrochemical industry began to improve, reaching 26.204%. During 2015–2019, China’s petrochemical industry achieved theoretical CO$_2$ emission reduction. Optimizing energy structure, improving energy efficiency and reducing

| Time periods | $\Delta F$ | $C^0$ | $\Delta C^\text{IA}$ | MRC$^a$ |
|--------------|-----------|-------|----------------------|---------|
| 1996–2000    | 32,944.667| 34,643.568| 27,241.960| 53.235 |
| 2000–2005    | $-3152.596$| 28,940.861| 17,589.900| $-6.775$|
| 2005–2010    | 3519.210  | 49,683.357| 16,324.814| 3.331  |
| 2010–2015    | 27,619.982| 62,488.960| 42,914.385| 26.204 |
| 2015–2019    | 35,544.036| 77,783.364| 22,870.440| 35.313 |
employees caused by industrial transformation are important reasons to alleviate CO₂ emissions.

**Conclusion and policy implication**

**Conclusion**

As an important pillar of China’s economic development, the petrochemical industry is also one of the main users of China’s energy consumption. In order to achieve the economic growth and carbon emission reduction targets of the petrochemical industry, this paper aims to study the decoupling trend and emission reduction potential of China’s petrochemical industry. This paper uses LMDI model to analyze the influencing factors of CO₂ emission from petrochemical industry. The decoupling index based on the influencing factors reflects the decoupling degree and the reasons for the decoupling state, and the CO₂ mitigation model can effectively reflect the effect of the carbon emission reduction policy adopted by the Chinese government. This paper puts forward valuable suggestions for the future carbon emission reduction policies of the petrochemical industry, and provides case experience for carbon emission reduction of other industries or the petrochemical industry between regions.

The results are as follows:

1. The CO₂ emission of China’s petrochemical industry is divided into three stages. From 2000 to 2015, the CO₂ emission of petrochemical industry increased rapidly, and the CO₂ emission of coal accounted for 76.68% in 2015. During the study period, although the carbon emission coefficient has a downward trend, it is relatively stable as a whole. From 1996 to 2019, the consumption of non-fossil energy in the petrochemical industry accounted for less than 20%. The per capita economic output is on the rise and the energy intensity is on the decline. The industry scale fluctuates, rising first and then falling.

2. The energy intensity effect was the most important factor in reducing CO₂ emissions during the study period. However, the economic growth effect played a leading role in increasing CO₂ emissions.

3. During 1996–2019, there were three decoupling states. From 1996 to 2019, China’s petrochemical industry CO₂ emissions showed a WD trend with economic development as a whole. WD also occurred during 2005–2010 and 2010–2015. During 1996–2000 and 2015–2019, SD occurred, and total CO₂ emission decreased with economic growth. The worst state of decoupling, EC, occurred in 2000–2005.

4. The CO₂ mitigation occurred in four stages: 1996–2000, 2005–2010, 2010–2015, and 2015–2019. However, the petrochemical industry did not achieve the goal of reducing CO₂ emissions between 2000 and 2005.

This study also has some limitations. Some unresolved issues related to this study must be considered. For example, (1) in terms of influencing factors of carbon emissions, some factors cannot be decomposed by the LMDI method, such as production technology and investment. Therefore, in the future, we will pay more attention to the impact of green technology innovation on carbon emissions. (2) In terms of research scope, the main research scope of this paper is the whole China. However, the carbon emission reduction of petrochemical industry in different regions is different. In the next step, we should carry out differentiation research according to the carbon emission of petrochemical industry in different regions, and put forward specific
carbon emission reduction suggestions according to the heterogeneity.

**Policy implication**

In general, during the research period, the decoupling status of China’s petrochemical industry is gradually improving. In recent three periods, the petrochemical industry has achieved CO2 emission reduction, but the CO2 emission reduction rate is not large. Therefore, it is necessary for the government to formulate effective policies and measures to strengthen CO2 emission reduction in the petrochemical industry. Based on the above conclusions and discussions, this paper puts forward some policy implications.

(1) Change the mode of economic growth in the petrochemical industry and establish an energy-saving and eco-friendly industrial production system. The research shows that the economic output effect plays the largest role in promoting the increase of carbon emissions of China’s petrochemical industry. Therefore, instead of pursuing output and relying on the extensive growth of energy intensity, we should pay attention to the sustainable and intensive development of quantity, quality and efficiency.

(2) Increase efforts to optimize energy structure, actively develop and utilize clean energy, reduce coal energy consumption. Although the effect of energy structure is one of the factors to reduce CO2 emissions, its effect is not obvious. We should formulate policies. First, adjust the proportion of China’s three major energy consumption, and increase the use of natural gas while reducing coal consumption. Second, encourage the maximum use of alternative energy, develop renewable and new energy.

(3) Continue to reduce energy intensity. At present, the energy intensity effect can inhibit the increase of CO2 emission most. During the research period, although the energy intensity of the petrochemical industry has decreased greatly, it is still higher than the global average. In the future, China should use technological change to reduce energy intensity, and pay special attention to the research and development of technologies related to energy conservation and emission reduction.

(4) Optimize the population structure and improve the quality of workers. Through the analysis of industry scale effect, it can be concluded that in the process of industrialization construction in the future, we should pay more attention to the importance of continuously improving the quality of the whole people. The issue of carbon emission should be highly valued by the whole people, continuously improve energy utilization efficiency, develop advanced energy-saving and environment protection technologies, and lay the foundation for the low-carbon transformation of energy intensive industries such as petrochemical industry.

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**Data availability** The datasets generated during and analyzed during the current study are available in China National Bureau of Statistics (http://www.stats.gov.cn/).

**Declarations**

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