

Analyzing Driving Forces of China's Carbon Emissions From 1997-2040 and the Potential Emission Reduction Path: Through Decomposition and Scenario Analyses

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Analyzing driving forces of China's carbon emissions from 1997-2040 and the potential emission reduction path: Through decomposition and scenario analyses

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Abstract

To assess the evolution trend of China's carbon emissions (CEs) and related driving factors, this paper used scenario analysis to predict China's CEs from 2017 to 2040 at the industrial level. Then, LMDI decomposition model was applied to evaluate the driving forces of CEs changes during 1997-2040. Finally, the ST-LMDI model was used to explore the CEs reduction potential and the potential reduction path at provincial level. The results showed that (1) as the reduction of energy intensity cannot offset the growth of industrial scale, the CEs of all industries have shown an increasing trend from 1997 to 2017; (2) In the current policy scenario, China's CEs cannot reach the peak before 2040. And only in the sustainable development scenario, the CEs of the three industries will all reach the peaks before 2030. And the development of non-fossil energy will reduce CEs by more than 30%; (3) Hebei, Shanxi, Inner Mongolia, Ningxia, and Heilongjiang are key provinces and improving energy efficiency of the secondary industry is a potential way to promote CEs reduction.

Key Words: carbon emissions, decomposition model, scenario analysis, provincial analysis

1. Introduction

China's economy has grown rapidly in recent decades and has become the second largest economy in the world (Jiang et al., 2018). However it also brings serious environmental problems. In 2009, China surpassed the United States to become the world's largest carbon emitter (Wang et al., 2010). In 2017, total CEs in China were 9866Mtons, accounting for 30.05% of the global total (IEA, 2018). Resources and environmental problems have brought huge potential threatens to the sustainable development of China (Liu et al., 2018). Faced with increasingly serious environmental problems, the Chinese government has issued a series of policies aimed at energy consumption transformation and industrial structure optimization in an attempt to control the fossil fuel consumption and related CEs (Deng et al., 2019). In 2016, the State Council promulgated the "13th Five-Year Plan", requiring China to decrease the carbon intensity (CI) by 18% in 2020 compared to 2015 (NDRC, 2017). In 2017, the Chinese government promulgated the National Independent Contribution Program (INDC), promising to reduce CI by 60% to 65% from the 2005 level, and peaked China's CEs in 2030 (Yuan et al., 2018). In 2021, according to the 14th Five-Year Plan, China pledged to achieve carbon neutrality by 2060 (NDRC, 2021).

The implementation of a series of emission reduction policies has had a certain effect on restraining the growth of CEs of China (Ding et al., 2019; Wang et al., 2018a). From 2013 to 2017, China's CEs increased from 9492.9Mtons to 9866Mtons, with an average annual growth rate of 0.98%, which was much lower than the 7.61% during 1997-2013 (NBSC, 1998-2018b). This raised some questions: What are the characteristics of China's CEs at different stages? How will China's CEs change in the future? In different scenarios, what

are the main drivers for the dynamics of CEs? In addition, China has a huge territory. The industrial structure and resource endowments vary greatly among provinces. There are serious inequalities in CEs among provinces. In 2017, the five provinces with the largest CEs were Shandong (806Mtons), Jiangsu (736Mtons), Hebei (726Mtons), Inner Mongolia (639Mtons) and Guangdong (542Mtons), accounting for 34.96% of the national total. On the contrary, the five provinces with the least CEs were Hainan (42Mtons), Qinghai (53Mtons), Beijing (85Mtons), Tianjin (141Mtons), and Gansu (151Mtons), accounting for only 4.78% of the national total. Considering that CEs reduction targets are closely related to each province, evaluating the driving factors of provincial CEs changes and identifying potential ways to reduce CEs in each province is of great significance for achieving China's CEs reduction targets.

To solve the above problems, this paper first analyzed the evaluation trends and driving forces of China's and provincial CEs during 1997-2017. Then, three scenarios were constructed to estimate the evolution trend of China's CEs in different scenarios during 2017-2040. Furthermore, LMDI method was used to assess the main driving forces for the dynamics of China's CEs during 2017-2040. Finally, ST-LMDI model was used to evaluate the CEs reduction potential of each province in different scenarios. In particular, this paper analyzed the relative contribution of the proportion of fossil energy in total energy consumption to CEs to indirectly illustrate the effect of non-fossil energy consumption on CEs changes. As this paper covered main types of primary energy sources including fossil and non-fossil energy, impacts of technological progress and non-fossil energy substitution can be presented. This supplemented more detailed information for assessing the potential for future CEs reduction, and provided new evidences for relevant government departments to make decisions.

The reminder of this paper was as follows. Section 2 presents an overview of existing relevant research. Section 3 introduces Kaya identities, Scenario analysis, decomposition analysis and the data sources. Section 4 provides the results. And section 5 concludes the research and gives the policy recommendations.

2. Literature review

Many researchers have focused on the issue of China's CEs through different kinds of models such as decomposition (IDA and SDA) model (Huang et al., 2019; Wang and Zhou, 2018), STIRPAT model (Zhang et al., 2017; Zhang and Zhao, 2019), decoupling indicator (Tang et al., 2018; Wang et al., 2018b), and regression analysis (Long et al., 2017; Wen and Liu, 2016). Logarithmic Mean Divisia Index (LMDI) model was used by many scholars to identify the impact factors of CEs (Liu et al., 2019b; Zhang et al., 2018). (Li et al., 2017a; Liu et al., 2019a; Wang et al., 2015; Xu et al., 2014) analyzed influencing factor of China's CEs. The results showed that economic activity was the major force for the growth of CEs. (Chen et al., 2019; Li et al., 2017b; Wang et al., 2016a) explored the drivers of China's growth of CEs. Results showed that energy intensity was the dominant driver to restrain the growth of CEs. Previous studies have fully demonstrated that economic activity and energy intensity are the main driving forces in promoting and curbing China's growth of CEs. Furthermore, an increasing number of scholars have shifted their focus to CEs at the regional level. (Song et al., 2021) studied the dynamics of China's provincial CEs and found that the CEs center shifted from east to west China during 2000-2017. (Wang and Feng, 2017) explored the drivers of CEs changes at China's

75 provincial level and found that the influencing factors vary greatly among different provinces. (Jiang et al.,
76 2017) analyzed the differences in the impact factors of CEs growth of various provinces, and found that Shanxi,
77 Anhui, and Hebei have made increased contributions on China's growth of CEs.

78 These studies have conducted extensive discussions on historical CEs changes. However, there is limited
79 researches on the potential evaluation trends and driving factors of future CEs. (Zhang et al., 2019) assessed
80 the influencing forces affecting growth of CEs in China during 2000-2016, and estimated the decline trend in
81 CI in 2020 and 2030. It was found that energy intensity was the leading factor for CEs reduction, and industrial
82 structure optimization would have an important impact on 2020-2030 CEs reduction. (Sun et al., 2019) found
83 that benefiting from non-fossil energy consumption, China's CI can be reduced by up to 72.7% in 2030
84 compared to 2005. Some studies have predicted the CEs of a single province in China. (Zhang et al., 2017)
85 predicted that future emission pattern of Henan province will show an increasing initially and follows by a
86 downward trend, which mainly depended on the population growth rate and changes in per capita GDP. (Wang
87 et al., 2019) found that based on the continuous economic development and urbanization process, CEs in
88 Guangdong will maintain a growth trend in 2015-2030. (Qin et al., 2019) predicted the changes of CEs in
89 Xinjiang and found that its CEs will peak at 626.21-662.25Mtons in 2030-2040. (Yu et al., 2019) predicted
90 the CEs reduction in the Beijing-Tianjin-Hebei region up to 2030, and found that energy intensity is the key
91 driver for achieving CEs reduction targets. (Wang et al., 2018a) predicted the CI of six provinces of Southeast
92 coast of China, and found that by 2030, the CI of these provinces will be reduced by 59.1%-69.7% compared
93 to 2005.

94 However, existing research is insufficient in predicting China's sub-sectoral CEs and CI, and analyzing the
95 CEs reduction potential at the provincial level. In limited research, (Zhang et al., 2020) estimated the dynamic
96 trends of CEs in 30 provinces up to 2030, and found that most provinces can achieve the CEs reduction target.
97 (Sun et al., 2019) estimated that China's CI can be reduced by up to 72.7% in 2030 compared to 2005, and
98 Hebei, Shandong, Shanxi, Liaoning, Xinjiang, and Inner Mongolia were the key provinces. However, exciting
99 studies ignore the impact of non-fossil energy and the differences between sectors. Therefore, this paper
100 applied Kaya identities and scenario analysis to predict China's potential CEs of three sub-sectors during
101 2017-2040 and applied ST-LMDI model to evaluate the influencing factors of CEs reduction in each province.

102 This paper contributes the literature as follows. First, this paper combined the scenarios of IEA and OECD
103 with the Kaya identities to predict the trend of China's CEs during 2017 to 2040. Previous studies have mainly
104 emphasized the inter-industry differences in historical CEs. Few studies have predicted China's CEs by sectors.
105 Then, this paper applied LMDI method to evaluate the drivers of China's CEs in different scenarios from 2017
106 to 2040. Finally, ST-LMDI model was applied to explore the potential path for CEs reduction in provincial
107 level. In Particular, this paper considered both fossil and non-fossil energy so that the effects of technological
108 progress and non-fossil energy substitution can be revealed.

109 3. Methodology and data

110 3.1 Kaya identities

111 Kaya identities has been widely applied in the study related to CEs drivers. This paper utilized different

Kaya identities to study CEs at both national and provincial levels respectively. At national level, CEs was decomposed into six influencing factors including the carbon coefficient, fossil energy structure, energy consumption structure, energy intensity, activity, and population. At provincial level, to eliminate the influence of geographic factors, this paper chose CI as the research object. CI was decomposed into four drivers including carbon coefficient, fossil energy structure, energy consumption structure, and energy intensity.

$$CE = \sum_i CE_i = \sum_i \sum_n \frac{CE_{ni}}{F_{ni}} \times \frac{F_{ni}}{F_i} \times \frac{F_i}{E_i} \times \frac{E_i}{Q_i} \times P_i = \sum_i \sum_n CF_{ni} \times ES_{ni} \times T_i \times EI_i \times A_i \times P_i \quad (1)$$

$$CI_j = \frac{CE_j}{Q_j} = \sum_i \sum_n \frac{CE_{nij}}{F_{nij}} \times \frac{F_{nij}}{F_{ij}} \times \frac{F_{ij}}{E_{ij}} \times \frac{E_{ij}}{Q_{ij}} = \sum_i \sum_n CF_{nij} \times ES_{nij} \times T_{ij} \times EI_{ij} \quad (2)$$

The definition of each variables are shown in **Table 1**.

Table 1 The definition of each variables.

Variables	Definition	Variables	Definition
CE	Carbon emissions	ES	Fossil energy structure
CI	Carbon emissions GDP per capita	T	Energy consumption structure
F	Fossil energy consumption	EI	Energy intensity
E	Total energy consumption	A	Activity
Q	Gross domestic product	P	Population
CF	Carbon coefficient	r	Growth rate

Note: $n = 1, 2, \dots, 17$ represents the n type of fossil energy; $i = 1, 2, 3$ represents the i sector (Primary sector, Secondary sector, Tertiary sector); $j = 1, 2, \dots, 30$ represents the j province of China.

Where CI means carbon intensity, represented by CEs GDP per capita; E means total energy consumption, equal to the sum of fossil and non-fossil energy consumption; CF means carbon coefficient, equal to the ratio of CEs to energy consumption; ES means fossil energy structure, represented by the proportion of fuel coal, oil, and gas consumption in fossil energy consumption respectively; T means energy consumption structure, represented by the proportion of fossil energy consumption in total energy consumption; EI means energy intensity, represented by energy consumption GDP per capita; A means activity, represented by economic output; P means population, represented by the number of employed population.

3.2 Scenario analysis

Scenario analysis is a common method for predicting the future trend of CEs. (Cui et al., 2021) applied scenario analysis to predict the CI of five urban agglomerations in China in 2025. (Zhu et al., 2020) estimated the peak of CEs in China's transportation sector under three scenarios. (Niu et al., 2020) evaluates China's CI in 2030 under different scenarios and finds that under the BAU scenario, China cannot meet its 2030 CEs reduction commitments. According to the scenario analysis method, this study forecasted the CEs of China's three industries and related influencing factors from 2017 to 2040. In different scenarios, the prediction methods for GDP and population are consistent. The relevant forecast data of GDP and population growth rate come from OECD and UN respectively (OECD, 2019; UN, 2018). The GDP and population in year t was calculated in Equation (3) and (4) respectively.

$$Q_i^t = Q_i^{t-1} \times (1 + r_i^Q) \quad (3)$$

$$P_i^t = P_i^{t-1} \times (1 + r_i^P) \quad (4)$$

The future employment population of various industries cannot be directly obtained from observational data. This paper assumes that the trend of the proportion of the employed population in each industry to the total population is stable. Thus, this study calculated the average annual growth rate of the employed population in each industry during 1997-2017. And based on this growth rate, this paper calculated the employment population data of each industry in 2040. Therefore, the predicted GDP and employment was shown in **Table 2**.

Table 2 Predicted GDP and employment in 2025, 2030 and 2040.

Variables		2025	2030	2040
Population (Million people)		1,448.98	1,453.30	1,435.50
GDP (Billion Yuan)	Primary	6,235.14	6,735.70	6,601.32
	Secondary	44,049.37	51,608.10	59,490.79
	Tertiary	50,662.83	65,194.27	90,661.89

Based on the forecasts given by World Energy Outlook 2018 (IEA, 2018), three scenarios were considered in this paper. NPS is the medium scenario, which aims to provide policy recommendations for achieving short-term energy and emission targets. In addition to considering the policies that have been implemented by the government, the NPS also considered the official goals and goals already mentioned in the plan. The Nationally Determined Contributions of the Paris Agreement provide an important reference for the government's policy making, although some of them have been supplemented or replaced by more specific documents. NPS reflects the impact of climate and environmental policies on CEs based on these agreements and documents. CPS is a baseline scenario that takes into account the potential environmental impact of documents or policies that have been already published. In this scenario, this paper assumes that the government lacks additional incentives to implement low-carbon strategies. Therefore, when the emission reduction target is a range, this paper assumes that the government is more inclined to achieve its lower threshold. SDS is a scenario that aims to achieve the climate change target. This scenario aims to achieve the sustainable development targets proposed by the United Nations (SDGs). The assumptions of each scenarios were shown in **Table 3**.

Table 3 Assumptions of each scenarios

Scenario	Assumptions
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NPS	<p>NDC GHG targets: achieve peak CO2 emissions around 2030, with best efforts to peak early; lower CO2 emissions per unit of GDP 60-65% below 2005 levels by 2030.</p> <p>NDC energy target: increase the share of non-fossil fuels in primary energy consumption to 20% by 2030.</p> <p>13th Five-Year Plan targets for 2020.</p> <p>“Made in China 2025” transition from heavy industry to higher value-added manufacturing.</p> <p>Expand the role of natural gas.</p> <p>ETS expansion to domestic aviation and selected industry sectors.</p> <p>Three-year action plan for cleaner air, announced in July 2018.</p> <p>Energy price reform, including more frequent adjustments in oil product prices and reduction in natural gas price for non-residential consumers.</p>
CPS	<p>Action Plan for Prevention and Control of Air Pollution.</p> <p>ETS for the power sector.</p>
SDS	<p>Universal access to affordable, reliable and modern energy services by 2030</p> <p>A substantial reduction in air pollution</p> <p>Effective action to combat climate change: to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels.</p>

174 3.3 Decomposition Analysis

175 3.3.1 LMDI Method

176 As mentioned above, IDA model was widely utilized in the research related CEs reduction. In this paper,
177 we applied additive LMDI model to evaluate the specific influence of various drivers on the evolution trend
178 of China's CEs. Therefore, the evaluation trend of CEs can be expressed as Equation (5).

$$179 \Delta CE = CE^t - CE^0 = \Delta CF + \Delta ES + \Delta T + \Delta EI + \Delta A + \Delta P \quad (5)$$

180 Where ΔCE stands for the evaluation of China's CEs during this period; CE^t and CE^0 stands for
181 China's CEs in year t and year 0 respectively; ΔCF , ΔES , ΔT , ΔEI , ΔA and ΔP stands for the changes
182 of China's CEs derived from various drivers. The impact of each driver can be calculated as Equation (6)-(11).

$$183 \Delta CF = \sum_i \sum_n \left[\frac{(CE_{ni}^t - CE_{ni}^0)}{(\ln CE_{ni}^t - \ln CE_{ni}^0)} \right] \times (\ln CF_{ni}^t - \ln CF_{ni}^0) \quad (6)$$

$$184 \Delta ES = \sum_i \sum_n \left[\frac{(CE_{ni}^t - CE_{ni}^0)}{(\ln CE_{ni}^t - \ln CE_{ni}^0)} \right] \times (\ln ES_{ni}^t - \ln ES_{ni}^0) \quad (7)$$

$$185 \Delta T = \sum_i \sum_n \left[\frac{(CE_{ni}^t - CE_{ni}^0)}{(\ln CE_{ni}^t - \ln CE_{ni}^0)} \right] \times (\ln T_{ni}^t - \ln T_{ni}^0) \quad (8)$$

$$186 \Delta EI = \sum_i \sum_n \left[\frac{(CE_{ni}^t - CE_{ni}^0)}{(\ln CE_{ni}^t - \ln CE_{ni}^0)} \right] \times (\ln EI_{ni}^t - \ln EI_{ni}^0) \quad (9)$$

$$187 \Delta A = \sum_i \sum_n \left[\frac{(CE_{ni}^t - CE_{ni}^0)}{(\ln CE_{ni}^t - \ln CE_{ni}^0)} \right] \times (\ln A_{ni}^t - \ln A_{ni}^0) \quad (10)$$

$$188 \Delta P = \sum_i \sum_n \left[\frac{(CE_{ni}^t - CE_{ni}^0)}{(\ln CE_{ni}^t - \ln CE_{ni}^0)} \right] \times (\ln P_{ni}^t - \ln P_{ni}^0) \quad (11)$$

189 In many studies, due to the specific characteristics of energy resources, researchers often assume that the
190 carbon coefficient is constant. Therefore, in this paper, the carbon coefficient effect was ignored, and the
191 impact of the remaining five driving factors on China's CEs changes were evaluated.

192 3.3.2 ST-LMDI method

193 At the provincial level, to make the CI of different provinces comparable, this paper applied the ST-LMDI

model to assess the requirements and potential of CEs reduction in different provinces. The ST-LMDI model can analyze the differences between CI of each province and the target value across temporal and spatial dimensions by constructing a benchmark. This is achieved through multi-region (M-R) comparative analysis. In this paper, the projected CI in 2040 of the three scenarios was established as the benchmark. Then, the CI of each province in 2017 was compared with the benchmark respectively. The specific calculation method was shown as Equation (12).

$$\Delta CI_j = \frac{CI_j^t}{CI_\mu} = \Delta CF_j \times \Delta ES_j \times \Delta T_j \times \Delta EI_j \quad (12)$$

Where ΔCI stands for the spatial differences of CI ; CI_j and CI_μ stands for CI in province j and the benchmark, respectively; ΔCF , ΔES , ΔT , and ΔEI stands for the spatial differences of CI caused by various factors. Since the decomposition object was an intensity indicator, this paper utilized the multiplicative decomposition method to evaluate the spatial differences of each factor. The specific calculation method were shown in Equation (13)-(16).

$$\Delta CF_j = \exp \left[\sum_i \sum_n \frac{L(C_{nij}^t/G_{ij}^t, C_{ni\mu}/G_{i\mu})}{L(CI_{ij}^t, CI_{i\mu})} \cdot \ln \left(\frac{CF_{nij}^t}{CF_{ni\mu}} \right) \right] \quad (13)$$

$$\Delta ES_j = \exp \left[\sum_i \sum_n \frac{L(C_{nij}^t/G_{ij}^t, C_{ni\mu}/G_{i\mu})}{L(CI_{ij}^t, CI_{i\mu})} \cdot \ln \left(\frac{ES_{nij}^t}{ES_{ni\mu}} \right) \right] \quad (14)$$

$$\Delta T_j = \exp \left[\sum_i \sum_n \frac{L(C_{nij}^t/G_{ij}^t, C_{ni\mu}/G_{i\mu})}{L(CI_{ij}^t, CI_{i\mu})} \cdot \ln \left(\frac{T_{nij}^t}{T_{ni\mu}} \right) \right] \quad (15)$$

$$\Delta EI_j = \exp \left[\sum_i \sum_n \frac{L(C_{nij}^t/G_{ij}^t, C_{ni\mu}/G_{i\mu})}{L(CI_{ij}^t, CI_{i\mu})} \cdot \ln \left(\frac{EI_{nij}^t}{EI_{ni\mu}} \right) \right] \quad (16)$$

For the same reason, in this section, this paper assumed that the carbon coefficient is constant during studying period. The spatial differences of the carbon coefficient effect on CI have not been evaluated, and the impact of remaining three factors were analyzed.

3.4 Data description

Due to the limitations of data acquisition, this paper only studied the data of 30 provinces in China (except Hong Kong, Macau, Taiwan, and Tibet) from 1997 to 2040. The historical GDP and Population data was obtained from “*National Bureau of Statistics of China*” (NBSC, 1998-2018c). The projected GDP data was from OECD (OECD, 2019) and the projected population data was from the United Nation (UN, 2018). The GDP data of each year was calculated based on the constant prices of sub-sector of each province and in 2010. The historical fossil energy data was obtained from “*China Energy Statistics Yearbook*” (NBSC, 1998-2018b). The historical non-fossil energy data was acquired from “*China Electricity Statistical Yearbook*” (NBSC, 1998-2018a). Besides, the projected fossil and non-fossil energy data were both acquired from “*World Energy Outlook 2018*” published by IEA (IEA, 2018). According to (Yuan et al., 2018), the economic indicator of power generation (tce/kwh) was utilized to convert the power generation by non-fossil energy (kwh) to energy consumption (tce). According to the method published by the IPCC in 2006 (IPCC, 2006), historical CEs was calculated based on fossil energy consumption data. This paper considered four types of energy including fuel coal, fuel oil, fuel gas, and non-fossil energy.

4. Results

4.1 Evaluation trend and drivers of China's carbon emissions

China's CEs increased dramatically from 2931.6Mtons to 9865.83Mtons during 1997 to 2017, with an average annual growth rate of 6.26% (Fig. 1). This process can be divided into four stages according to growth of CEs characteristics. The first stage is 1997-2002. CEs growth at this stage is relatively slow, with an average annual growth rate of 3.69%. The second stage is 2002-2007. During this period, the CEs increased significantly, with an average annual growth rate of 14.19%. The third stage is 2007-2012. The CEs growth at this stage is relatively flat, with an average annual growth rate of 6.85%. The fourth stage is 2012-2017. The CEs hardly increased, with an average annual growth rate of 0.77%. From an industry perspective, the CEs of different industries varied greatly. The primary industry's CEs increased from 76.7Mtons in 1997 to 139.44Mtons in 2017, with an average annual growth rate of 3.03%. The secondary industry's CEs increased from 2447.1Mtons in 1997 to 8261.85Mtons in 2017, with an average annual growth rate of 6.27%. The tertiary industry's CEs increased from 407.8Mtons in 1997 to 1464.54Mtons in 2017, with an average annual growth rate of 6.60%. From proportion perspective, the secondary industry contributed the most to CEs, accounting for 83.74% of national total in 2017. The tertiary industry has the fastest growth rate. In 1997, the tertiary industry accounted for 13.91% of the national total CEs. However in 2017, this proportion rose to 14.84%. The proportion of the primary industry's CEs in the national total has dropped significantly from 2.62% in 1997 to 1.41% in 2017.

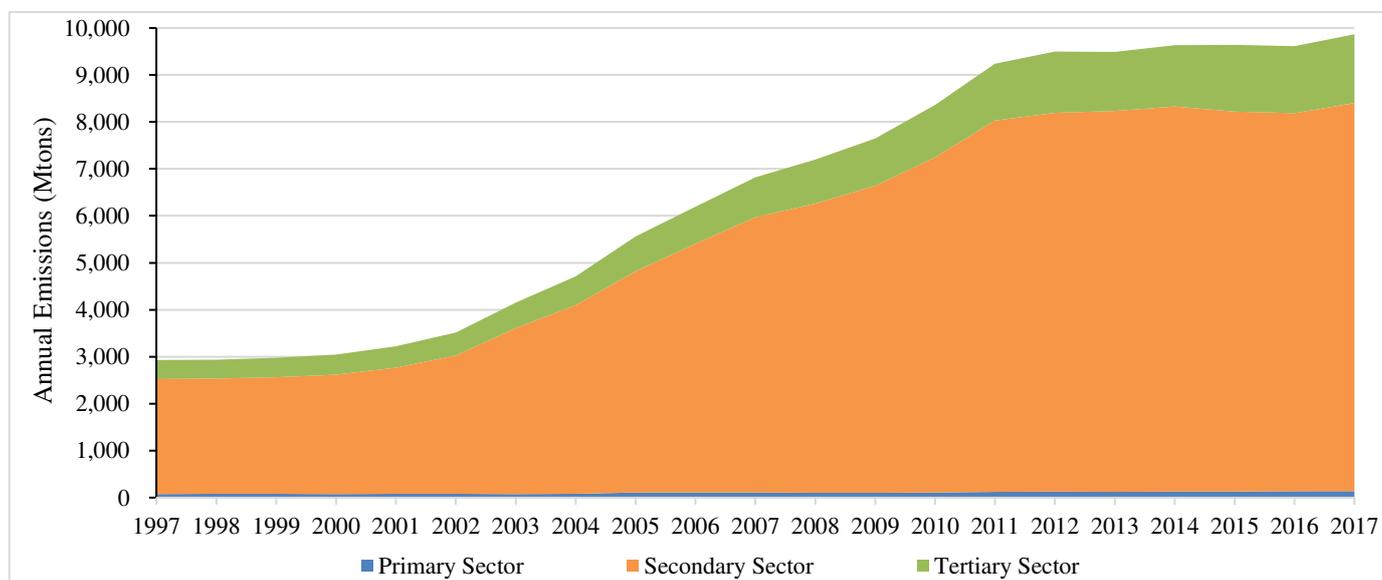


Fig. 1 China's CE's during 1997-2017

LMDI model was applied to analyze the drivers of China's CEs growth in these four period. Results were shown in Fig. 2. From 1997 to 2002, due to the slow development of energy structure optimization and non-fossil energy application, the effects of fossil energy structure and energy consumption structure hardly inhibited growth of CEs in various industries. Energy intensity effect was the leading driver for all three industries to restrain the growth of CEs. Benefiting from technological progress, the energy efficiency of the secondary and tertiary industries has been significantly improved. Energy intensity has reduced the CEs in secondary and tertiary industries by 42.19% (-1022.85Mtons) and 33.49% (-136.13Mtons) in this period,

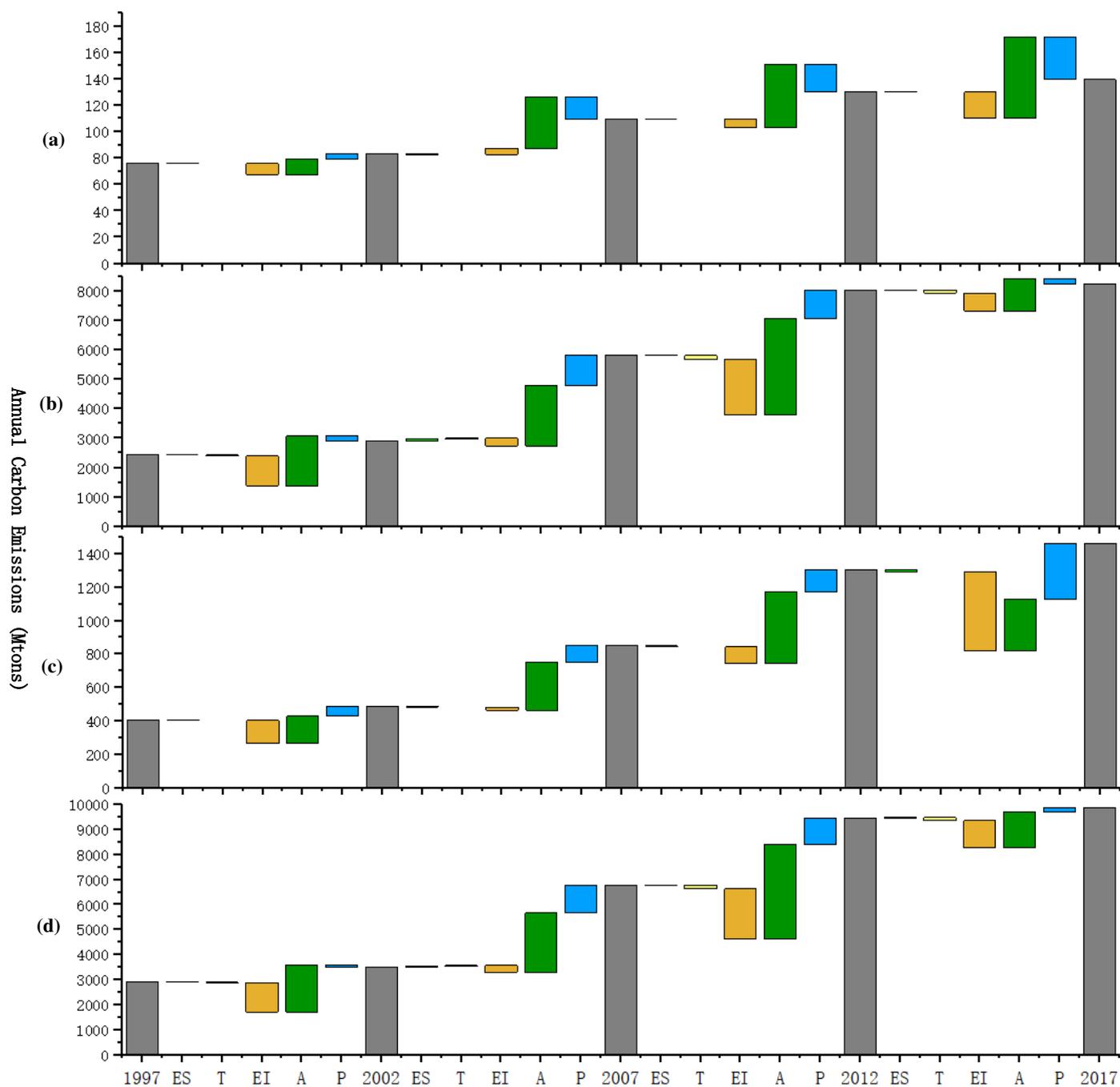
254 respectively. While it only reduces the CEs of the primary industry by 11.21% (-8.56Mtons). Activity effect
255 was the leading force to promote the growth of CEs. From 1997-2002, the average annual growth rate of value
256 added in secondary and tertiary industries was 9.12% and 9.62%, while that of the primary industry was only
257 2.88%. Therefore, the promoting role of activity effect on CEs in secondary (1693.65Mtons, 69.87%) and
258 tertiary industries (162.34Mtons, 39.94%) was much greater than that of the primary industry (11.85Mtons,
259 15.53%). The population effect is positively correlated with changes in the employment number in various
260 industries. During this period, the employment number in primary and tertiary industries increased by 5.17%
261 and 13.70%. Therefore, the population effect increased the CEs of primary and tertiary industries by 5.5%
262 (4.20Mtons) and 13.87% (56.37Mtons) respectively. However, due to the development of industrialization
263 process, the employment number in secondary industry dropped by 5.23% during this period. This also led to
264 a population effect that reduced the secondary industry's CEs by 6.57% (-159.31Mtons).

265 From 2002 to 2007, due to the rapid expansion of the industries, the employees and the added value of the
266 secondary and tertiary industries increased rapidly, which became the main reason for promoting the growth
267 of CEs. Population and activity effect promoted the secondary industry's CEs growth by 35.58%
268 (1037.29Mtons) and 20.60% (100.02Mtons), and promoted the tertiary industry's CEs growth by 70.35%
269 (2050.70Mtons) and 58.77% (285.38Mtons). But for the primary industry, due to the continuous reduction of
270 employees, the population effect reduced its CEs by 19.48% (-16.26Mtons). At this stage, various industries
271 paid their attention to scale expansion, ignoring energy structure improvement and technological progress.
272 Therefore, the effect of fossil energy structure, energy consumption structure, and energy intensity on CEs
273 changes were not significant.

274 From 2007 to 2012, the scale of each industry continued to expansion, and the value added of each industry
275 grew rapidly. Activity effect became the main driver for promoting the CEs growth, which promoted primary
276 industry's CEs by 43.92% (48.22Mtons), secondary industry's CEs by 56.47% (3290.39Mtons), and tertiary
277 industry's CEs by 50.28% (427.29Mtons). Due to the increasing employment number, population effect also
278 promoted the growth of CEs in secondary (16.35%, 952.66Mtons) and tertiary (15.65%, 133.03Mtons)
279 industries. Benefiting from the continuous improvement of mechanization, the employment number in
280 primary industry gradually decreased, and the population effect inhibited CEs growth in primary industry by
281 19.01% (-20.87Mtons). Besides, during this period, due to the transformation from extensive to energy-saving
282 especially in secondary industry, energy intensity dramatically curbed the growth of CEs from the primary
283 industry by 6.2% (-6.8Mtons), from the secondary industry by 32.61% (-1900.22Mtons), and from third
284 industry's by 11.28% (-95.87Mtons). Particularly, benefiting from the application of non-fossil energy in
285 secondary industry, the energy consumption structure effect has slightly restrained the growth of CEs in
286 secondary industry (2.23%, -129.70Mtons).

287 From 2012 to 2017, due to the implementation of environmental protection policies and the improvement
288 of energy efficiency, energy intensity was the dominant driver restraining the CEs growth, which restrained
289 CEs growth from the primary industry by 15.14% (-19.73Mtons), secondary industry by 6.77% (-
290 543.31Mtons), and tertiary industry by 36.39% (-475.69Mtons). Activity effect was the main driver promoting

291 growth of CEs especially in primary industry (46.99%, 61.23Mtons). Benefiting from poverty alleviation and
 292 agricultural policies, output value of primary industry has grown rapidly at this stage. Besides, activity effect
 293 promoted CEs growth from secondary industry by 12.76% (1024.85Mtons), and tertiary industry by 23.69%
 294 (309.65Mtons) respectively. It is worth noting that there has been a clear labor transfer between industries at
 295 this stage. A large amount of labor resources have been transferred from primary to tertiary industry. This
 296 caused the population effect to promote the tertiary industry's CEs by 25.68% (335.70Mtons), while inhibited
 297 the primary industry's CEs growth by 24.66% (-32.13Mtons). For the secondary industry, energy consumption
 298 structure (1.9%, -152.54Mtons) and population (1.40%, -112.25Mtons) effect respectively had a slight
 299 inhibitory effect.



300
 301 **Fig. 2** Decomposition result of historical CEs during 1997-2017 (a) Primary Sector; (b) Secondary Sector; (c) Tertiary Sector;
 302 (d) National Total

4.2 Scenario analysis of China's carbon emissions

According to the assumptions in section 3.2, this paper predicted the CEs in China during 2017-2040. **Fig. 3** and **Fig.4** presented the evolution trend of CEs and CI of various industries in different scenarios from 2017 to 2040 respectively. In the current policies scenario (CPS), China's CEs show an overall upward trend and reach 10729.00Mtons in 2040. The CI continues to decrease from 0.144Mt/By in 2017 to 0.085 Mt/By in 2030 and 0.068 Mt/By in 2040. Thus, the total CEs of China do not reach the peak before 2040, and the 2030 CI reduction target does not be achieved. From an industrial perspective, the increase in CEs is dominantly attributed to tertiary industry. The CEs increase from 1464.54Mtons in 2017 to 2048.59Mtons in 2040. This is mainly due to the process of industrial upgrading. Benefiting from the dramatically expansion of the industries, the proportion of the tertiary industry will rise from 46.04% in 2017 to 57.84% in 2040.

In the new policies scenario (NPS), China's CEs continue to grow and reach the peak of 9917.79Mtons in 2030. Then, the CEs begin to decline and reach 8584.45Mtons in 2040. It is worth noting that CEs from the tertiary industry continue to increase from 1464.54Mtons in 2017 to 1601.1Mtons in 2040. The key to helping China's CEs peak in 2030 is the secondary industry. From 2017 to 2030, the CEs of secondary industry drop from 8261.85Mtons to 7946.47Mtons. The CI continues to decrease to 0.080 Mt/By in 2030, with a decrease rate of 60.19% compared to that of 2005. This also means that China achieves the lower limit of 2030 CEs reduction target.

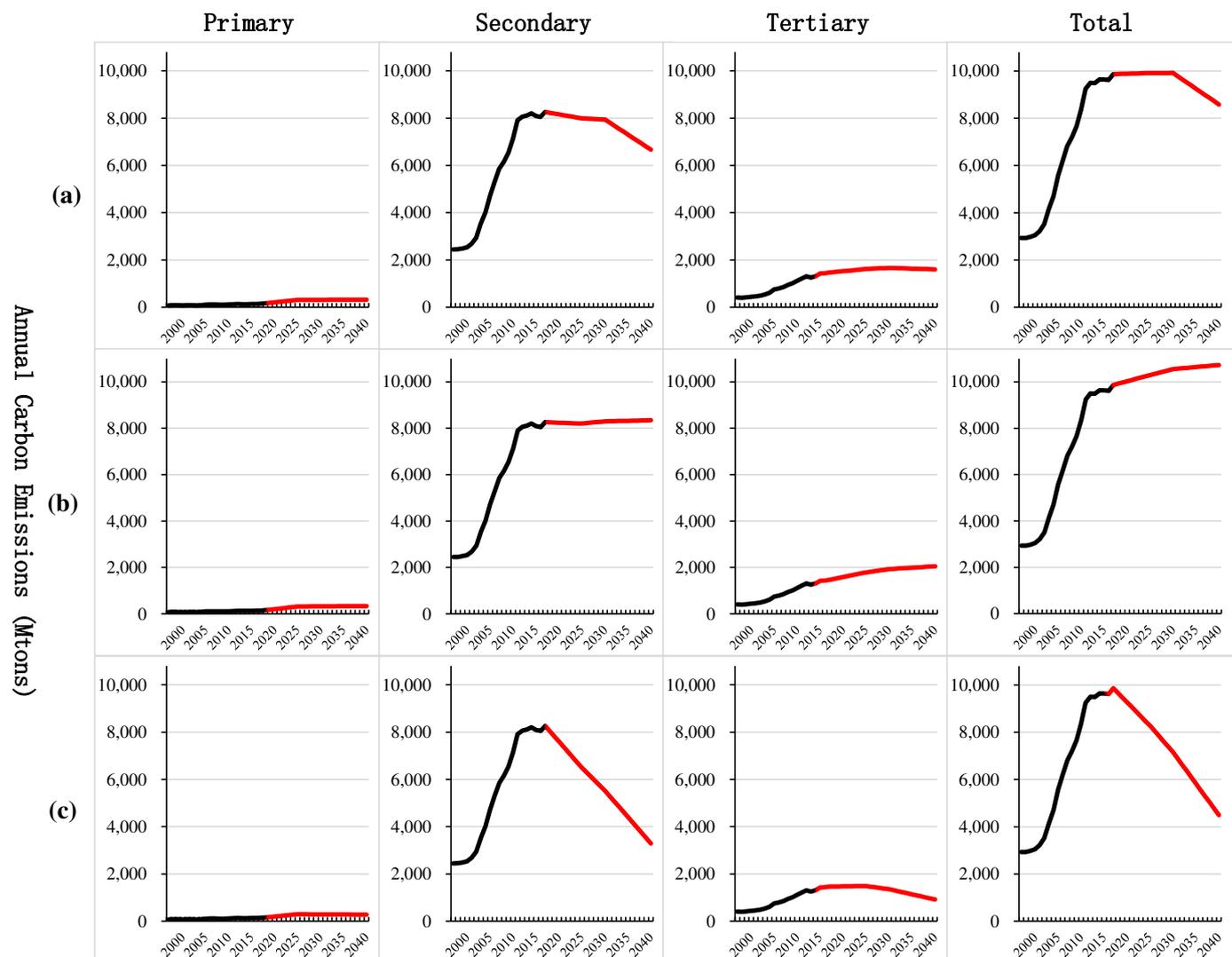


Fig. 3 China's CEs during 1997-2040 in different sector. (a) New Policies Scenario; (b) Current Policies

In the sustainable development scenario (SDS), the CEs continuously decrease from 2017 to 2040. This is mainly caused by the significant drop of CEs from the secondary industry. Subject to strict energy consumption and emission policies, from 2017 to 2040, the proportion of fossil energy consumption in secondary industry dropped from 87.14% to 48.98%, and the energy intensity decreased from 0.11Mt/By to 0.05Mt/By. It caused that CEs in secondary industry dropped from 8261.85Mtons to 3294.29Mtons. Particularly, the CEs of the primary and tertiary industries have shown an increasing trend between 2017 and 2025. This means that the energy and emission policies of the government are lagging in primary and tertiary industries, and the relevant policies mainly have effects on the secondary industry. Besides, the CI decreased to 0.058Mt/By in 2030, with a decrease rate of 72.46% compared to that of 2005. This means that China better achieves its 2030 CEs reduction target, and sustainable energy and industrial policies can play a huge role on environmental improvement and energy conservation.

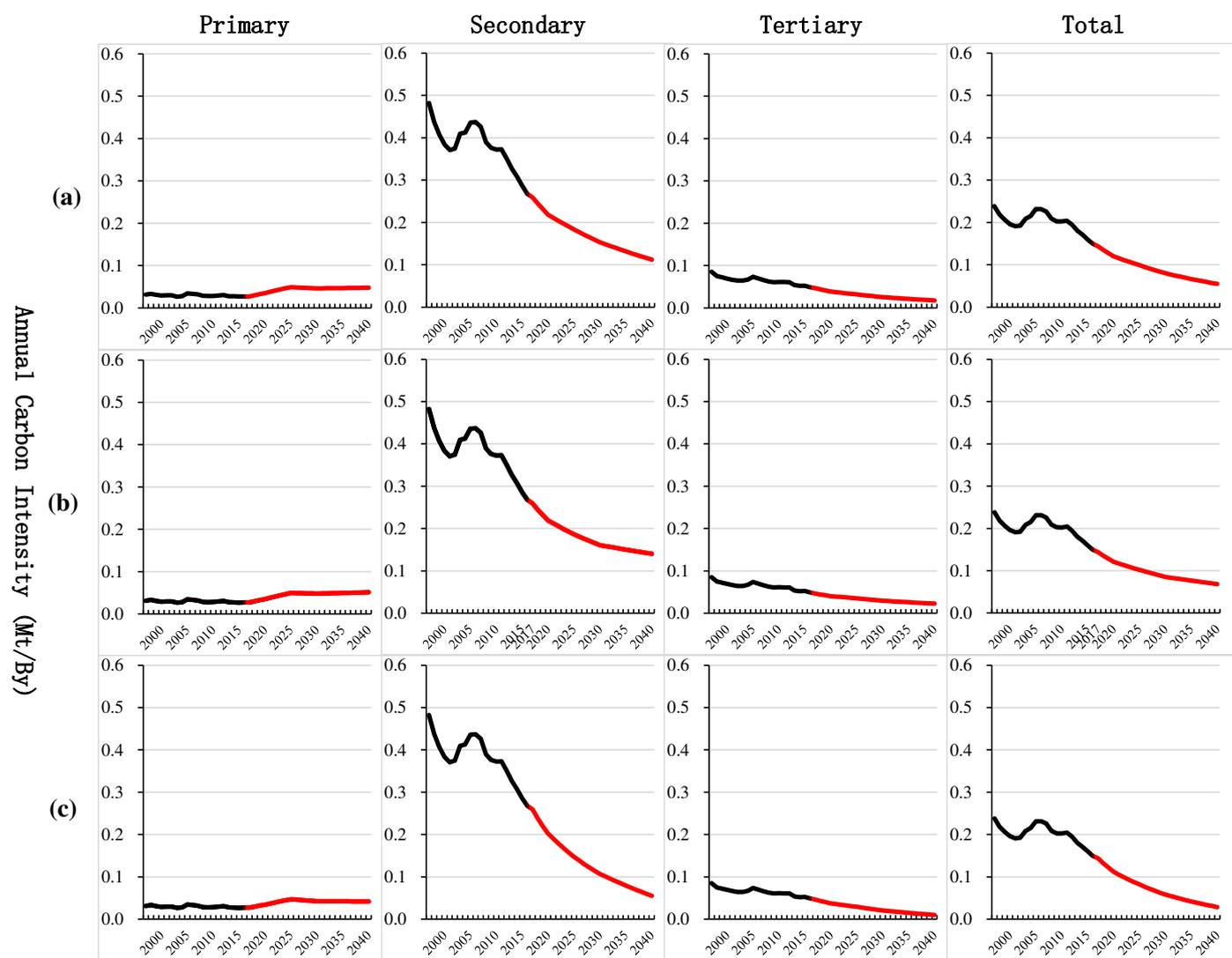


Fig. 4 China's CI during 1997-2040 in different sector. (a) New Policies Scenario; (b) Current Policies Scenario; (c) Sustainable Development Scenario.

4.3 Decomposition analysis of predicted carbon emissions

According to the LMDI method, this paper analyzed China's CEs in different scenarios during 2017-2040 at industrial level. The decomposition results are shown in **Fig.5**. In the current policies scenario (CPS), with

the rapid expansion of the scale of the industry, the activity effect promotes the continuous growth of China's CEs, which respectively contributes to CEs increasing by 191.80% (267.79Mtons) in primary industry, 26.38% (2179.27Mtons) in secondary industry, and 55.89% (818.49Mtons) in tertiary industry. In view of the targeted energy policies for energy-intensive industries, energy intensity as a leading force reduces CEs in secondary industry by 17.19% (-1420.18Mtons), and in tertiary industry by 50.98% (-1993.59Mtons). However for primary industry, due to the increase of energy consumption, energy intensity promotes the CEs growth by 124.04% (173.18Mtons). With the application of non-fossil energy, energy consumption structure effect inhibits the CEs growth in primary industry by 3.03% (-4.23Mtons), the secondary industry by 4.95% (-408.71Mtons), and the tertiary industry by 14.95% (-218.87Mtons). The result of population effect is a manifestation of labor transfer between industries. From 2017-2040, the employment number in primary and secondary industries decreases by 75.71% and 11.38%, while the employment number in tertiary industry increased by 60.72%. This is in line with the trend of agricultural mechanization and industrial intelligence. It is worth noting that the fossil energy structure has a 2.9% (239.79Mtons) promotion effect on CEs growth in secondary industry. It means that current fossil energy policy cannot curb growth of CEs process.

In the new policies scenario (NPS), activity effect is still the main impact factor, which increases CEs in primary industry by 183.37% (256.02Mtons), secondary industry by 36.96% (3052.83Mtons), and tertiary industry by 53.5% (783.46Mtons). In NPS, the government implements a series of stricter energy consumption and energy substitution policies. Energy intensity effects have a more obvious effect on CEs decrease in secondary (32.96%, -2722.41Mtons) and tertiary (66.87%, -979.33Mtons) industries. The new policies require the non-fossil energy consumption to reach 24.85% in 2040, which reduce CEs by 3.08% (-4.3Mtons) in primary industry, 13.60% (-1123.07Mtons) in secondary industry, and 19.17% (-280.70Mtons) in tertiary industry. Besides, the proportion of coal consumption drop to 45.36% in 2040. This makes the fossil energy structure effect slightly reduce the CEs from the secondary industry (1.07%, -88.32Mtons). Compared with the development of non-fossil energy, the impact of fossil energy structure optimization on CEs reduction is limited.

In the sustainable development scenario (SDS), the activity effect on CEs growth is further suppressed, increasing CEs in primary industry by 169.67% (236.89Mtons), in secondary industry by 30.51% (2520.03Mtons), and in tertiary industry by 39.30 % (575.60Mtons). Energy policies in SDS further reduce the energy intensity. In secondary and tertiary industries, energy intensity effect reduces CEs by 41.77% (-3450.21Mtons) and 80.54% (-1179.45Mtons), respectively. Due to the substantial decline in coal consumption and the increase of non-fossil energy consumption, fossil energy structure and energy consumption structure effects have had significant effects in reducing CEs. Especially for the energy consumption structure effect, in SDS, the proportion of the non-fossil energy consumption is 44.33% in 2040, which results in a reduction of CEs by 6.26% (-8.74Mtons) in primary industry, 33.84% (-2794.70Mtons) in secondary industry, 21.25% (-311.21Mtons) in tertiary industry. This further proves that vigorously developing non-fossil energy is of great significance for achieving CEs reduction targets.

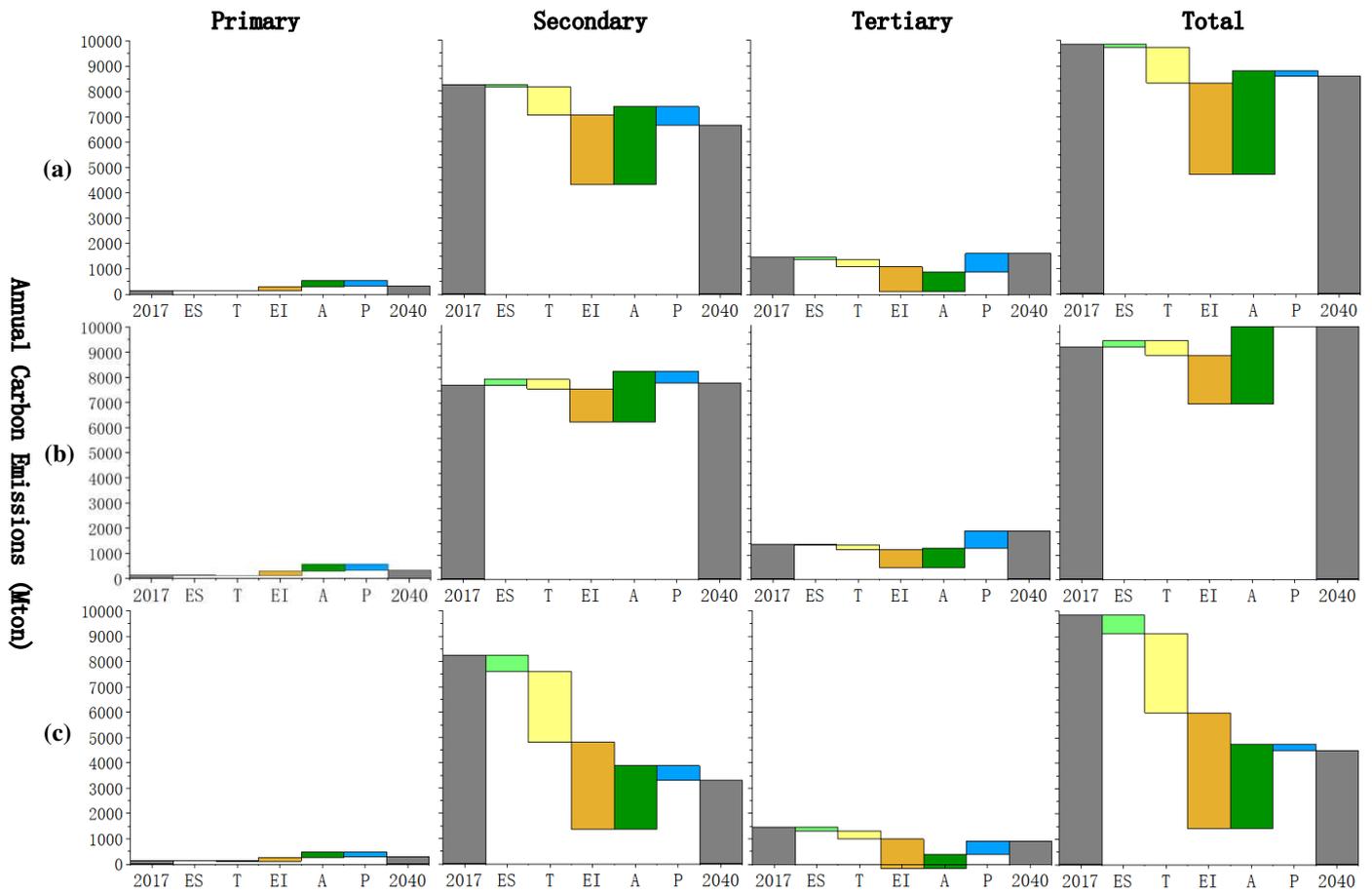


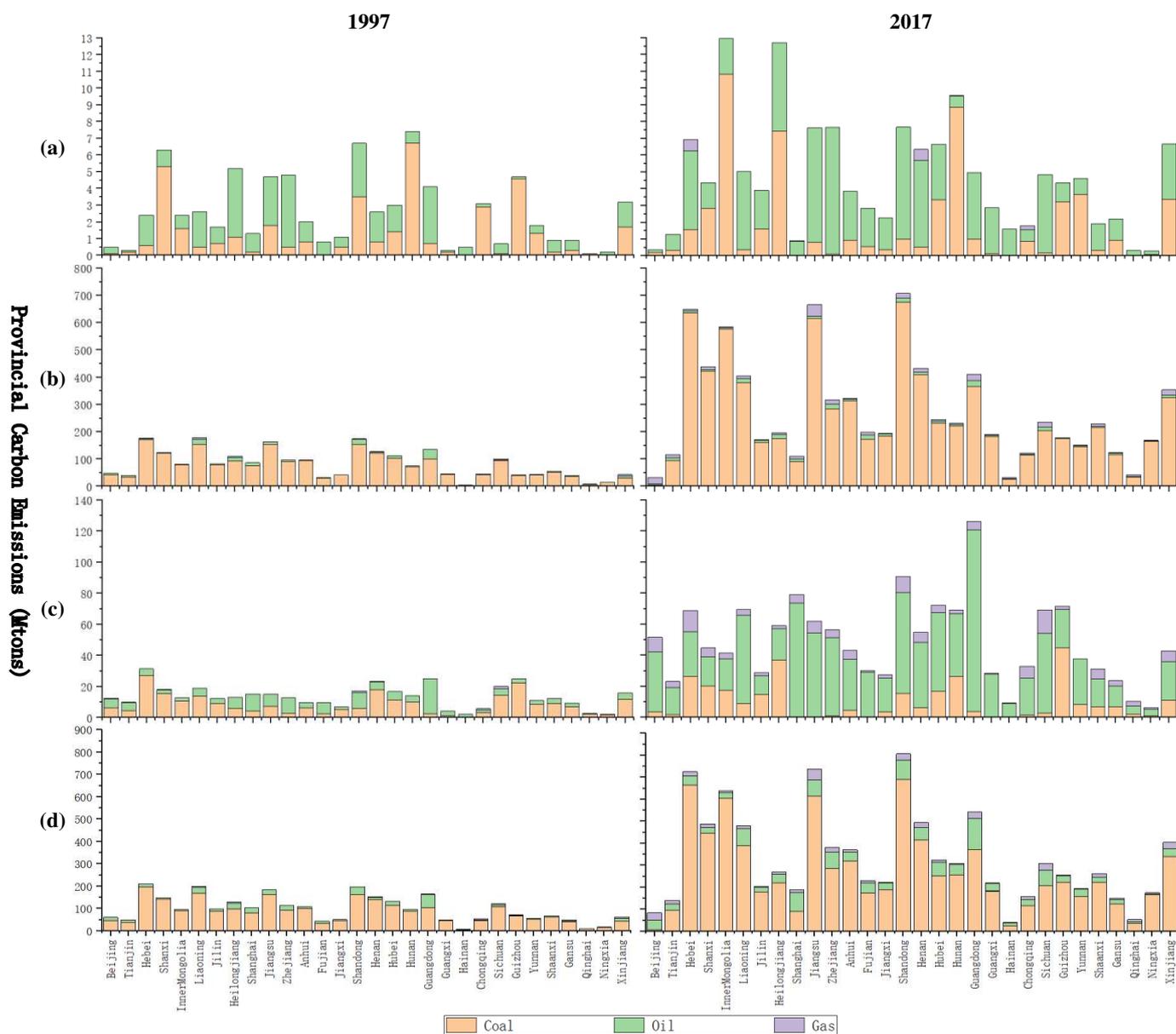
Fig. 5 Decomposition result of China's CE during 1997-2040 in different sector. (a) New Policies Scenario; (b) Current Policies Scenario; (c) Sustainable Development Scenario.

4.4 Provincial emission analysis

4.4.1 Evaluation trend of provincial emissions

The dynamic of provincial CE during 1997-2017 was shown in **Fig. 6**. The CE has undergone different evolutionary trends at the provincial level during 1997-2017. In primary industry, due to the continuous expansion of the industry, most provinces have experienced rapid growth in CE except Beijing, Shanxi, Shanghai, Chongqing and Guizhou. The decrease in fuel coal consumption led to CE reduction of Shanxi, Shanghai, Chongqing and Guizhou by 46.23%, 95%, 70.34% and 30%, respectively. For Beijing, the CE reduction was mainly due to the decrease of fuel oil consumption. On the contrary, during this period, Hebei, Inner Mongolia, Heilongjiang and Sichuan had the largest CE growth in the primary industry, which increased by 4.54Mtons (189.17%), 10.56Mtons (440.00%), 7.51Mtons (144.42%) and 4.14Mtons respectively (591.43%). It is mainly caused by the growth of fuel coal and fuel oil consumption. In secondary industry, only CE in Beijing declined between 1997 and 2017. This is mainly due to the shutdown or transfer of energy-intensive industries, which is Beijing's great achievement in easing the functions of the capital (Liu et al., 2019b). The CE of secondary industry in other provinces have experienced different degrees of growth especially for Hebei, Inner Mongolia, Jiangsu and Shandong. With the rapid increase in industrial output value, industrial energy, especially coal consumption in various provinces has increased significantly (Qiao et al., 2019). This directly causes a growth of CE. In tertiary industry, the CE of all provinces showed a clear upward trend, which is consistent with the continuous expansion of the tertiary industry. Especially in

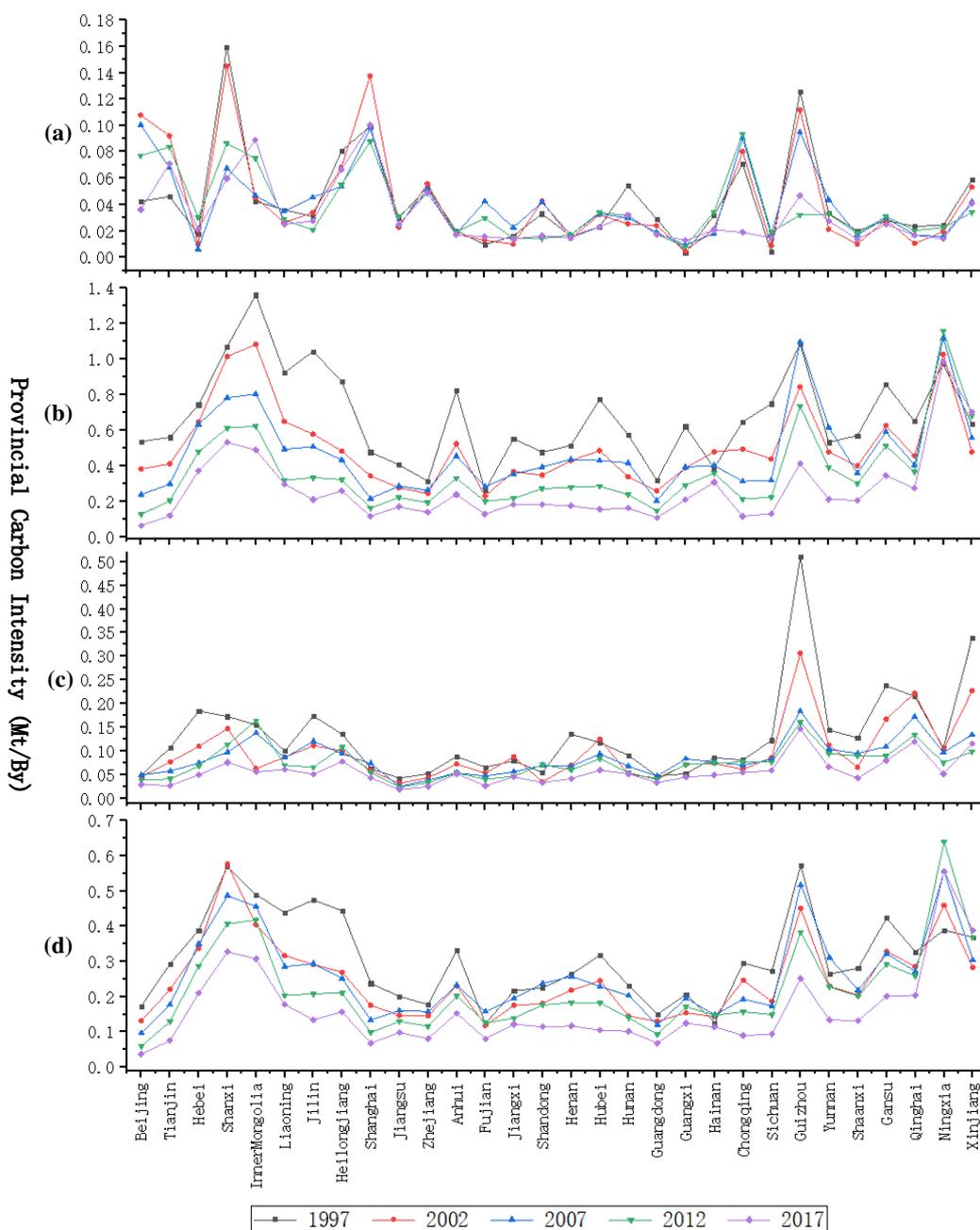
396 developed provinces such as Beijing, Shanghai, Jiangsu, Zhejiang, Shandong and Guangdong, rapid
 397 development of the tertiary industry has also driven their energy related CE to grow rapidly by 314.24%
 398 (39.28Mtons), 416.67% (63.75Mtons), 311.72% (47.07Mtons), 345.43% (43.87Mtons), 424.57%
 399 (73.45Mtons), and 401.23% (101.11Mtons) respectively. In particular, there are clear differences in the CE
 400 growth pattern among secondary and the tertiary industries. The CE growth of secondary industry mainly
 401 derived from coal consumption, while that of the tertiary industry mainly derived from oil consumption (Wang
 402 et al., 2019).



403
 404 **Fig. 6** Provincial CE during 1997-2017 (a) Primary Sector; (b) Secondary Sector; (c) Tertiary Sector; (d) National Total.

405 **Fig. 7** showed the changes on CI at the provincial level from 1997 to 2017. Form 1997-2002, the CI of most
 406 provinces declined except Shanxi, Hainan and Ningxia. This is mainly affected by the secondary industry.
 407 Only the secondary industry's CI in Hainan and Ningxia increased between 1997 and 2002. Particularly, the
 408 CI of various industries in Shanxi showed a downward trend during this period. However, due to the significant
 409 growth in the proportion of the secondary industry, its CI has increased slightly. From 2002 to 2007, the CI of
 410 18 provinces showed an increasing trend. Especially for Fujian, Shandong and Yunnan, the growth rate of CI
 411 was all above 30%. This is the result of extensive economic development. It is worth noting that the CI of

412 Beijing and Shanghai both decreased more than 20% during this period, especially the CI of the secondary
 413 industry, which decreased more than 30%. It depends on the city positioning of Beijing and Shanghai. As an
 414 international metropolis, Beijing and Shanghai have been committed to alleviating energy-intensive industries,
 415 but these policies has also led to the CEs growth in neighboring provinces (Sun et al., 2019). From 2007-2012,
 416 local governments introduced a series of environmental and energy policies, and only Ningxia and Xinjiang
 417 showed a growth in CI. It is dominantly caused by the increase of CEs of secondary industry. Due to the
 418 relatively backward development, the economic growth of Ningxia and Xinjiang is more dependent on
 419 resource-driven development of the coal industry, which has caused the continuous increase of CEs. From
 420 2012-2017, only CI in Xinjiang showed a growth trend. Moreover, from industrial perspective, the CI of the
 421 secondary and tertiary industries in most provinces has declined except Xinjiang. Governments should give
 422 more policy support to Xinjiang, and develop clean energy in accordance with local conditions to reduce CEs.



423

424

Fig. 7 Provincial CI during 1997-2017 (a) Primary Sector; (b) Secondary Sector; (c) Tertiary Sector; (d) National Total.

4.4.2 Provincial decomposition results

Analyzing the spatial difference of CI between each province and the ideal state is of great significance for identifying key provinces and assessing potential approaches for CEs reduction. Based on the above analysis, the sustainable development scenario (SDS) is the most ideal scenario. Therefore, in this section, China's average CI in 2040 under the sustainable development scenario is established as a benchmark, and ST-LMDI model was applied to evaluate the spatial differences between provinces and the benchmark. **Table 4** presented the spatial-temporal decomposition results. For primary industry, the spatial differences mainly depends on fossil energy structure and energy intensity effects. With the process of agricultural mechanization, modern large-scale agricultural machinery has gradually replaced manpower, leading to a dramatic growth of energy consumption in 2040 (Lin and Liu, 2017). The energy intensity effect of most provinces is lower than the benchmark except Tianjin, Inner Mongolia, Heilongjiang and Shanghai. Inner Mongolia and Heilongjiang are the provinces with the largest energy consumption in primary industry, accounting for about 20% of national total. Reducing their energy consumption is critical to controlling CEs in primary industry. The energy structure effect of Shanxi, Inner Mongolia, Hunan, Guizhou and Yunnan was higher than that of benchmark. In these provinces, coal consumption accounted for more than 60% of the energy consumption in primary industry. Increasing oil and gas consumption may significantly reduce their CI of the primary industry. Besides, the energy consumption structure effect of all provinces is higher than the benchmark, and there is no obvious spatial difference among these provinces.

In secondary industry, energy intensity effect is the leading driver for inter-provincial differences of CI. The energy intensity effect of most provinces is higher than the benchmark except Beijing. This indicates that the energy intensity of secondary industry in Beijing is lower than that of the benchmark. As a developed province, Beijing is committed to alleviating non-capital functions, vigorously develop high-tech industries, and eliminate low-value-added energy-intensive industries. On the contrary, the energy intensity effect of Shanxi, Ningxia and Xinjiang is much higher than that of other provinces. Traditional energy-intensive industries have always been pillar industries in Shanxi province, and the economic development of Shanxi is heavily dependent on fossil energy consumption (You et al., 2021). Due to the weak industrial base, the manufacturing industry in Ningxia and Xinjiang developed slowly and their energy efficiency was relative low. Therefore, Shanxi, Ningxia and Xinjiang have great potential for CEs reduction, and promoting industrial upgrading and technological progress is a valid method to decrease their CI. The energy consumption structure effect of most provinces is higher than the benchmark except Yunnan. This is mainly due to the development of hydropower in Yunnan, and its non-fossil energy consumption accounts for much higher proportions than other provinces. Some other studies have also obtained similar results (Xiao et al., 2019; Zhang et al., 2018).

In tertiary industry, the spatial differences mainly derive from energy intensity effect. The energy intensity effects of all provinces are higher than the benchmark, especially Guizhou, Qinghai, and Xinjiang. In these provinces, tourism takes a high proportion of the tertiary industry. However, tourism industry in these provinces is still in a stage of rapid development, and their energy efficiency is relatively low. It is critical to integrating tourism resources and vigorously developing eco-tourism to reduce CEs (Wang et al., 2016b). On the contrary, the CI of tertiary industry in the developed provinces such as Beijing, Tianjin, Jiangsu, Zhejiang,

and Fujian was relatively low compared to other provinces. This is mainly due to the relatively high consumer demand and the relatively mature development of the service industry in these provinces. The spatial differences of fossil energy structure effect and energy consumption structure effect are similar. All provinces have great potential in optimizing the energy structure. Vigorously developing non-fossil energy sources take a crucial position in decreasing CI.

In general, the GDP of the secondary industry accounts for less than 50%, but related CEs occupy more than 80% of the national total. Therefore, evolution of CI is mainly affected by the secondary industry. Reducing energy intensity is the most valid method to reduce CEs in all provinces except Beijing. For the secondary industry, there are two major ways to improve energy intensity. The first is to promote technological progress and improve energy efficiency. The second is to optimize the industrial structure and develop modern manufacturing. For provinces dominated by traditional manufacturing, such as Hebei, Jilin, and Liaoning, improving energy efficiency is the most valid method to reduce the CI of secondary industry. For provinces dominated by modern manufacturing such as Tianjin and Jiangsu, improving technological innovation capabilities and developing high-tech industries are of great significance to achieving CEs reduction goals. For Beijing, improving the energy structure and increasing non-fossil energy consumption are the most active method to decrease CEs. The development of clean energy power generation in accordance with local conditions and improving the long-distance transmission capacity of the power grid are essential to promote non-fossil energy consumption.

Table 4 Decomposition result of provincial CI during 2017-2040 in different sector from Sustainable Development Scenario.

Provinces	Primary			Secondary			Tertiary			Total		
	ES	T	EI	ES	T	EI	ES	T	EI	ES	T	EI
Beijing	0.89	1.04	0.66	0.82	1.82	0.78	1.08	1.32	1.96	0.91	1.67	0.82
Tianjin	0.63	1.03	1.06	0.96	2.02	1.24	1.09	1.32	1.79	1.03	1.78	1.59
Hebei	0.62	1.04	0.51	1.26	1.90	2.93	1.28	1.28	2.97	1.30	1.69	3.43
Shanxi	1.02	1.05	0.93	1.21	1.94	7.72	1.49	1.27	3.88	1.26	1.71	9.09
Inner Mongolia	1.32	1.05	1.24	1.23	1.83	4.25	1.42	1.27	3.04	1.36	1.62	5.28
Liaoning	0.41	1.02	0.71	1.12	1.87	2.86	1.26	1.30	3.55	1.19	1.67	3.44
Jilin	0.17	1.04	0.56	1.16	1.86	1.84	1.52	1.26	2.58	1.24	1.66	2.37
Heilongjiang	0.95	1.04	1.01	1.16	1.91	2.32	1.85	1.24	3.48	1.21	1.70	2.86
Shanghai	0.47	1.01	1.13	0.92	2.00	1.37	1.16	1.31	2.65	1.01	1.74	1.48
Jiangsu	0.44	1.03	0.68	1.14	1.93	1.35	1.09	1.31	1.26	1.18	1.70	1.62
Zhejiang	0.43	1.01	0.94	1.10	1.72	1.26	1.11	1.31	1.65	1.12	1.56	1.52
Anhui	0.52	1.03	0.48	1.23	1.90	1.84	1.14	1.31	3.37	1.25	1.70	2.47
Fujian	0.48	1.03	0.48	1.06	1.49	1.40	1.16	1.30	1.68	1.11	1.37	1.76
Jiangxi	0.43	1.03	0.47	1.21	1.82	1.40	1.19	1.30	2.81	1.23	1.63	1.94
Shandong	0.42	1.03	0.53	0.29	1.93	1.40	1.15	1.30	2.13	1.21	1.72	1.82
Henan	0.37	1.03	0.46	1.17	1.94	1.43	1.15	1.31	2.72	1.20	1.72	1.98
Hubei	0.79	1.04	0.48	1.19	1.37	1.64	1.29	1.29	3.51	1.18	1.33	2.20
Hunan	1.46	1.06	0.49	1.20	1.67	1.33	1.42	1.27	2.89	1.21	1.55	1.74
Guangdong	0.49	1.03	0.50	1.06	1.70	1.04	1.17	1.30	2.08	1.08	1.56	1.34
Guangxi	0.33	1.02	0.55	1.22	1.49	1.80	1.23	1.30	2.69	1.23	1.38	2.20

Hainan	0.23	1.00	0.95	0.06	1.64	2.97	1.19	1.30	3.01	1.01	1.52	2.22
Chongqing	0.86	1.05	0.36	1.16	1.74	1.05	1.06	1.32	3.71	1.12	1.60	1.68
Sichuan	0.33	1.02	0.61	1.08	1.05	2.10	1.06	1.32	3.98	1.07	1.06	2.80
Guizhou	1.13	1.05	0.75	1.27	1.47	3.72	2.15	1.24	5.62	1.30	1.43	4.54
Yunnan	1.17	1.05	0.47	1.21	0.86	3.56	1.42	1.28	3.57	1.23	0.88	4.06
Shaanxi	0.45	1.03	0.46	1.14	1.93	2.53	1.15	1.30	2.76	1.16	1.71	3.23
Gansu	0.71	1.04	0.53	1.21	1.49	3.63	1.29	1.29	4.67	1.22	1.39	4.27
Qinghai	0.46	1.03	0.53	1.01	1.17	4.08	1.16	1.31	7.62	1.04	1.14	5.83
Ningxia	0.53	1.04	0.41	0.82	1.81	8.71	1.16	1.31	3.28	1.44	1.60	9.64
Xinjiang	0.82	1.04	0.72	1.15	1.79	6.45	1.28	1.30	6.76	1.22	1.60	7.25

5. Conclusions and policy recommendations

This study first analyzed the evolution trend and influencing factors of China's CEs during 1997-2017. Then, scenario analysis was applied to analyze China's CEs and CI at industrial level from 2017 to 2040 in different scenarios. Next, the LMDI model was used to explore the driving force of China's CEs reduction in different scenarios. Furthermore, this paper analyzed the differences in CEs and CI of various provinces from the provincial level. Finally, the ST-LMDI model was used to explore the CEs reduction potential and potential paths at provincial level based on sustainable development scenario. The main conclusions are as follows.

5.1 Conclusions

During 1997-2017, China's CEs growth was continuous, with an average annual growth rate of 6.26%. Secondary industry was the main source of CEs, accounting for more than 80% of national total. Activity effect was the dominant force for CEs growth. Benefiting from technological progress, energy intensity was a key driver in restraining the growth of CEs. However due to extensive economic development, the restraining effect was not obvious during 2002-2007. Population effect was a key factor for CEs growth in tertiary industry especially during 2012-2017 (25.68%). With the development of non-fossil energy, the energy consumption structure effect began to curb the CEs growth (-2.23%) during 2007-2012, and continued to show restraint effect (-1.40%) during 2012-2017.

In the scenario analysis, different energy and environmental policies have had a clear influence on CEs. In the current policy scenario, China's CEs increase continuously in 2017-2040, and 2030 CI reduction target will not come true. In the new policies scenario, China's CEs will peak at 2030 due to the improvement of energy efficiency and optimization of energy structure. In addition, China's CI will drop by 60% in 2030 compared to 2005, which means that China will achieve the lower limit of 2030 CEs reduction target. It is dominantly caused by the decrease in CEs from secondary industry. In the sustainable development scenario, CEs continue to decline from 2017-2040. CI will drop by 72.46% compared to 2005. This scenario is far better than the other two scenarios in terms of CEs reduction. However, CEs reductions mainly occur in secondary industry. It means that energy efficiency improvement and energy structure optimization have a great effect on the CEs reduction of the secondary industry. But it has limited effects on the primary and tertiary industries.

From provincial level, the CEs have undergone different growth trends at the provincial level during 1997-2017 except Beijing. This is mainly benefitted from Beijing's efforts to relieve non-capital functions. Due to the expansion of traditional industries, CEs in Inner Mongolia, Heilongjiang, Shandong, and Hebei have

512 grown rapidly. The downward trend of CI in Xinjiang, Ningxia and Shanxi is not obvious. It is mainly due to
513 that the economic growth of these provinces is more dependent on resource-driven development of the coal
514 industry. For most provinces, reducing energy intensity is the most effective way to achieve CEs reduction
515 targets. However, for developed provinces such as Beijing and Shanghai, the potential for energy intensity
516 decline is limited. Improving the energy structure and promoting non-fossil energy consumption are potential
517 ways to reduce CEs.

518 5.2 Policy recommendations

519 Based on the above analysis, some potential measures can be implemented to control China's CEs. In the
520 current policy scenario, existing energy and technology policies are not sufficient to restrain CEs growth.
521 More effective methods should be implemented to reduce energy intensity especially in secondary industry.
522 For provinces dominated by traditional manufacturing, such as Hebei, Shanxi, and Inner Mongolia, improving
523 energy efficiency is the most effective way. While for provinces with a weak industrial foundation, efforts
524 should be made to develop modern industries in accordance with local conditions. Besides, for developed
525 provinces such as Beijing and Shanghai, it is essential to develop high-tech industries, further expand
526 investment in low-carbon infrastructure, and advocate low-carbon consumption, which is also in line with the
527 assumption of sustainable development scenarios.

528 Optimizing the energy structure and promoting non-fossil energy consumption are the keys to ensuring the
529 achievement of CEs reduction targets. From the new policy scenario, the optimization of the energy structure
530 is a crucial driver in the peak of CEs in secondary industry. However, relevant energy structure policies cannot
531 help the CEs of the primary and tertiary industries reach their peak before 2030. Therefore, more measures
532 need to be taken for the optimization of energy structure. On the one hand, more vigorous "coal-to-gas"
533 policies should be extended to more provinces such as Shanxi, Inner Mongolia, Shandong and Ningxia. On
534 the other hand, develop non-fossil energy in accordance with local conditions. For example, Hubei, Chongqing
535 and Yunnan can make full use of their geographical advantages to develop hydro power generation. Striving
536 to achieve non-fossil energy power generation accounting for 50% of the national total by 2030 (NDRC, 2016).

537 The development of low-carbon infrastructure and the overall planning of smart grids are important
538 guarantees for de-carbonization. In the sustainable development scenario, CEs from the tertiary industry reach
539 a peak around 2025. This is mainly due to the growth of clean energy especially green power consumption.
540 However, in the current and new policy scenarios, the relevant policies cannot curb CEs growth due to the
541 increase of energy consumption. Therefore, the government should increase relevant investments such as the
542 construction of new energy vehicle charging stations and the laying of long-distance power transmission
543 networks. Reduce obstacles to the promotion of clean energy on the consumer side.

544 Compliance with Ethical Standards

545 Conflict of Interest: The authors declare that they have no conflict of interest.

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554 **Declarations**

555 Ethics approval and consent to participate

556 Not applicable

557 Consent for publication

558 Not applicable

559 Availability of data and materials

560 The datasets generated and analyzed during the current study are available in the National Bureau of Statistics
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562 <http://www.stats.gov.cn/tjsj/ndsj/>

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569 Authors' contributions

570 CS did the scenario and decomposition analysis, and was a major contributor in writing the manuscript. TZ
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572 provided a lot of work for the revision of the paper. All authors read and approved the final manuscript.

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Figures

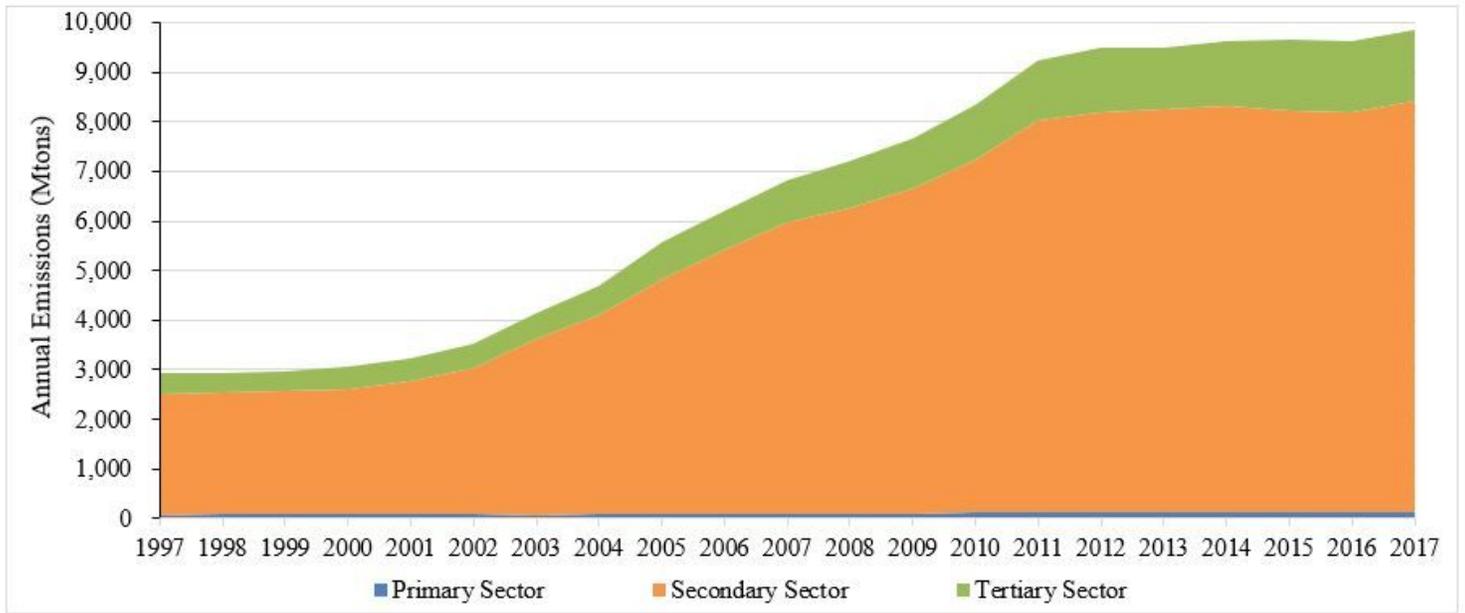


Figure 1

China's CEs during 1997-2017

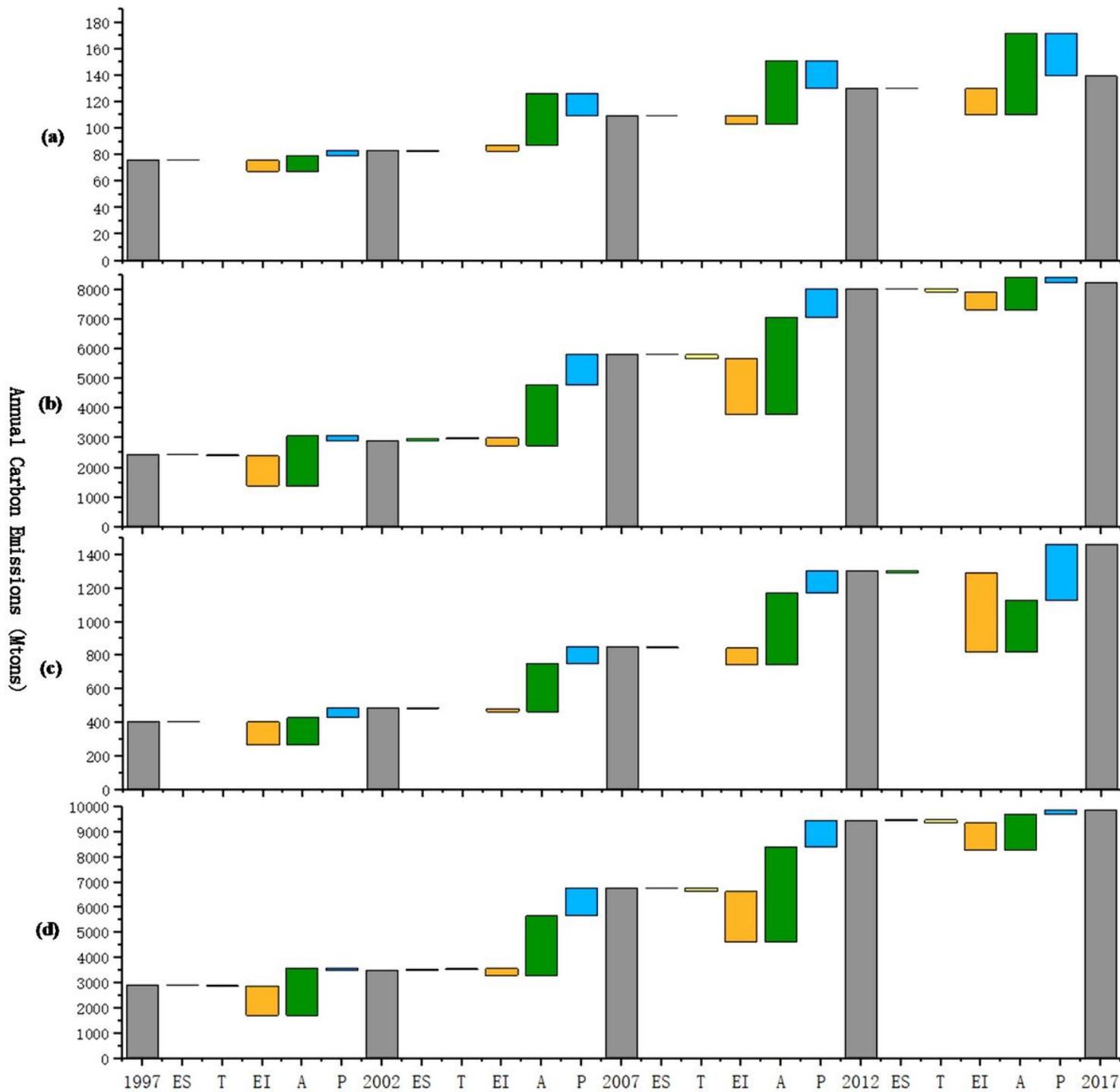


Figure 2

Decomposition result of historical CEs during 1997-2017 (a) Primary Sector; (b) Secondary Sector; (c) Tertiary Sector; (d) National Total

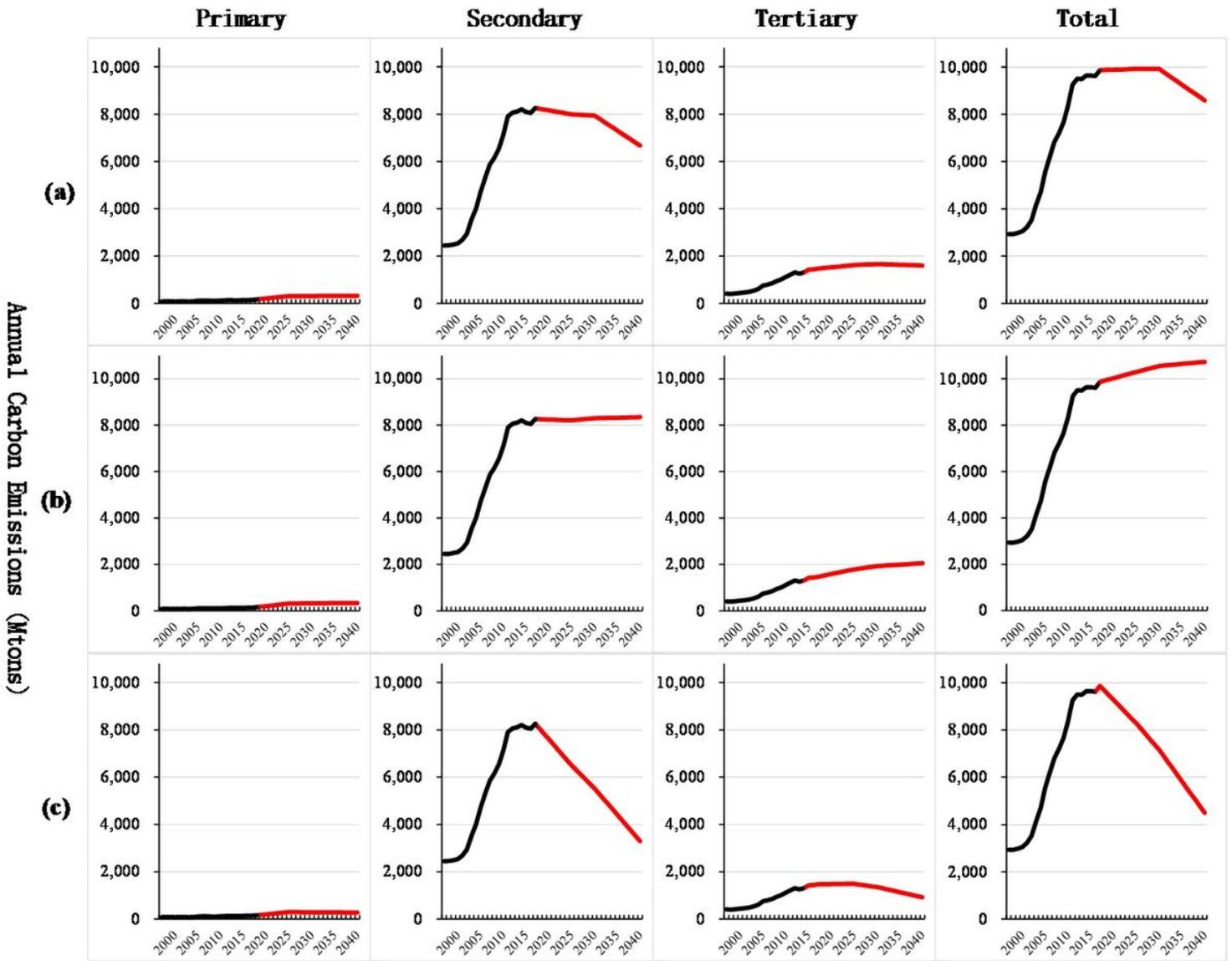


Figure 3

China's CE during 1997-2040 in different sector. (a) New Policies Scenario; (b) Current Policies

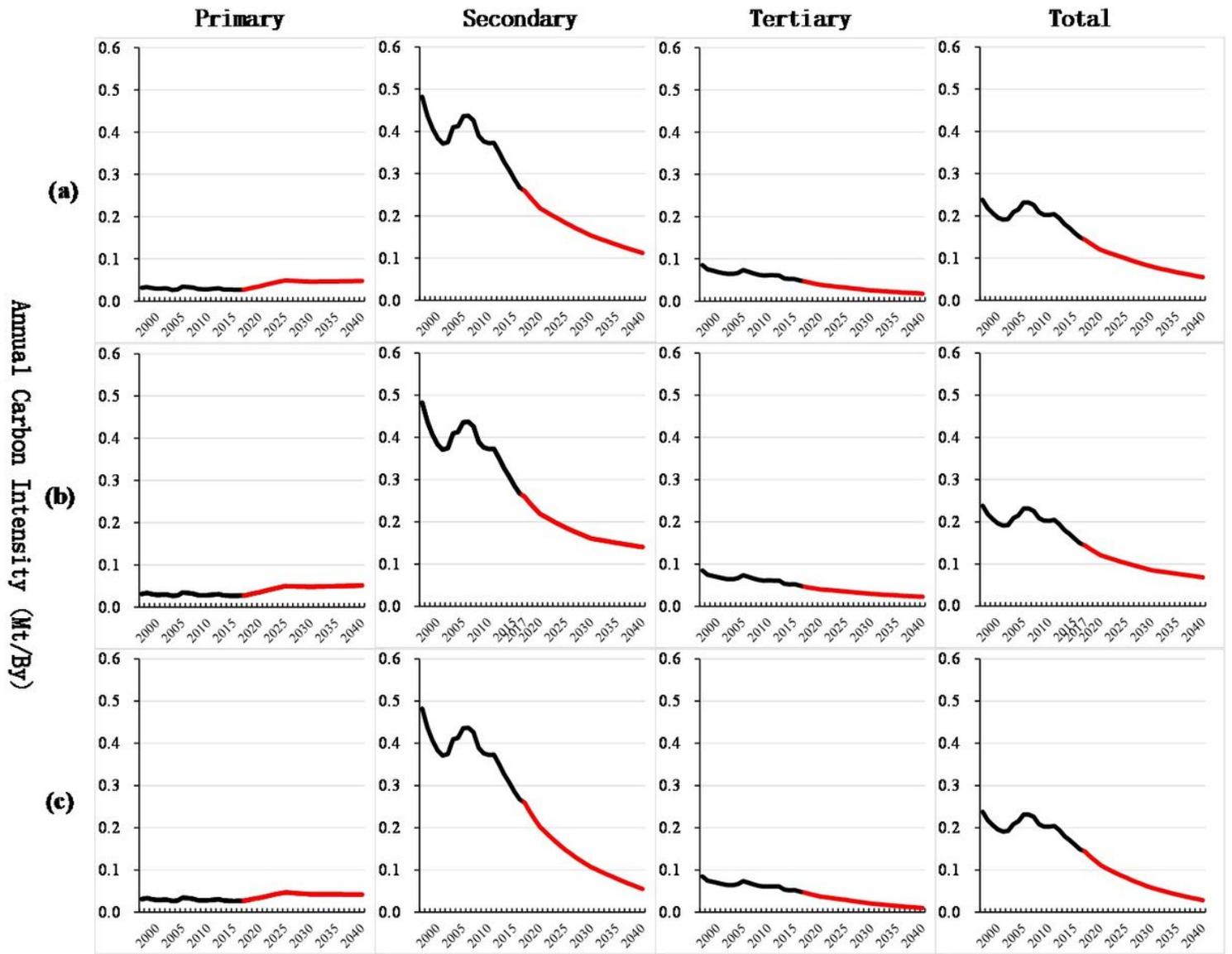


Figure 4

China's CI during 1997-2040 in different sector. (a) New Policies Scenario; (b) Current Policies Scenario; (c) Sustainable Development Scenario.

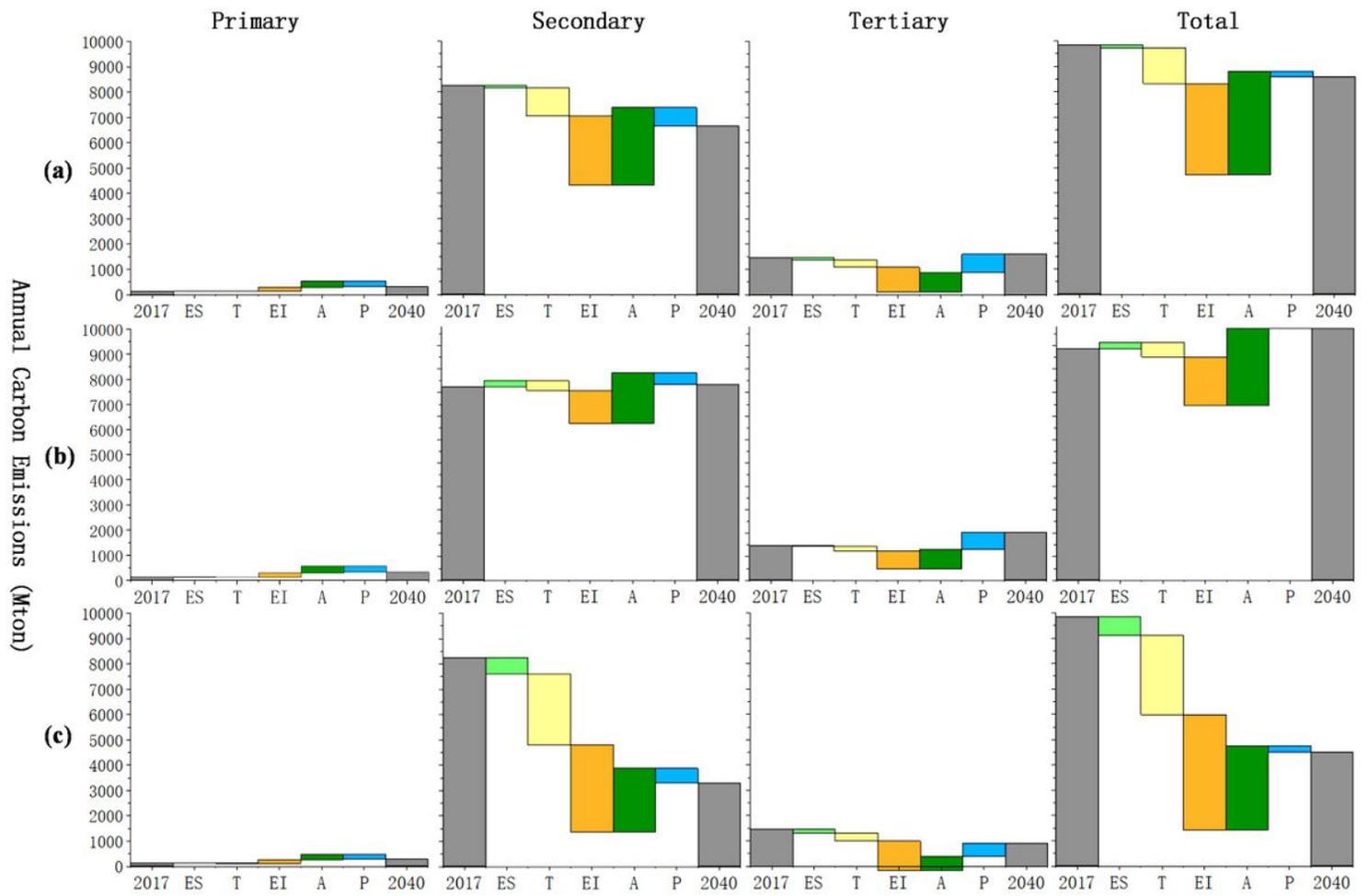


Figure 5

Decomposition result of China's CE during 1997-2040 in different sector. (a) New Policies Scenario; (b) Current Policies Scenario; (c) Sustainable Development Scenario.

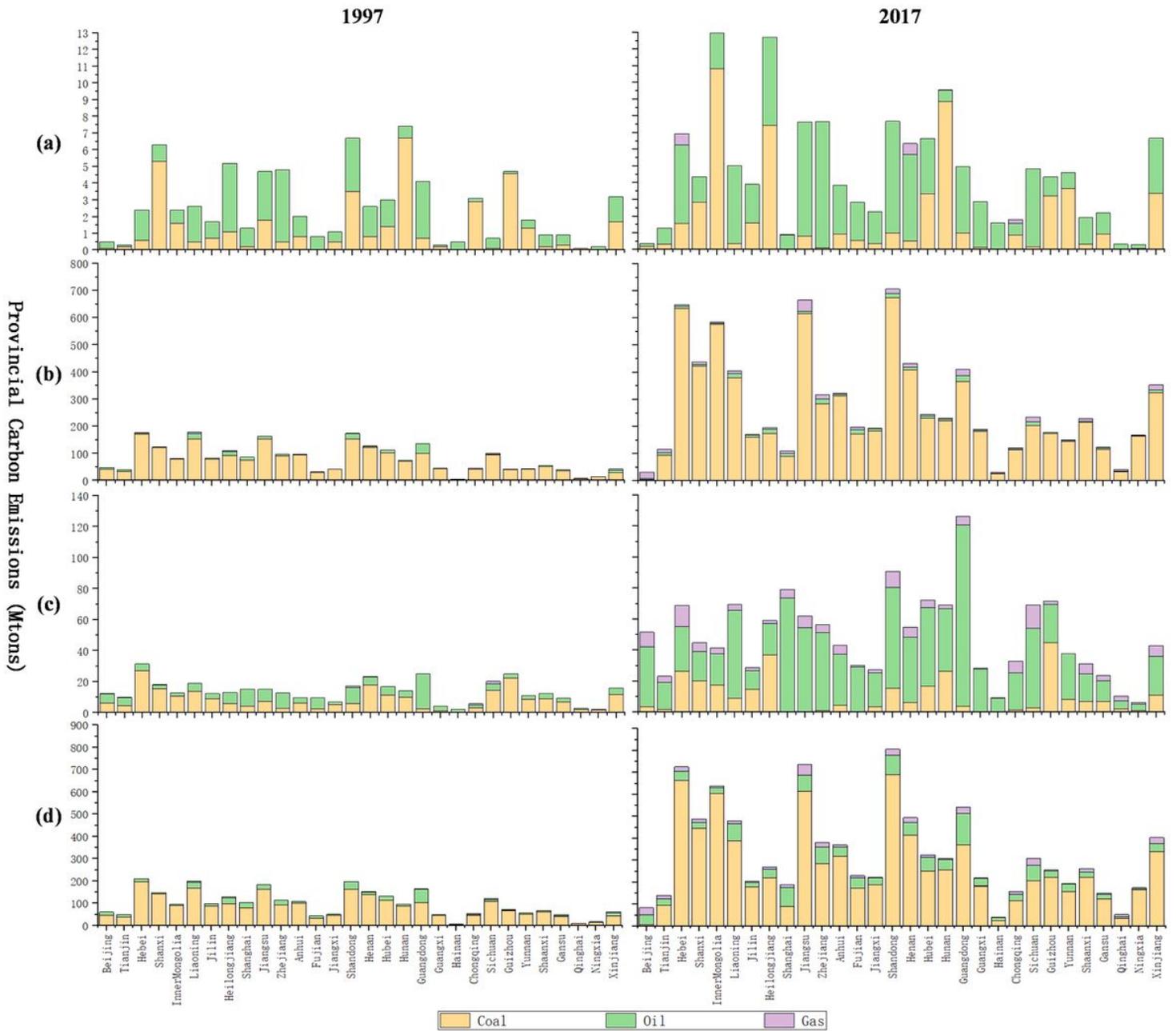


Figure 6

Provincial CEs during 1997-2017 (a) Primary Sector; (b) Secondary Sector; (c) Tertiary Sector; (d) National Total.

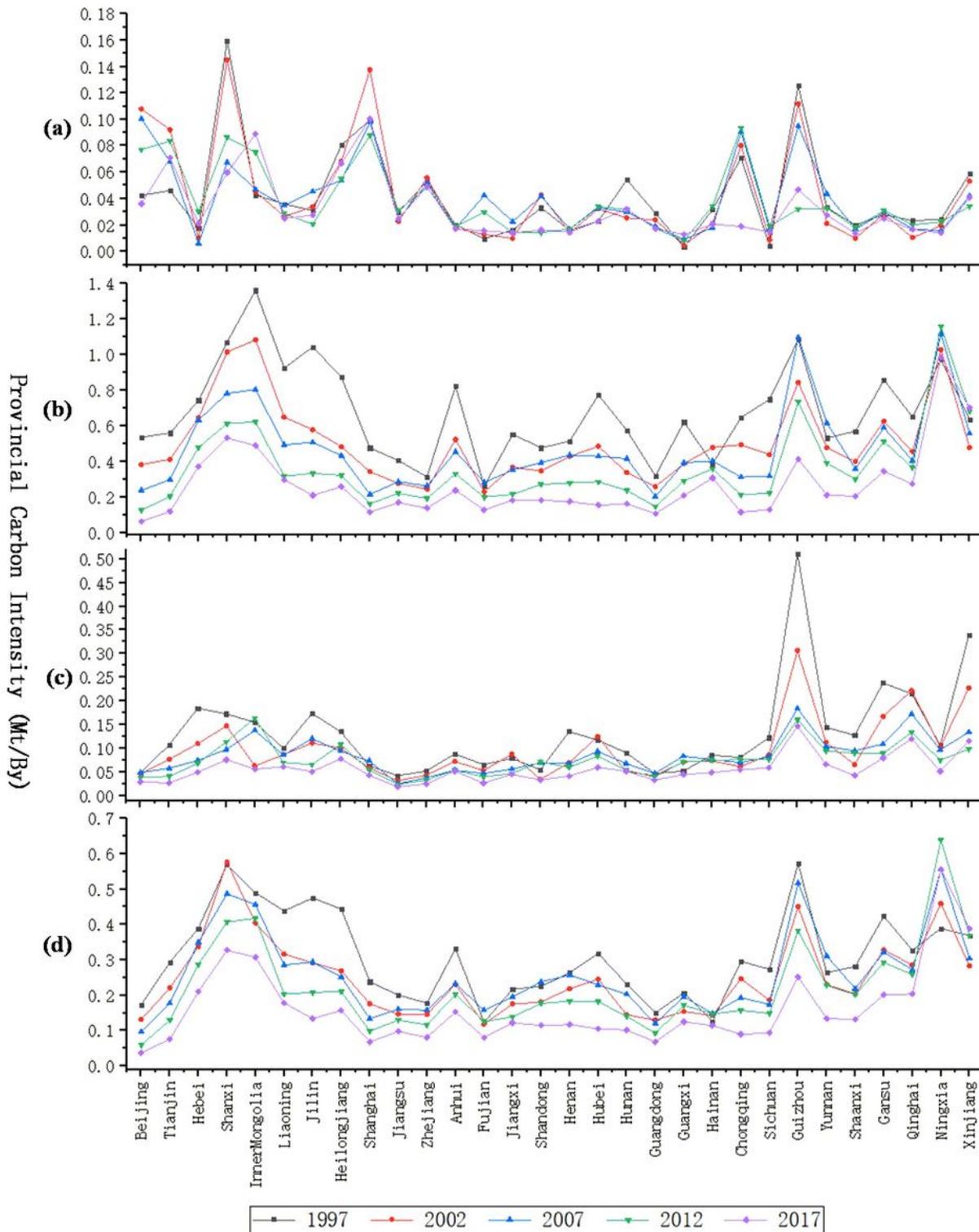


Figure 7

Provincial CI during 1997-2017 (a) Primary Sector; (b) Secondary Sector; (c) Tertiary Sector; (d) National Total.

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