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Research Article

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Posted Date: June 10th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1649352/v1

Decoupling and scenario analysis of economy-emissions pattern in China's 30 provinces

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Abstract

The tension between reducing CO_2 emissions and economic growth has become increasingly prominent in recent years, while China is vigorously promoting ecological civilization to achieve sustainable development. We analyze the decoupling of emissions at the national and provincial levels of the Chinese economy from the perspective of historical patterns and current drivers from 1997 to 2019. Also, we developed three scenarios (i.e., pessimistic, median, and optimistic scenarios) to analyze the impact of decoupling relationship changes. We find that China's national decoupling relationship has eased since 1997, but it has not yet reached the ideal state, with provinces mainly exhibiting weak decoupling. The EKC hypothesis is tested for the whole country and 30 provinces and find that 15 provinces have two turning points, 13 provinces have one turning point, and the others have no turning point. Based on the scenario analysis, the total emissions in the Pessimistic Scenario (S1) without any improvement of decoupling would increase by 73.97% compared to the level of 2019. However, the total emissions in the Optimistic Scenario (S3), in which all provinces obtained strong decoupling, are almost half of the level of 2019. This is mainly from the reduction of emissions in the western less developed regions (e.g., Shanxi, Inner Mongolia and Xinjiang) and developed coastal regions (e.g., Jiangsu and Shandong). On the basis of the results of factor analysis, we put forward policy recommendations for expand electrification, optimize industrial structure, and promote technological innovation.

Keywords: Economic-emissions pattern; Decoupling analysis; EKC; LMDI; Scenario analysis.

1 Introduction

In 2015, the Paris Agreement proposed a major operational goal of keeping global mean temperature rise to well below 2°C and working to limit it to 1.5°C above pre-industrial levels (UNFCCC, 2015). Pachauri et al. (2014) point out a nearly linear relationship between global mean temperature change and cumulative CO_2 emissions in the atmosphere, thus controlling CO_2 emissions at an appropriate level for a period has been the most key environmental issue for governments globally. As the largest

CO_2 emitter in the world, China promised to peak its absolute emissions before 2030 (Liu, 2015). This reflects the strong ambitions of China to reduce CO_2 emissions to deal with global climate change (Duan et al., 2018; Elzen et al., 2016).

However, considering the diversity of economic developments in China's provinces, the measures of promoting the adjustment of economic structure and energy structure to deal with global warming might lead to the risk of slowdown economic development. Thus, the contradiction between emissions reductions and economic development has become increasing prominent in recent years. Some analyses have emphasized the decoupling status of carbon emissions in China from its economic growth (Zhao et al., 2017; Zhang and Da, 2015). For example, Wang and Jiang (2019) quantified the decoupling elasticity and analyzed the contribution of six industries to promote the decoupling effect. Moreover, some studies proposed that the correlation between emissions and economic development was nonlinear considering regional heterogeneity (Zhang and Zhao, 2019; Zhou et al., 2017). Thus, some scholars have analyzed the Kuznets curve of carbon emissions and its regional heterogeneity. For example, Song et al. (2019) explored the decoupling relationship and verified whether the environmental Kuznets curve (EKC) of carbon emissions and GDP per capita satisfy the inverted U-shaped characteristics. However, more questions, such as what is China's current relationship between CO_2 emissions and economic development from the regional and provincial perspectives, what factors are influencing the economy-emissions nexus? Whether China's strong decoupling can provide a sustainable development future? also need to be answered.

Here, based on the data of 1997-2019, we develop a comprehensive evaluation of China's economy-emissions decoupling at the national and provincial levels from the context of historical patterns, current drivers, and future impacts. Our work contributes to the existing knowledge in three aspects. First, we analyze the economy-emissions decoupling relationship at the national, regional, and provincial levels and discuss the differences between developed and developing provinces. Importantly, we use the EKC model to analyze the turning points of China's 4 regions and 30 provinces in order to further investigate the decoupling relationship between economic development and emissions. Also, we apply threshold regression to make up for deficiencies of the EKC model that can only identify one or two turning points. Second, we analyze the driving factors combined with decoupling experiences, especially focusing on the emissions impact of renewable development and electrification which are rarely discussed before. This is helpful for understanding the decoupling mechanism of emissions and proposing more targeted emission reduction measures. Third, as the decoupling relationship between economy and emissions have an impact of the total emissions, we develop three scenarios to analyze future emissions changes based on different economy-emissions development path. This provides evidence to reflect how decoupling efforts impact future climate change.

The rest of our paper is organized below. *Section 2* present literature review. *Section 3* provides a brief overview of the methods and data. *Section 4* presents results. *Section 5* discusses empirical results and *Section 6* concludes.

2 Literature review

The decoupling theory was first proposed by the Organization for Economic Cooperation and Development (OECD) and defined as the relationship between economic growth and industrial pollution emissions whether they change in tandem (OECD, 2002). With the increasing concern about the issue of energy use and environmental impact, there is a growing interest in the study of economy-emissions relationship. Studies of decoupling worldwide were mostly at the national level, such as China, the United States (Wang et al., 2018), V4 countries (Czech Republic, Hungary, Poland and Slovakia) (Chovancová and Vavrek, 2019), OECD countries (Chen et al., 2018), and typical developed and developing countries (Wu et al., 2018b). Since China is the world's largest emitter of CO_2 after 2009 (IEA, 2009), a number of scholars have conducted a series of decoupling studies between economic growth and carbon emissions based on the Chinese context (Wang and Jiang, 2019; Li and Qin, 2019). In addition to at the national level, some literatures have analyzed the decoupling relationship between economic development and emissions in China's different industries, for example the construction industry (Wu et al., 2018), the transportation sector (Pan et al., 2018), six major sectors (Jiang et al., 2018), the commercial building sector (Ma et al., 2019), and the power industry (Xie et al., 2019). Most of these studies have been conducted at the national level, while Chinese provinces differ greatly in terms of resources endowment and economic development, which may lead to different emission profiles (Zhang et al., 2017; Bao and Fang, 2013). Therefore, it is crucial to study each province in China separately. Wu et al. (2019) analyzed 30 Chinese provinces and showed a strong decoupling relationship between GDP and carbon intensity in most provinces. Song et al. (2020) studied 30 provinces and constructed a two-dimensional decoupling model to explore the decoupling status and its dynamic path. Jiang et al. (2019) and Dong et al. (2016) both conducted case studies with individual provinces, analyzing the interaction between CO_2 emissions and economic development in Guangdong and Liaoning, respectively. Wang et al. (2019) compared decoupling trends and decoupling effects at the city level for Beijing and Shanghai from a sectoral perspective.

Furthermore, the EKC hypothesis is an important current approach to study the energy-economy nexus. There are many related studies in the global context. For example, Simionescu (2021) studied Eastern European countries to obtain the conclusion of an inverted N-shaped relationship. A similar EKC hypothesis was tested for Egypt (Mahmood et al., 2021), Turkey (Pata, 2018) and France (Shahbaz et al., 2018). For the case of China, most studies concluded that China as a whole cannot confirm the EKC hypothesis. Pata and Caglar (2021) concluded that the EKC hypothesis did not apply to China. Pal and Mitra (2017) similarly obtained a different CO_2 emissions and Ouyang and Lin (2017) used the Johansen Cointegration approach to consider an Inverted U-shaped relationship. At the provincial and regional levels, some studies have shown that the energy-economy relationship in 30 Chinese provinces was supportive of the EKC hypothesis (Zhao et al., 2020; Zhang and Zhao, 2019). At the sectoral level, the validation of the EKC hypothesis and relationship analysis of different single sectors were studied, e.g., agricultural sector (Zhang et al., 2019a), construction sector (Ahmad et al., 2019), commercial buildings (Ma and Cai, 2019), manufacturing industry (Xu and Lin, 2016). The results show that most sectors support EKC.

The drivers behind the understanding of coupling are further investigated mainly through the decomposition analysis in which the logarithmic mean Divisia index (LMDI) model is the most widely used. By decomposing the drivers of carbon emissions, previous studies confirmed that China's emission growth was mainly dominated by strong economic growth (Li and Qin, 2019; Ma et al., 2019; Jia et al., 2018), while energy intensity was the main influence of suppression (Du et al., 2018; Yang et al., 2020). Sheng et al. (2018) concluded that population size and energy mix were the next most important factors contributing to the increase in carbon emissions, but Chen et al. (2020) proposed that a slight fluctuation in energy mix had a small impact on the emissions in four sectors studied. Zheng et al. (2019) indicated that industrial structure and energy mix contributed to the increase in emissions in several regions, but the two drivers have led to emission reductions at the national level. They also suggested that the effect of industrial structure optimization on CO_2 emissions was dynamic. Overall, the most prominent decomposition factors in the current literature were economic growth, energy intensity, population, energy structure, and industrial structure, while a few studies focused on urbanization and technological development. However, the above studies ignored the assessment of the impact of electrification and power generation efficiency on the CO_2 mitigation from the energy development perspective, which our study addresses.

3 Methods and data sources

3.1 Decoupling index

The decoupling index (DI) is used to illustrate the environmental burden of economic development. Based on the elastic coefficient method, Tapio (2005) define the decoupling state with the range of elastic value. It is also widely used in the field of economic growth, resources, and environment. It can be presented as:

$$D = \frac{\%\Delta C}{\%\Delta Y} \tag{1}$$

where $\%\Delta C$ indicates the growth rate of Carbon emissions per capita and $\%\Delta Y$ is the growth rate of GDP per capita. It can be calculated year on year or as an average annual growth rate in a given period. The 8 different decoupling state is listed in Table 1.

Table 1 Definition of decoupling state

The value of D	The value of GDP and C	Decoupling state
D<0	$\%\Delta Y$>0, $\%\Delta C$<0	Strong decoupling
	$\%\Delta Y$<0, $\%\Delta C$>0	Strong negative decoupling
0<D<0.8	$\%\Delta Y$>0, $\%\Delta C$>0	Weak decoupling

	$\%\Delta Y<0$, $\%\Delta C<0$	Weak negative decoupling
0.8<D<1.2	$\%\Delta Y>0$, $\%\Delta C>0$	Expansive coupling
	$\%\Delta Y<0$, $\%\Delta C<0$	Recessive coupling
D>1.2	$\%\Delta Y>0$, $\%\Delta C>0$	Expansive negative decoupling
	$\%\Delta Y<0$, $\%\Delta C<0$	Recessive decoupling

3.2 Fitting models

Fitting models, including linear models and parametric polynomial models, are common to identify the nexus between carbon emissions and economic growth. In this case, the log-linear model, which is used to identify the emission-economy relationship at the national level, is written as:

$$\ln C_t = \alpha + \beta \ln Y_t + \varepsilon_t \tag{2}$$

where t is the year, C is carbon emissions per capita, and Y is GDP per capita, ε_{it} is the standard error term, α and β_3 are the estimated coefficients.

The second-order polynomial, called the Environmental Kuznets Curve (EKC) model, assumes an inverted U-shape curve between economic growth and emissions. Moreover, the cubic polynomial is an extension of the tradition inverted U-shape EKC, which is used to identify the relationship between economic development and emissions at the regional/provincial level in this paper:

$$\ln C_t = \beta_0 + \beta_1 \ln Y_t + \beta_2 (\ln Y_t)^2 + \beta_3 (\ln Y_t)^3 + \varepsilon_t \tag{3}$$

where β_1, β_2 and β_3 are the estimated coefficients. Eq. (3) allows different relationships between carbon emissions and GDP growth within the EKC. Table 2 reports the shape of the EKC, which results from the parameter constraints.

Table 2. Shapes of the EKC depends on the values of the coefficients.

Coefficients	Relationships
$\beta_1 = 0; \beta_2 = 0; \beta_3 = 0;$	No relationship
$\beta_1 > 0; \beta_2 = 0; \beta_3 = 0;$	Monotonic increasing linear relationship
$\beta_1 < 0; \beta_2 = 0; \beta_3 = 0;$	Monotonic decreasing linear relationship
$\beta_1 > 0; \beta_2 < 0; \beta_3 = 0;$	Traditional EKC (inverted-U)
$\beta_1 < 0; \beta_2 > 0; \beta_3 = 0;$	Inverted EKC (U-shaped)
$\beta_1 > 0; \beta_2 < 0; \beta_3 > 0;$	Extended EKC (N-shaped)
$\beta_1 < 0; \beta_2 > 0; \beta_3 < 0;$	Inverted extended EKC

We can identify the turning points for different shapes of the EKC. For the traditional (inverted-U) or inverted (U-shaped) EKC, the turning point of GDP per capita is $\exp(\frac{-\beta_1}{2\beta_2})$. The extended (N-shaped) or inverted extended EKC has two turning points, which can be calculated using the following formula:

$$Y_T = \exp\left(\frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}\right) \tag{4}$$

Moreover, we can determine the turning year (*TY*) by the following formula:

$$Y_0 \times (1+g)^{TY} = Y_T \tag{5}$$

where Y_0 and Y_T indicate GDP per capita in the base year and turning point year respectively, g indicates the average growth rate of GDP per capita.

We also used a fixed-effect panel threshold regression model to test the threshold effect of economic development level on economy-emissions patten as:

$$\begin{aligned} lnC_{r,t} &= \alpha + \beta_1 lnY_t I\left(\ln Y_{r,t} < \eta_1\right) + \beta_2 lnY_{r,t} I\left(\eta_1 \le \ln Y_t < \eta_2\right) \\ &+ \ldots + \beta_k lnY_{r,t} I\left(\ln Y_t \ge \eta_{k-1}\right) + year + u_r + e_{r,t} \end{aligned} \tag{6}$$

where η_k is the threshold parameters that divide the economy-emissions trend into *k-1* regimes with coefficients β_k; The parameter u_r is the individual effect, while $e_{r,t}$ is the disturbance.

3.3 Kaya identity and LMDI

The LMDI decomposition analysis can estimate the impact of each candidate factor on carbon emissions (Ang and Zhang, 2000; Xu and Ang, 2013; Ang and Goh, 2019). This method has the advantage of residual-free and aggregation-accurate (Ang, 2004). According to the Kaya identity, we first decomposed carbon emissions into 9 influencing factors. The specific model is as follows:

$$\begin{aligned} C &= P\left(\frac{GDP}{P}\right)\left(\frac{CE}{GDP}\right)\left(\frac{CR}{CE}\right)\left(\frac{CF}{CR}\right)\left(\frac{CP}{CF}\right)\left(\frac{OP}{CP}\right)\left(\frac{IV}{OP}\right)\left(\frac{C}{IV}\right) \\ &= P \bullet Y \bullet E \bullet R \bullet F \bullet L \bullet R \bullet V \bullet K \end{aligned} \tag{7}$$

where C is carbon emissions; P is total population; GDP is total GDP; CE is energy consumption; CR is renewable energy consumption; CF is fossil fuel consumption; CP is the energy consumption from the power sector; OP is the electricity output in the power sector; IV is investment scale; HT is total household consumption; $Y = \frac{GDP}{P}$ is GDP per capita; $E = \frac{CE}{Y}$ is energy intensity; $R = \frac{CR}{CE}$ is renewable energy-energy substitution, $F = \frac{CF}{CR}$ is fossil fuels-renewable energy substitution; $L = \frac{CP}{CF}$ is the ratio of energy consumption from power sector to the total fossil fuel consumption, reflecting the effect of electrification on emissions; $G=\dfrac{OP}{CP}$ is the ratio of the electricity output to the energy input in the power sector, reflecting the power generation efficiency on emissions; $V=\dfrac{IV}{OP}$ is investment efficiency; $K=\dfrac{C}{IV}$ is carbon emissions intensity.

The additive decomposition method proposed by Ang et al. (2015) for energy consumption can further quantify the impact of factors on carbon emissions. The overall effects are formulated as follows:

$$\begin{aligned}&\Delta C = C^t - C^0 = \\ &\Delta C_P + \Delta C_Y + \Delta C_E + \Delta C_R + \Delta C_F + \Delta C_L + \Delta C_G + \Delta C_V + \Delta C_K\end{aligned} \tag{8}$$

where ΔC is the total change of carbon emissions and the right-hand side of the equation gives the effects associated with the 9 factors between the year t and 0. The general formulas of LMDI for the effect of each factor can be as:

$$\Delta C_P = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{P^t}{P^0}) \tag{9-1}$$

$$\Delta C_Y = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{Y^t}{Y^0}) \tag{9-2}$$

$$\Delta C_E = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{E^t}{E^0}) \tag{9-3}$$

$$\Delta C_R = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{R^t}{R^0}) \tag{9-4}$$

$$\Delta C_F = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{F^t}{F^0}) \tag{9-5}$$

$$\Delta C_L = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{L^t}{L^0}) \tag{9-6}$$

$$\Delta G_P = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{G^t}{G^0}) \tag{9-7}$$

$$\Delta C_V = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{V^t}{V^0}) \tag{9-8}$$

$$\Delta C_K = \sum \frac{C^t - C^0}{\ln(C^t - C^0)} \times \ln(\frac{K^t}{K^0}) \tag{9-9}$$

3.4 Scenario analysis

We further provide future perspective of emissions based on possible changes of economy-emissions patterns. Three main scenarios are developed. The first is a Pessimistic scenario (S1), in which no further decoupling takes place in all provinces. This means that the current relationship between economic development and emissions growth keeps unchanged through 2030. The second scenario is a Median scenario (S2) and the final one is an Optimistic scenario (S3). In the S2, we assume that provinces with current strong decoupling remain unchanged economy-emissions relationship until 2030 while provinces without current strong decoupling will be improved to a better status. We select the province with the smallest value among the strong decoupling status as the benchmark. For example, the smallest value among provinces with strong decoupling is -0.35, thus we assume the future decoupling status of these provinces are -0.35. This means that the provinces with weak decoupling will be improved to a convergent level with strong decoupling. Then in the S3, we further assume that all provinces are improved to a best state in 2030. This means that we select the province with the highest value in the strong decoupling state as the benchmark. For example, the value of the highest degree decoupling currently is -2.14, thus we improve the future decoupling state of all provinces to -2.14. By comparing these three scenarios, we quantify the potential emissions impact of adjusting economy-emissions relationship.

To do this, we first need to project total GDP and population for 30 provinces in 2030 using the annual average growth rates during 2010-2019. Since OECD and UN has provided the projection of total GDP and population for China respectively, we constraint that the sum of the estimated future total GDP and population of 30 provinces equals to the official projections for China. Thus, we use the official projection as scale factor and the estimated project data by province as proxies. Mathematically, the projected population and total GDP can be obtained as:

$$P_{r,2030} = \frac{P_{UN}}{\sum_{r}^{30}\left[P_{r,2019}(1+g^{P})^{11}\right]} \times \left[P_{r,2019}(1+g_r^{P})^{11}\right] \tag{10-1}$$

$$GDP_{r,2030} = \frac{GDP_{OECD}}{\sum_{r}^{30}\left[GDP_{r,2019}(1+g^{GDP})^{11}\right]} \times \left[GDP_{r,2019}(1+g_r^{GDP})^{11}\right] \tag{10-2}$$

where $P_{r,2030}$ and $GDP_{r,2030}$ are the total population and GDP in province *r* in the target year 2030 respectively; where $P_{r,2019}$ and $GDP_{r,2019}$ are the total population and GDP in province *r* in the base year 2019 respectively; g^P and g^{GDP} are the annual average growth rate of total population and GDP in province *r*; P_{UN} and GDP_{OECD} are the total population in China from the UN projection and OECD projection. Using the projected total GDP and population, we can obtain future GDP per capita in 30 provinces.

Then based on the decoupling value of 30 provinces in different scenarios, we estimate the emissions in 2030 as:

$$C_{r,2030} = C_{r,2019} * (1 + g_r^C)^{11} \tag{11-1}$$

$$g_r^C = D_{r,2030} \times g_r^Y \tag{11-1}$$

$$g_r^Y = \sqrt[n]{(1+R)} - 1 \tag{11-2}$$

where *R* is the total change rate of GDP per capita in province *r*; g_r^Y and g_r^C are the compound annual change rate of GDP per capita and emissions per capita in province *r*; $D_{r,2030}$ is decoupling status of province *r* in 2030; $C_{r,2019}$ and $C_{r,2030}$ are the total emissions of province *r* in 2018 and 2030 respectively. Finally, we define the "emissions gap" as the difference in emissions between the two of three scenarios, using the Pessimistic scenario and Median scenario as an example:

$$EG = C_{pes,2030} - C_{med,2030} \tag{12}$$

3.5 Data sources

To discover the connection between CO_2 emissions and economic development at national, regional, and provincial levels in China, data on total carbon dioxide emissions for 30 Chinese provinces from 1997 to 2019 were collected from Carbon Emission Accounts and Datasets (CEADs). The individual drivers of carbon emission decoupling were collected from the National Bureau of Statistics and the Provincial Statistical Yearbook.

4 Results

4.1 Historical economy-emissions pattern

Figure 1a illustrates the trajectory of the national decoupling values for the period 1998-2019. The decoupling value increased between 1998-2003, from a strong decoupling in 1998 (-0.087) to an expansive negative decoupling (1.253). This means that the growth rate of emissions per capita gradually surpassed the growth rate of GDP per capita, reflecting the arduousness of China's emissions reduction during the economic development process. The period from 2003 to 2016 shows a somewhat mitigated trend of increasing decoupling, reaching a strong decoupling again in 2016 (-0.125). This is because that Chinese government actively implemented sustainable development policies to relieve the great pressure from CO_2 emissions increase. For example, the Chinese government pledged to the international community in November 2015 that China would reach peak CO2 emissions around 2030 and work to achieve this goal as soon as possible. However, during the period between 2016 and 2019, the decoupling value again shows an increasing state, such that China was in expansive negative decoupling state in 2019. This represents a decoupling for emissions since the 2016 have not been as persistent. An ideal decoupling state of emissions is only temporary through a short-term tradeoff between economic development and environmentally friendly performance.

As can be seen from Figure 1b, the decoupling index of the 30 Chinese provinces are mainly weak decoupling, and the degree of decoupling improved with increasing years. In the earlier part of the study period, the degree of decoupling was higher in Chinese provinces which means that the economic-emissions nexus is weaker. The decoupling in the provinces was similar to the national situation and this may be also due to the fact that China's economy was less developed and slower in the early period. While the decoupling index decreased in the middle period as the economic growth rate improved at a high rate. In the middle and late stages of the study period, China placed more emphasis on the quality of economic growth rather than the speed of growth, and at the same time further emphasizing energy conservation and energy structure optimization and implementing four "energy revolutions". Therefore, the degree of decoupling increased and reached strong decoupling in some provinces during this phase. Overall, Figures 1a and 1b analyze decoupling for the country and provinces, respectively, but the two always correspond to each other and to China's economic conditions during the study period.

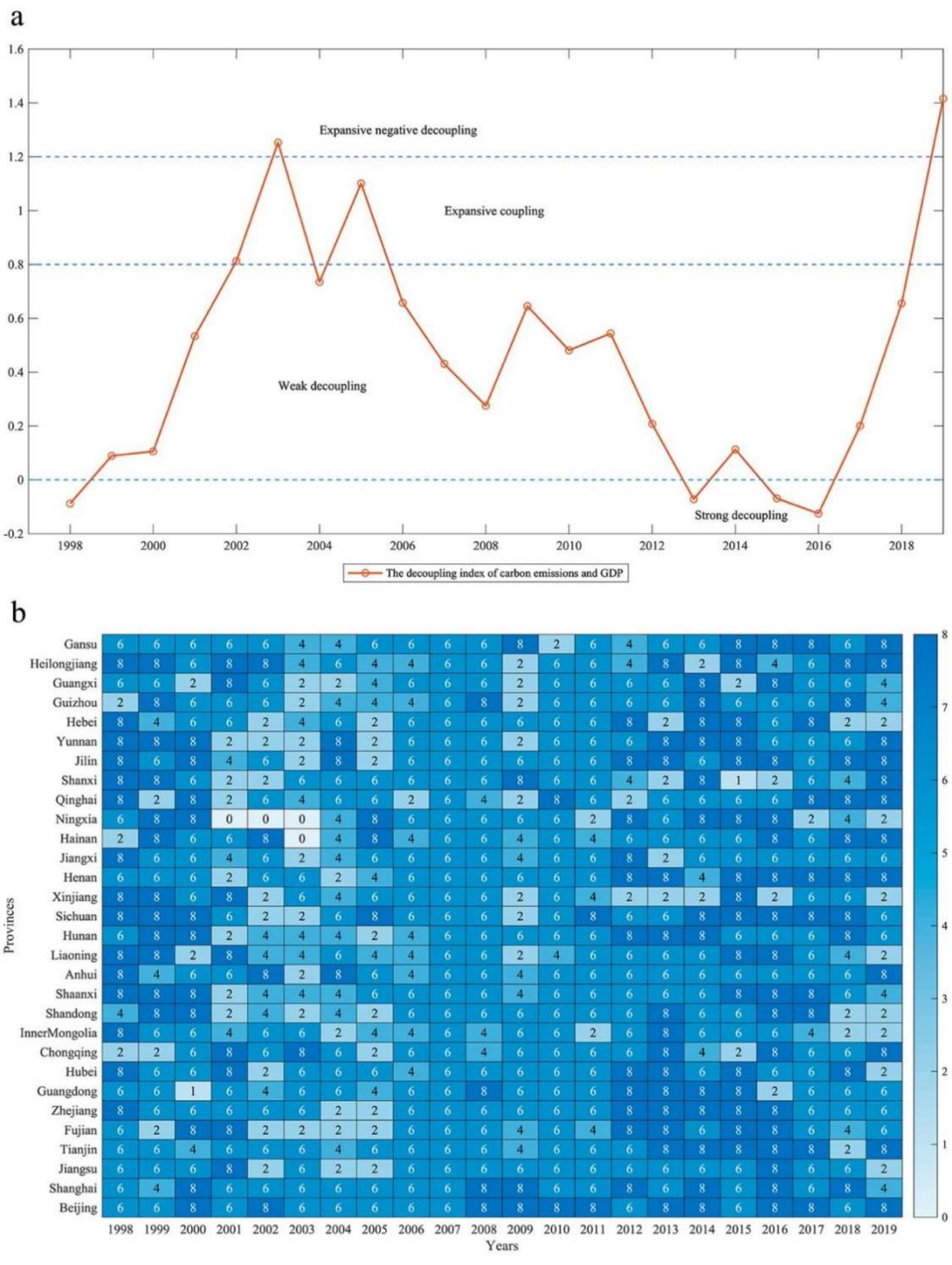


Figure 1. Decoupling index during 1997-2019 (a) At the national level. (b) At the provincial level. Note: Numbers in the Figure 1(b) shows the different decoupling states. 0: No data, 1: Recessive decoupling, 2: Expansive negative decoupling, 3: Recessive coupling, 4: Expansive coupling, 5: Weak negative decoupling, 6: Weak decoupling, 7: Strong negative decoupling, 8: Strong decoupling

Figure 2a clearly shows that the economic-emissions nexus at the national level is generally positive and nonlinear during the whole period, indicating that carbon emissions increase was closely related to economic growth. Throughout the period from 1997 to 2019, we can find that there is a cubic relationship between emissions and economic development, and two turning points occurred in the years of 2012 and 2016. The first period (1997-2012) saw rapid growth in emissions, and the higher slope line (0.015) implies that 0.015 tons of emissions per capita was needed to support GDP growth of 100 per capita. The DI score of 0.41 in the period of 1997-2012 is a weak decoupling state. In the period of 2012-2016, the emissions grew relatively slowly, which can be derived from the flatter slope coefficient (0.0005) and DI score (0.03), representing a weak decoupling. The period of 2016-2018 with a slightly flatter slope of 0.0083 compared with the period of 1997-2012 shows a weak decoupling (0.71).

The economic-energy model is diverse at the regional level. We divided 30 provinces into 5 regions according to the level of GDP per capita and conducted an EKC test based on the data of carbon emissions per capita and GDP per capita for each region (Figure 2b-f). This means that we examine whether a cubic relationship is showed in each region, and if none, then we analyze the existence of inverted U-shaped relationship. All five regions showed a cubic linear trend. The inverse "U" shape of the EKC curve was not significant, and CO_2 emissions were not increasing with the growth of GDP. The subplots for all five regions passed the cubic better fit, and the goodness-of-fit was above 0.98. Comparing the slopes of the cubic terms of the five plots shows that the regions with lower overall GDP per capita had larger slopes. Only the "Lowest" region had a slope of 0.002, while the slope of the other regions gradually decreased. This indicates that the lower the correlation between the economy and carbon emissions in regions with higher GDP per capita, the greater the degree of decoupling.

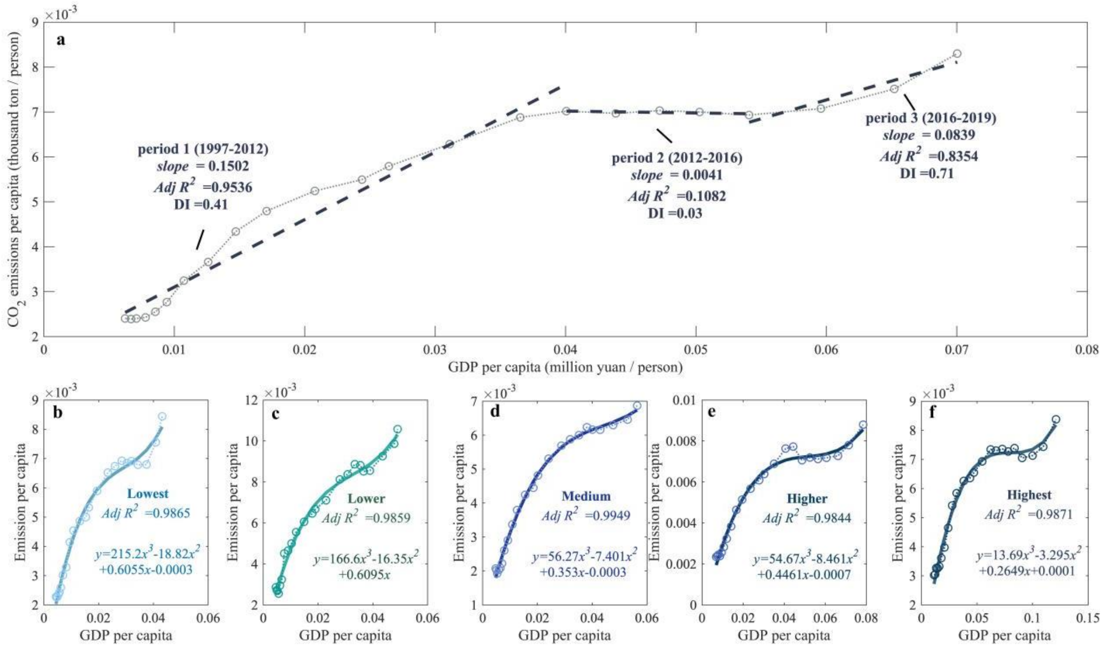


Figure 2. Economy–emissions nexus. (a) at the national level during 1997-2019. (b-f) at the regional level during 1997-2019. Note: the regions are divided by the level of GDP per capita. The 5 regions are aligned following an ascending order by GDP per capita in 2019.

We also developed an EKC test based on the data of carbon emissions per capita and GDP per capita in each province (Figure 3). The results illustrate that there were 15 provinces with a cubic relationship, noting that there are two turning points, such as Beijing, Tianjin and Shanghai. These are economically developed regions in China, where low-carbon development mechanisms are better developed, and also have advantages in energy efficiency, technologies, and industrial structure. For example, Beijing and Shanghai are the international metropolises in China, and have experienced rapid technological and economic development in recent years. The relationship between economic development and emissions in these regions has reached a better state. In addition, 13 provinces have a significant inverted U-shaped relationship with a good fit, indicating that CO_2 emissions do not continue to increase but rather decrease when the economy reaches a certain level of development. Several provinces (e.g., Jilin, Anhui, Hainan and Sichuan) with one turning point have already reached the inflection, while others have not yet reached, such as Liaoning, Qinghai and Ningxia. These provinces with one turning points are mostly less developed, as their GDP per capita levels are largely backward. Since the production technology and environmental awareness are far behind the provinces with two tuning points, the decoupling relationship of provinces with only one inflection point has not yet reached an ideal state. Furthermore, two provinces, Heilongjiang and Xinjiang, do not have a turning point. This also means that in these two provinces carbon emissions and economic growth are exactly the same situation. These two provinces are also relatively backward provinces in China. Xinjiang is located in the northwest of China, with low industrial development and slow economic development due to special events. Heilongjiang, located in the eastern provinces, is a typical old industrial base with relatively lower production efficiency, higher energy consumption and single industrial structure.

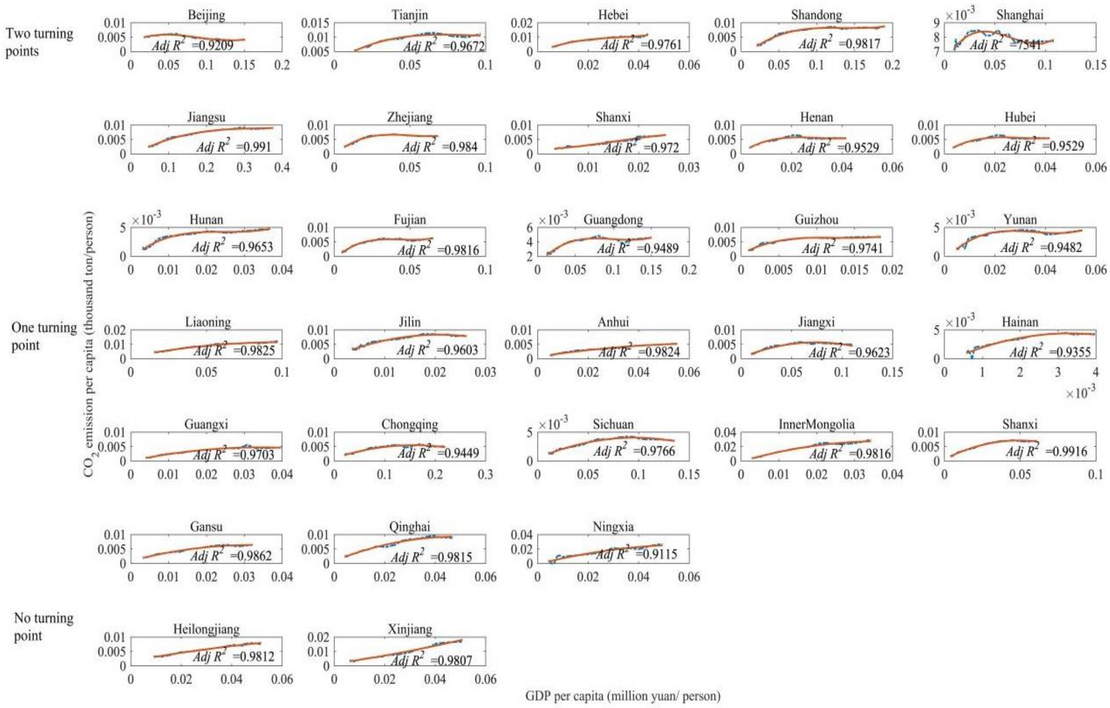


Figure 3 The fitted result of GDP per capita and emissions in 30 provinces in 2019. The 30 provinces are aligned following an ascending order by GDP per capita in 2019.

To illustrate the spatial distribution of the turning points, the results obtained from the above samples were plotted on a map of China (see Figure 4). We find that most of the northwestern and northeast regions had an inverted U-shaped relationship between per capita carbon emission and GDP per capita, while the southeastern region was likely to have two turning points. Provinces with two inflection points were relatively more economically developed, which were generally located in the eastern coastal region and Beijing-Tianjin-Hebei urban area. This is consistent with the huge gap in the economic development between the north and the south of China. For the relatively economically backward regions with only one inflection point, they were mainly distributed in the eastern region. Finally, Xinjiang and Heilongjiang located in the northwestern and northeastern regions, respectively. Affected by the single economic structure, and geographical reasons with the inland, the economic development was sluggish and there was no EKC curve.

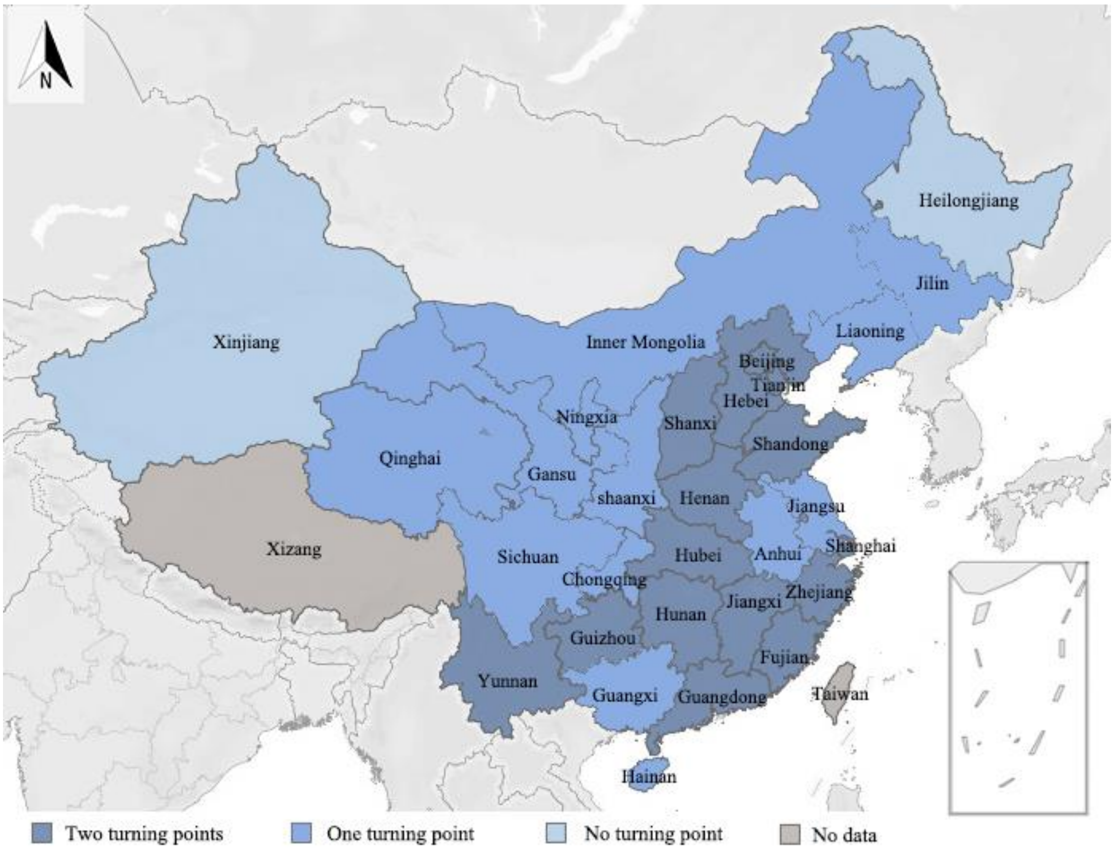


Figure 4 Results of turning year of 30 provinces in Chinese map.

Next, the results of turning point and turning year for the 30 provinces are shown in Table 3, presenting in order by numbers of turning points. 28 of the 30 provinces (93.33%) support the EKC hypothesis. This suggests that economic growth was positively correlated with carbon emissions at the beginning, but after reaching the threshold level of economic growth, carbon emissions will decline as the economy grows. This also reveals that past economic growth increased carbon emissions but improved the environmental quality by reducing carbon emissions after the turning point. Among these 28 EKC exists provinces, 16 provinces (57.14%) reached the turning point during the survey period. For example, Beijing reached the turning point in 2008, Shanghai in 2012, Zhejiang in 2017, Anhui in 2010, and Sichuan in 2021. This demonstrates that economic growth has led to a decline in carbon emissions per capita in these provinces, which may be the result of a massive transition to low-carbon technologies in the manufacturing and construction sectors in these provinces. However, 12 regions have yet to reach the turning point, such as Gansu, Guangxi, Hebei, Shanxi, Qinghai, and Liaoning. Among these provinces, Liaoning needs to take 62 years to reach the turning point of carbon emissions per capita, which is the longest time required, followed by Gansu, which takes 30 years, Qinghai takes 25 years, and Inner Mongolia 24 years.

Table 3. Turning points and the turning years for 30 provinces.

Type	Province	EKC	TP	TY
Two Turning points	Beijing	EKC exists and TY>0	3.98	2008
	Tianjin	EKC exists and TY>0	9.78	2023
	Hubei	EKC exists and TY>0	6.34	2020
	Shandong	EKC exists and TY>0	5.86	2020
	Shanghai	EKC exists and TY>0	7.18	2013
	Jiangsu	EKC exists and TY>0	34.23	2031
	Zhejiang	EKC exists and TY>0	6.83	2018
	Shanxi	EKC exists and TY>0	15.99	2033
	Henan	EKC exists and TY>0	3.57	2018
	Hubei	EKC exists and TY>0	6.34	2020
	Hunan	EKC exists and TY>0	5.45	2021
	Fujian	EKC exists and TY>0	7.53	2019
	Guangdong	EKC exists and TY>0	6.95	2019
	Guizhou	EKC exists and TY>0	4.01	2021
	Yunnan	EKC exists and TY>0	2.83	2017
One Turning point	Liaoning	EKC exists and TY>0	1316.88	2084
	Jilin	EKC exists and TY>0	2.31	2015
	Anhui	EKC exists and TY>0	1.46	2011
	Jiangxi	EKC exists and TY>0	45.14	2040
	Hainan	EKC exists and TY>0	5.37	2021
	Guangxi	EKC exists and TY>0	8.29	2028
	Chongqing	EKC exists and TY>0	10.15	2024
	Sichuan	EKC exists and TY>0	5.54	2022
	Inner Mongolia	EKC exists and TY>0	134.17	2047
	Shaanxi	EKC exists and TY>0	40.46	2035
	Gansu	EKC exists and TY>0	90.46	2053
	Qinghai	EKC exists and TY>0	88.25	2047
	Ningxia	EKC exists and TY>0	16.05	2031

No turning point	Xinjiang	EKC does not exist	-	-
	Heilongjiang	EKC does not exist	-	-

We are also interested in the threshold effect of economic development on emissions by investigating the existence of a nonlinear economy-emissions relationship. In Table 4, the regression results are given for a sample of 30 provinces in China. The results show that the single-threshold model, double-threshold and triple-threshold models are significant, so there is a triple-threshold effect of GDP per capita on carbon emissions per capita. Turning points exist at the threshold values of 1.39, 191, and 2.36, which can further confirm the existence of EKC.

Table 4. Model specification test results.

Threshold type	Estimator of threshold	LR test of thresholds
Single threshold	1.91	211.26***
Double threshold	1.39	53.55**
	1.91	
Triple threshold	1.39	103.12***
	1.91	
	2.36	

Note: ***, **, and * denote coefficients that are significant at the 1%, 5% and 10% significance levels, respectively.

4.2 Economic and other driving factors

Economic growth and other factors driving energy use were examined from 1997 to 2019 through the Kaya characteristic and the LMDI decomposition method. Figure 4a shows the results of this 21-year nationwide decomposition, during which the national total carbon emissions increased from 2935.8 Mt in 1997 to 11623.55 Mt in 2019, with an annual growth rate of 6.77% yr^{-1}. It can be clearly seen that the first stage has the highest annual growth rate of 7.62% yr^{-1}, followed by the third stage 4.86% $yr^{-1}$and the lowest is the second stage 0.53% yr^{-1}. Throughout the study period, total population effect, GDP per capita effect, renewable energy-energy substitution effect, effect of electrification on emissions, power generation efficiency on emissions, investment efficiency effect together drove the total carbon emission increase. On the other hand, the energy intensity effect, fossil fuels-renewable energy substitution effect, the ratio of investment scale to carbon emissions change together offset part of the carbon emission growth.

The GDP per capita effect was the dominant factor in the growth of carbon emissions in China in the first phase. In the first stage (1997-2012) China's GDP per capita had an effect of 170.48% yr^{-1} on the increase of carbon emission per capita. In the early stage of economic development, it was more common for carbon emissions to maintain a high correlation with economic output. In the second and third stages, the effect of increasing economic output on the increase of carbon emission per capita was weakened, producing an increase effect of 8.06% yr^{-1} and 8.70% yr^{-1}, respectively. The weakening effect was closely related to the degree of China's economic development. In the first stage, China's economy was growing at a high rate, and a new situation emerged in 2001 when China joined the WTO and the economy fully recovered. In the second phase, the Chinese economy slowed down and was shifting from a high-growth model to a sustainable, high-quality model. China's economic restructuring and energy saving were the result of a development strategy that focused much on quality and efficiency.

The investment efficiency effect was the second most significant contributor to the growth of carbon emissions during the period 1997 to 2012. In parallel with the economic slowdown and the significant decrease in the effect of increased economic output after 2012, the investment efficiency effect decreased from 112% yr^{-1} to 9.16% yr^{-1} in the second stage. Even in the third stage investment efficiency shifted to a slight inhibitory effect of -0.26% yr^{-1}. This may be due to the fact that although an increase in investment may promote a relative increase in cumulative GDP growth, it also promotes an increase in production technology research and development, input application and environmental awareness, thus reducing carbon emissions. Population size also had an effect on the growth of carbon emissions in the country during this period, but the effect was small compared to other factors. The effect of population on the growth of carbon emissions was 0.67% yr^{-1}, 0.62% yr^{-1} and 0.42% yr^{-1} in the three phases of the study period, respectively, with a decreasing trend since 1997. This may be due to the fact that the population growth rate in China is influenced by the domestic family planning policy, although the population effect always has a positive driving effect on environmental pressure, but its degree of influence was gradually weakening.

The scale of investment, on the other hand, was the most significant inhibitor of carbon emission growth in the first stage (-140.26% yr^{-1}). However, the inhibitory effect of investment size on carbon emissions had a significant decrease in the second and third stages. The energy intensity was the second most significant inhibiting factor in the first stage, with a 69.99% yr^{-1} inhibiting effect on carbon emissions. In the first stage, the energy intensity effect was significant probably due to the introduction and development of energy-saving and consumption-reducing technologies in China. However, the huge energy consumption brought by the rapid economic development weakened the second phase of energy intensity suppression of emissions. The energy intensity effect was also reduced to -6.12% yr^{-1}. In contrast, the energy intensity effect in the third stage changes from suppression to promotion (+26.92% yr^{-1}) with the increase of energy consumption compared to the second stage.

The substitution effect of fossil fuel consumption, which was the main source of the increase in CO_2 emissions, is bound to have some impact on carbon emissions. This is because different types of energy sources have different carbon emission factors and fossil fuels were the highest one. The increase in the proportion of renewable energy will certainly accelerate the leapfrog development of China's energy structure from coal-fired to clean and low-carbon. The renewable energy substitution effect and the fossil fuel renewable energy substitution effect presented a boost and a dampening effect on the growth of carbon emissions in the first two stages, respectively, but the effects of the two largely cancelled each other out. In the third stage, they had a greater effect, but in the opposite direction from the first two stages. Overall, the renewable energy substitution effect and the fossil fuel renewable energy effect were similar in value and opposite in direction, and had a smaller impact on the overall carbon emission change.

The effect of electrification on emissions was not significant in the first two phases showing slight growth and suppression benefits (+7.29% yr^{-1} and -0.95% yr^{-1}), but in the third phase electrification had a significant growth suppression effect on emissions. The development of the power sector had significantly increased carbon emissions, with national electricity generation increasing year by year in recent years. The share of energy-efficient and environmentally friendly generating units had steadily increased by improving the technology level of mainly coal-fired power generation, which has helped to improve the energy efficiency level. The electrification of end-use energy consumption had been rapidly developed in China during industrialization and urbanization, and it will directly affect CO_2 emissions. The electrification level has increased significantly from 14% in 1997 to 22% in 2016 (IEA, 2020). In 2016, the National Development and Reform Commission and eight other departments jointly issued the Guidance on Promoting Electric Energy Substitution to improve the supporting policy system of electric energy substitution and promote the trend of electric energy substitution. In the subsequent third phase (2016-2019), the electrification produced a dampening effect of up to 21.64% yr^{-1}on the increase of total carbon emissions. The power generation efficiency had a significant impact on the reduction of carbon emissions. However, the impact of power generation efficiency on emissions diminishes throughout the study period, from +18.59% yr^{-1}, +4.66% yr^{-1} to +1.70% yr^{-1} boost.

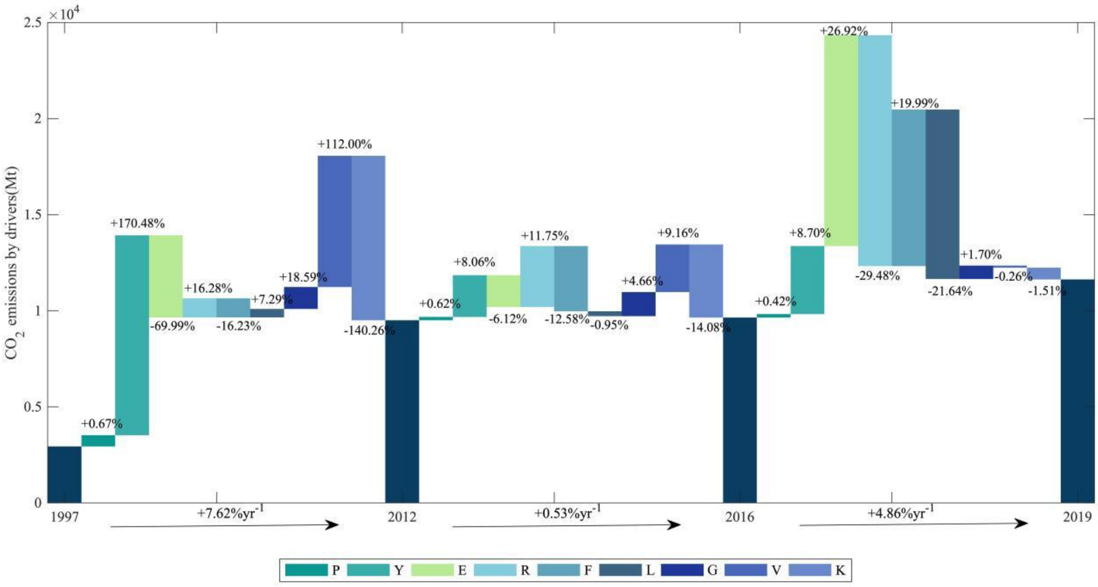
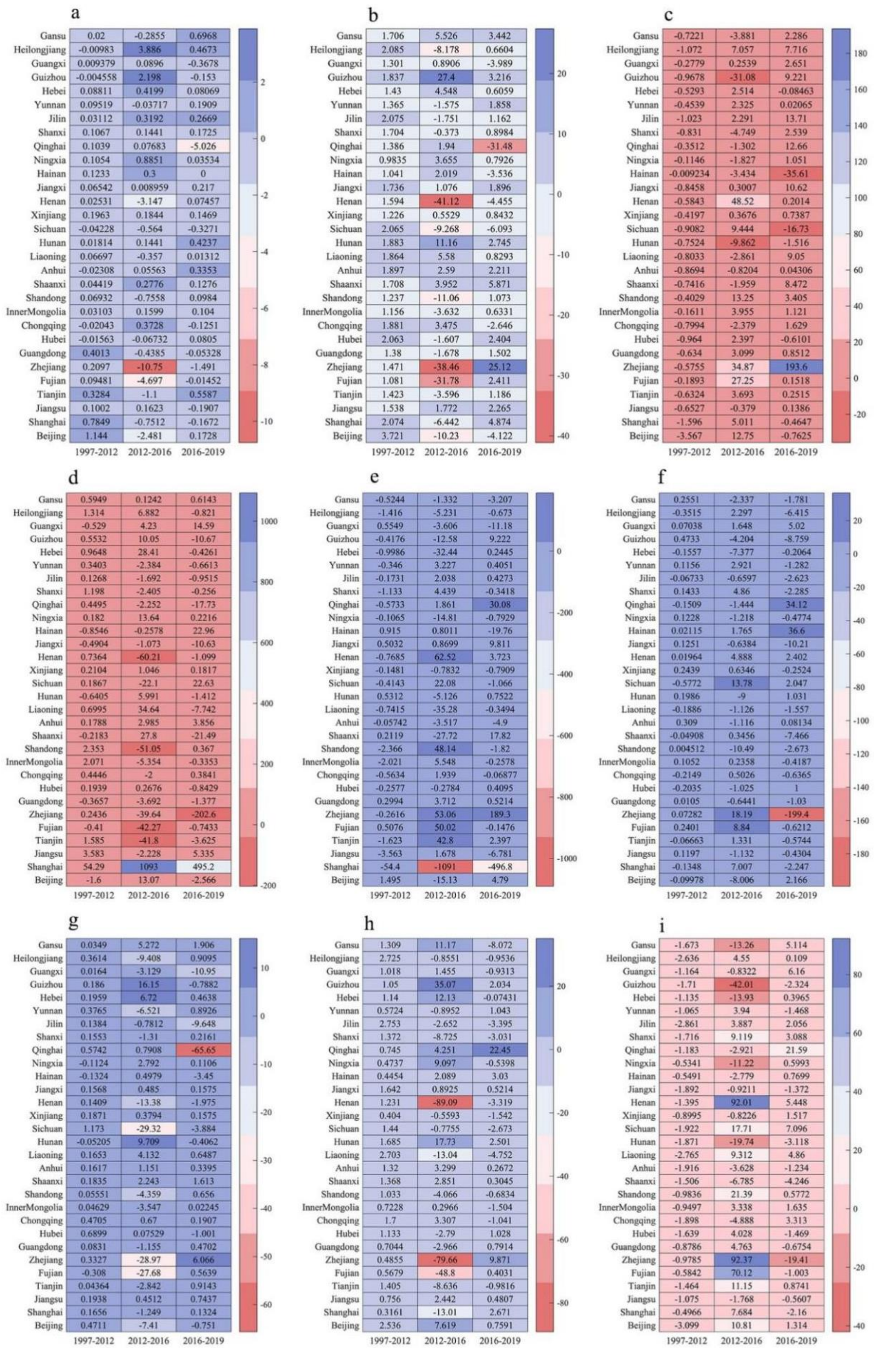


Figure 5. National contributions of driving factors during 1997-2019. Note: as the number of years is not the same in both periods, we display compound annual growth or reduction. The

compound annual rate of total emissions (r) is related to the total rate (R) across n years as $r = \sqrt[n]{(1+R)}$-1, and compound annual contribution of a given factor (k) is $r \times S_k$ where S_k is the share of the contribution of the factor during the whole period.

Figure 6a reveals that in developed regions such as Beijing and Shanghai were blue in most intervals and the population-driven carbon emissions have weakened, while other less developed regions experienced an increasing in CO_2 emissions because of population growth. Figure 5b illustrates that Qinghai, Henan, Zhejiang, and Fujian showed red color in some periods (especially in the second stage), which implies that their carbon emissions decreased with the growth of GDP per capita. In contrast, most of the other blue markers became darker over time, signifying a large increase in carbon emissions due to GDP per capita growth. In Figure 5c, Zhejiang shifted from red to blue at three stages, indicating that the energy intensity shifted from a negative to a facilitative effect on carbon emissions. From Figure 5d it can be seen that renewable energy-energy substitution basically maintained a long-term inhibitory effect on carbon emission growth in all three stages in each province, except for Shanghai. Figure 5e-h shows the long-term effects of fossil fuels-renewable energy substitution, electrification on emissions, power generation efficiency on emissions. In the long run, the contribution of investment efficiency to the increase in carbon emissions was demonstrated. Throughout the study period, most of the provinces were dominated by blue areas, with only the inhibitory effect of increasing carbon emissions in individual provinces. In Figure 5i, the ratio of investment scale to carbon emissions in the first and third phases demonstrated similar inhibitory effects on the increase of carbon emissions.

452 

453 **Figure 6.** Contributions by provinces during 1997–2018. (a) Total population effect. (b) GDP per
454 capita effect. (c) Energy intensity effect. (d) Renewable energy-energy substitution effect. (e)
455 Fossil fuels-renewable energy substitution effect. (f) effect of electrification on emissions. (g)

Power generation efficiency on emissions. (h) Investment efficiency effect. (i) The ratio of investment scale to carbon emissions. Note: numbers reflect the compound annual contribution of a given factor to the emissions change during the whole period, which can be calculated referring to the method in Figure 5.

4.3 Future perspective of economy-emissions pattern by 2030

In Figure 7, in the Pessimistic scenario (S1) with the decoupling state unchanged, the total carbon emissions in 2030 are 11623.55 Mt, 73.97% higher than the level for 2019. However, when the decoupling state of all provinces shift to the strong decoupling with a value 0.51, the carbon emissions in the Median Scenario (S2) are 10551.84 Mt. This is a significant decrease compared to the S1 and is similar to the total carbon emissions in 2019. When using the best decoupling level among all provinces, i.e., a D value of -2.15, the total emissions in the S3 are 5213.54Mt, which is almost half of the amount of 2019.

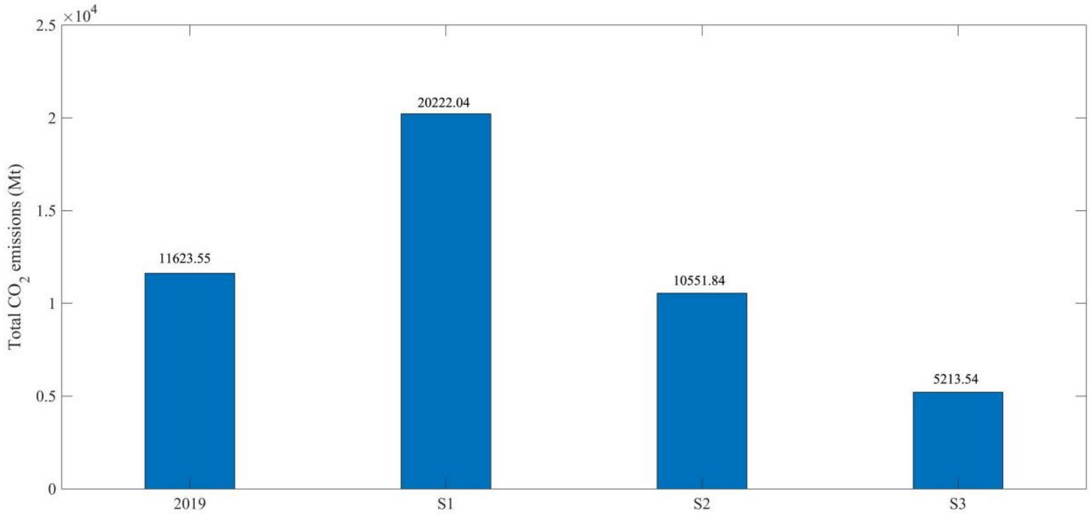


Figure 7. China's CO_2 Emissions in the three scenarios. S1: Pessimistic scenario, S2: Median scenario, S3: Optimistic scenario.

There are no provinces in the 'Higher' region and 'Highest' region where the total carbon emission in 2030 in the S1 are smaller than the current levels in 2019, implying that under current economy-emission patterns, the future emissions of these provinces are somewhat worrisome. While the national total carbon emissions with the 2019 situation increased by 8598.49Mt is mainly derived from some areas with significant growth in carbon emissions, such as Shanxi increased by 103807.74Mt, Inner Mongolia by 3776.60Mt, Jiangsu by 428.43Mt, Xinjiang by 328.40Mt, Shandong by 324.95Mt. There are still some provinces in the other three regions where total carbon emissions decrease in 2030 compared to 2019, such as Gansu (170Mt to 60Mt), Hebei (1106Mt to 904Mt), Qinghai (51Mt to 23Mt), Hunan (322Mt to 198Mt), and Anhui (417Mt to 248Mt). The decoupling levels in these regions are relatively high, and the total carbon emissions from future development have been reduced with the current decoupling status. However, there are fewer provinces with some decrease in carbon emissions, mainly increasing total carbon emissions, so the number of carbon emissions in the country increase significantly. In the S2, the six provinces mentioned above still maintain the same value of total carbon emissions as in the S1. And it can be significantly seen that other provinces decrease in total carbon emissions, such as Inner Mongolia decreases from 4637Mt in S1 to 679Mt in S2, and Tianjin decreases from 437Mt to 133Mt. Provinces such as Shanxi, Inner Mongolia, Jilin, etc. are likewise the provinces that contribute the most to the reduction of total carbon emissions nationwide. Compared with the total carbon emissions of each province in 2019, the values in 2030 in S2 remain basically the same or decrease. This means that when the decoupling level of each province reaches this level, the emissions will not grow any more, which is a better state. And in the S3, we optimize the decoupling degree further, and all provinces reach the optimal state of the current decoupling level. The Figure 6 shows that most provinces in the S3 reduce their emissions to roughly 1/2 of those in the S2, which is a very optimistic emissions state for the future. For example, from the S2 to the S3, Heilongjiang, Shaanxi and Beijing decreases from 220Mt, 260Mt and 79Mt to 56Mt, 113Mt and to 41.5 Mt respectively.

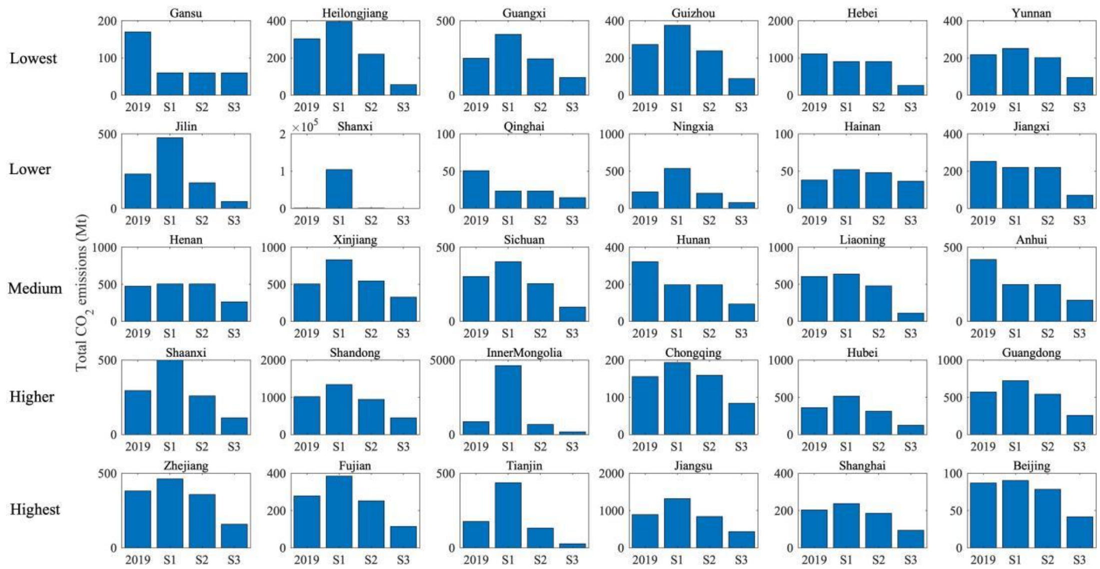


Figure 8 CO_2 Emissions in the three scenarios for 30 provinces. Noted: S1: Pessimistic scenario, S2: Median scenario, S3: Optimistic scenario. The 30 provinces are divided into five regions by the level of GDP per capita in 2019 and aligned following an ascending order by GDP per capita in 2019.

5. Conclusions and policy implications

5.1. Conclusions

We investigated the economy-emissions pattern by the decoupling analysis, the EKC model and panel threshold regression model at the national and provincial level over the period 1997 to 2019. The national decoupling trend had eased since 1997 and reached a strong decoupling again in 2016. However, the decoupling of emissions had not been sustained, and the ideal state of decoupling of emissions was temporary. The decoupling index for the 30 Chinese provinces was mainly weak decoupling, with the degree of decoupling increasing with each year. In addition, 15 provinces had two turning points, 13 provinces had one turning point, and Heilongjiang and Xinjiang had no turning points. We highlighted that the lower the correlation between economy and carbon emissions, the greater the decoupling in regions with higher GDP per capita.

We also investigated the drivers of carbon decoupling, using the LMDI analysis to assess the situation across China. The GDP per capita was the dominant factor in carbon emission growth in the first stage (1997-2012), while the effect of economic output growth on carbon emission growth per capita diminished afterwards, which was closely related to the degree of China's economic development. The investment efficiency was the second largest contributor to carbon emission growth in the first period, and the effect was significantly weakened or even transformed into a slight inhibitory effect in the subsequent period. The increase in investment contributed to the cumulative GDP growth and the increase in production technology research and development, thus resulting in the reduction of carbon emissions. Investment size and energy intensity were the most significant inhibitors of carbon emission growth in the first stage, but the inhibitory effects both significantly reduced in the subsequent phases. And the initial effect of electrification on emissions was not significant, showing a slight growth and inhibition benefit, but in the third stage (2016-2019), the electrification had a significant growth inhibition effect on emissions. In addition, the renewable energy substitution and the fossil fuel renewable energy had been similar in value and opposite in direction in different stages, and both had small impact on the carbon emission changes.

We also constructed three scenarios to analyze the future impacts of emission-economy decoupling on emissions. At the national level, the total carbon emissions in the Pessimistic Scenario (S1) would increase by 73.97% compared to the level of 2019. In contrast, the total carbon emissions in the S2 are approximately the same as those in 2019. The total emissions in the S3 are almost half of the amount of 2019. At the regional level, the significant increase the emissions in the S1 is mainly derived from the large increase in emissions in several less developed provinces, including Shanxi, Inner Mongolia, Jiangsu, Xinjiang, and Shandong. In the S2, the emissions in most provinces decrease, and Shanxi, Inner Mongolia, and Jilin are the provinces that contribute the most to such decrease. In the S3, most provinces reduce their emissions to about half of the S2.

5.2. Policy implications

Overall, China has experienced significant economic growth and is gradually optimizing its economic structure and improving energy efficiency. However, since China has not yet achieved a sustained state of desirable emissions decoupling, a better comprehension of the correlation between past and current carbon emissions and economic development help the government to make appropriate decisions and strategies. According to the above findings, we make the relevant recommendations.

First, the government should increase the policy efforts to promote electrification and better utilize the curbing benefits of electrification on carbon emissions, e.g., promote the process of electrification in some regions, introduce incentives for electric energy substitution, and allocate clean energy more comprehensively. While focusing on electrification development, it is more important to focus on the low carbonization of electricity and to achieve as much clean energy-based electricity development as possible.

Secondly, China should continuously promote the optimization and transformation of industrial structure and realize the reform of energy system mechanism. Improve the policy and incentive mechanism of industrial structure optimization and upgrading, establish a fair market competition environment, and strengthen the supervision of high energy consumption and high pollution industries have a greater impact on reducing carbon emissions. The government should adjust the layout of industrial structure, develop low-carbon agriculture, and increase the proportion of tertiary industry in the national economy. At the same time, it should promote the integration of resources in heavy industry and further adjust the industrial structure. The state should emphasize on relevant policies so as to also strengthen the residents' relevant emission reduction concepts and achieve better reasonable green consumption.

Third, the government should increase investment to reduce the increase of carbon emissions through technological innovation. Technological progress is a significant limiting factor for energy restructuring and energy efficiency improvement. Coal-based fossil energy still accounts for a large share of China's energy use, and for energy structure optimization may lie more in the development and use of renewable energy. The shift in the role of energy mix from facilitation to suppression of carbon emissions growth from LMDI decomposition suggests that accelerating energy mix adjustment is conducive to better control of carbon emissions. The development and planning of clean energy is crucial, and China's 14th Five-Year Plan clearly requires that the share of non-fossil energy in energy consumption be increased to about 20% by 2035. The current restrictions on the development of renewable energy mainly stem from technical limitations, and the instability of wind power, light, tidal energy and other energy sources at this stage makes it difficult to completely get rid of the dependence on fossil energy in the short term. Relevant Chinese departments should specifically and precisely increase funding for clean energy development. Combined with the current situation of China's energy reserves, the energy development strategy should be improved to the maximum extent without affecting the economic growth and dirty situation. Along with energy restructuring, energy efficiency improvements are an important means of reducing emissions. The government should expand research and development in energy efficiency and promote the industry to form a production scale.

Statements & Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

All authors contributed to the study conception and design. Specific contributions for each author are below.

Jiayang Chen: Conceptualization, Data curation, Formal analysis, Methodology, Software, Investigation, Writing-original draft.

Rong Yuan: Conceptualization, Methodology, Writing-review, Editing, Supervision.

Shenglin Zheng: Data curation, Methodology.

Funding

This work is financially supported by the Major Project of the National Social Science Foundation of China (19ZDA082), the Young Project of the National Natural Science Foundation of China (72103027).

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request. All data generated or analyzed during this study are included in this published article.

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