Structural decline in China's CO2 emissions through transitions in industry and energy systems

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Structural decline in China's CO_2 emissions through transitions in industry and energy systems

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As part of the Paris Agreement, China pledged to peak its CO_2 emissions by 2030. In retrospect, the commitment may have been fulfilled as it was being made—China's emissions peaked in 2013 at a level of 9.53 gigatons of CO_2, and have declined in each year from 2014 to 2016. However, the prospect of maintaining the continuance of these reductions depends on the relative contributions of different changes in China. Here, we quantitatively evaluate the drivers of the peak and decline of China's CO_2 emissions between 2007 and 2016 using the latest available energy, economic and industry data. We find that slowing economic growth in China has made it easier to reduce emissions. Nevertheless, the decline is largely associated with changes in industrial structure and a decline in the share of coal used for energy. Decreasing energy intensity (energy per unit gross domestic product) and emissions intensity (emissions per unit energy) also contributed to the decline. Based on an econometric (cumulative sum) test, we confirm that there is a clear structural break in China's emission pattern around 2015. We conclude that the decline of Chinese emissions is structural and is likely to be sustained if the nascent industrial and energy system transitions continue.

China is the top CO_2-emitting nation, with emissions making up nearly one-third (29.5%) of the global total in 2015[1]. For this reason, international efforts to stabilize the Earth's climate depend heavily on the trajectory of Chinese emissions, and the country's recent pledge to reduce its annual emissions before 2030 has been widely celebrated[2,3]. Now, it is becoming clear that China may have already fulfilled this commitment. Estimates made by various organizations indicate that—after more than a decade of rapid growth—China's annual CO_2 emissions have decreased year on year over the period 2013–2016.

Although undoubtedly a watershed event, the peak of Chinese emissions prompts important questions about what factors are driving the current decrease, their relative importance, and whether or not the decline can be sustained or even accelerated. In particular, if China's emissions have fallen primarily as a result of slowing economic activity, as happened in the USA during the global financial crisis[4], renewed economic growth could reverse the decrease[5,6].

Here, we assess the drivers of Chinese emissions from 2007 to 2016. Details of the analytical approach and data sources are provided in the Methods and Supplementary Information. In summary, we have updated emissions inventories for China for 2000–2016 using the Intergovernmental Panel on Climate Change's (IPCC) sectoral approach[7] and the most recently published and revised statistics from the Chinese Government's Yearbooks. This was necessary to ensure consistency and sufficient sectoral detail, and because the underlying Chinese data have been repeatedly updated and revised. We use index decomposition analysis (IDA) to quantitatively evaluate the relative influence of eight socioeconomic factors on China's energy-related emissions. We then perform a cumulative sum test to investigate whether there has been any structural change in China's recent emissions patterns.

Trends in China's emissions and related indicators

The red curve in Fig.1a shows our estimates of Chinese emissions from 2000 to 2016, with other curves exhibiting similar emissions trends from five other prominent sources for comparison (see Methods for a more detailed comparison). China's emissions grew at an average annual rate of 9.3% between 2000 and 2013, from ~3.0 Gt in 2000 to a peak of 9.53 Gt CO_2 in 2013 (Fig. 1a). Emissions then declined by 1.0%, 1.8% and 0.4% in 2014, 2015 and 2016, respectively, reaching 9.2 Gt CO_2 in 2016 (8.5 Gt from fossil fuel combustion and 0.7 Gt from industrial processes).

Figure 1b shows contemporaneous trends in China's economic growth (green curve) and carbon intensity (purple curve): gross domestic product (GDP) growth has been rapid and monotonic, outpacing the growth of CO_2 emissions since 2007. As a result, the carbon intensity of the Chinese economy declined by 27% between 2000 and 2016 (Fig. 1b). As we will show, such decreases in emissions intensity hint at the underlying changes in China's industrial structure and energy efficiency. Meanwhile, Fig. 1c shows that China's energy consumption has continued to increase over the same period, but at a decelerated rate after 2011. Moreover, energy

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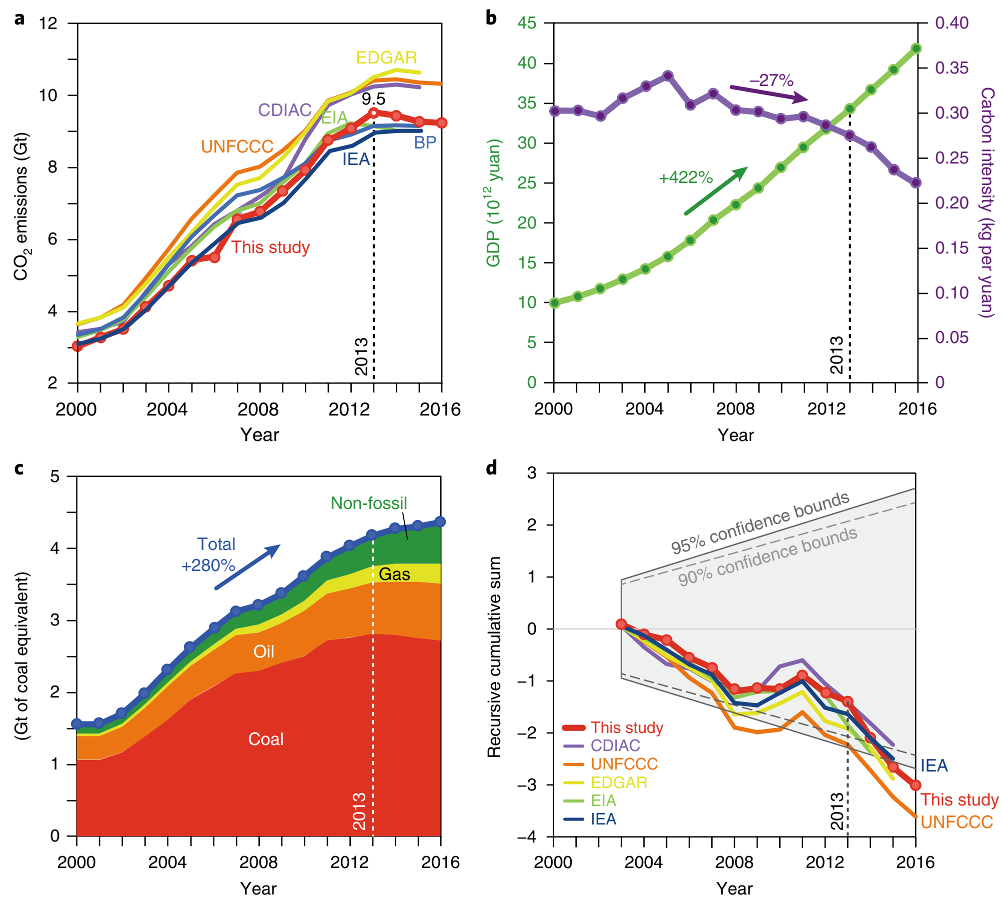

Fig. 1 | Temporal change of CO_2 emissions and related indicators in China from 2000 to 2016. a, Total carbon emissions from combustion of fossil fuels and cement production from different sources (EIA (https://www.eia.gov/), IEA (https://www.iea.org/statistics/topics/CO2emissions/) and BP[32] estimates exclude emissions from cement production). **b**, GDP and CO_2 emission intensity. **c**, Total energy consumption by fuel. **d**, Recursive cumulative sum plot of CO_2 emissions from different sources. The recursive cusum results for this study are the result of energy-related CO_2 emissions. If the plot of the recursive cusum process crosses the confidence bands, this indicates a significant structural break in that period.

from fossil fuels (areas shaded red, orange and yellow in Fig. 1c) has been essentially flat since emissions peaked in 2013, and the increase in total consumption in 2014–2016 has been met by non-fossil sources (green shading in Fig. 1c).

Based on our decomposition analysis, Fig. 2 shows the relative and absolute contribution of each of eight socioeconomic factors on Chinese energy-related CO_2 emissions: (1) population growth (dark blue); (2) economic growth (green); changes in the shares of Chinese energy supplied by (3) coal (light blue), (4) natural gas (yellow) and (5) oil (purple); (6) changes in the quality of fossil fuels burned (that is, fuel-specific changes in CO_2 emissions per unit energy; orange); (7) changes in energy intensity (that is, energy consumed per unit of GDP; red); and (8) changes in industrial structure (that is, the relative contributions of different types of industry to GDP). To facilitate this presentation and discussion, we subdivide the results from 2007 to 2016 into three 3-year periods.

Growing emissions 2007–2010 and 2010–2013

Between 2007 and 2013, the 40.9% increase in Chinese emissions was dominated by strong economic growth (Fig. 2, green bars), which—in the absence of other factors—would have caused emissions to increase by 29.3% and 24.6% during the periods 2007–2010 and 2010–2013, respectively. The next most important driver of increasing emissions during this time frame was the increasing quality of the fuels, and particularly coal, being burned in China (Fig. 2, orange bars). Higher quality coal (that is, anthracite) contains more carbon by mass, which results in more CO_2 emissions per ton of fuel burned than for lower quality coal (brown coal)[7]. Independent of other factors, changes in fuel quality led to emissions increases of 12.5% and 5.4% during the periods 2007–2010 and 2010–2013, respectively. Population growth also pushed Chinese emissions upward steadily during these time periods, by 1.6% in both 2007–2010 and 2010–2013 (Fig. 2, blue bars). Changes in the share of energy provided by oil and natural gas also caused small increases in emissions in 2007–2010 and 2010–2013, respectively (Fig. 2, purple and yellow bars).

During 2007–2013, when total Chinese emissions were increasing, several factors also acted to decrease emissions, effectively restraining the growth rate. Between 2007 and 2010, the most important of these was change in energy intensity (energy consumed per unit GDP), which—in the absence of other factors—would have caused emissions to decrease by 15.4% (Fig. 2, red bars). Although changing energy intensity continued to suppress emissions growth between 2010 and 2013, its influence during those years waned substantially, to a 3.2% decrease. Conversely, changes in China's industrial structure accounted for only a modest decreasing force in 2007–2010 (1.1%), but gained strength over the period 2010–2013, when it drove emissions down by 7.3% (Fig. 2, pink bars). Decreases in the share of China's energy derived from coal also acted to reduce emissions by 6.2% and 1.1% during the periods 2007–2010 and 2010–2013, respectively (Fig. 2, light blue bars). Similar changes in the share of energy provided by natural gas and

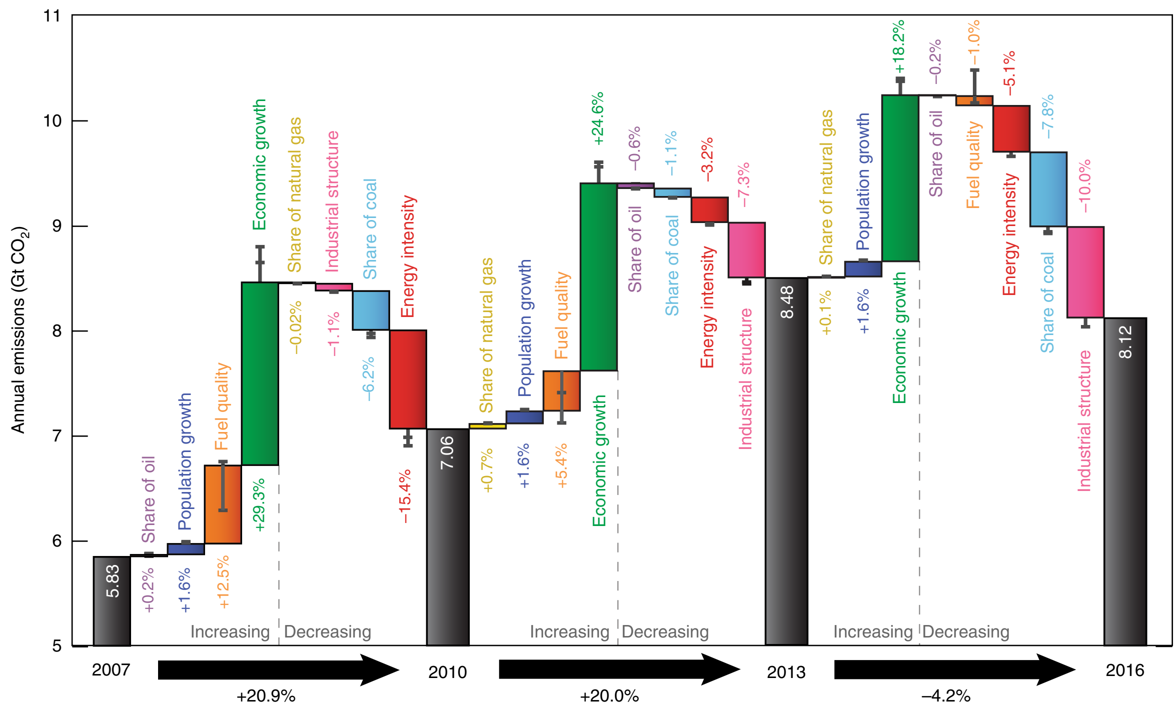

Fig. 2 | Contribution of each driver to the change in energy-related CO_2 emissions in the periods 2007–2010, 2010–2013 and 2013–2016. The length of each bar reflects the contribution of each factor per year. Error bars for each column are based on the range of decomposition results of emissions from EIA, IEA and BP statistics.

oil were responsible for small declines in emissions over 2007–2010 and 2010–2013, respectively (Fig. 2, yellow and purple bars).

Decreasing emissions 2013–2016

Chinese CO_2 emissions have declined since 2013, and a cumulative sum (cusum) test indicates that this decline is a structural change (Fig.1d and Supplementary Table 3). We examine the energy-related industrial emissions from 2000 to 2016, and, although the emissions show turning points around both 2008 and 2013, the cusum test suggests that only the change around 2015 (at the 95% confidence interval) is structurally significant. This evidence of structural change reflects changes in the driving forces during 2013–2016 having a more significant impact on the change in industrial CO_2 emissions than that in other periods. Between 2013 and 2016, the 4.2% decrease in Chinese emissions was driven by the combination of changes in industrial structure and further decreases in both the share of energy derived from coal and the energy intensity of China's economy (Fig. 2, pink, light blue and red bars, respectively). In the absence of other factors, these three factors would have caused emissions in the period 2013–2016 to decrease by 10.0%, 7.8% and 5.1%, respectively (22.9% in total). In addition, Chinese economic growth in 2013–2016 was somewhat slower than in the previous analysed periods, driving emissions up by 18.2% (6.4% less than in the period 2010–2013; green bars in Fig. 2). The 2013–2016 population growth continued to push emissions upward at the same pace as in the two previous three-year periods (1.6%; blue bars in Fig. 2), and changes in the share of energy derived from natural gas and oil exerted a very small influence (+0.1% and −0.2%, respectively; yellow and purple bars in Fig. 2). Finally, the quality of fuels being burned in China declined over 2013–2016, contributing to a small decrease in overall emissions (1.0%; orange bar in Fig. 2).

Figure 3 reveals further details underlying the decreases due to changes in industrial structure, coal consumption and energy intensity during the period 2013–2016. Figure 3a highlights the shift in China's industrial output in 2013–2016, away from energy- and emissions-intensive manufacturing towards higher value-added (for example, high technology) manufacturing and services. Such high-technology manufacturing and services have been the main source of growth in the Chinese economy in recent years, accounting for 71.9% of total value added in 2016, up from 64.4% in 2007. Service industries' value added increased from 46.9% of national GDP in 2013 to 50.5% in 2015 and 51.6% in 2016, thus reaching its largest proportion of the Chinese economy since 1952. Meanwhile, output from China's heavy industry has declined progressively, decreasing at an annual rate of 2.7% prior to 2013 and accelerating to an average annual decrease of 6.9% in 2013–2016[8].

Figure 3b reveals the sectors that have accounted for the drop in Chinese coal consumption in 2013–2016. Whereas coal consumption in China grew by an average of 6.6% per year between 2007 and 2013, supporting a tremendous expansion of capital infrastructure, coal consumption peaked at 4.2 Gt in 2013 and declined by an average of 5.6% per year in 2013–2016. The largest decreases in coal consumption occurred in the electricity sector, which accounted for 81.7% of the total reduction between 2013 and 2016 (pink bar in Fig. 3b). Other energy-related sectors, the coal washing and coking, together accounted for 21% (purple and green bars in Fig. 3b, respectively).

Importantly, the reduction in coal consumption occurred despite continued growth of total energy consumption by 2.2%, 0.9% and 1.1% in 2014, 2015 and 2016, respectively (Fig. 1c). As coal use decreased, rising energy demand was met by the rapid growth of renewable and nuclear energy, which increased at an average annual rate of 10.5% per year in 2007–2013 and 11% in 2013–2016. Although increasing from a small base (8% of total energy consumed in 2002), persistently high growth rates have led to non-fossil fuel energy supplying 13.3% of China's energy in 2016. Meanwhile, coal's share in the energy mix was essentially constant at ~68% in 2007–2013, then dropping to 62% in 2016 (Fig. 1c).

The structural trends in China's economy have been reinforced by contemporaneous improvements in efficiency and thereby

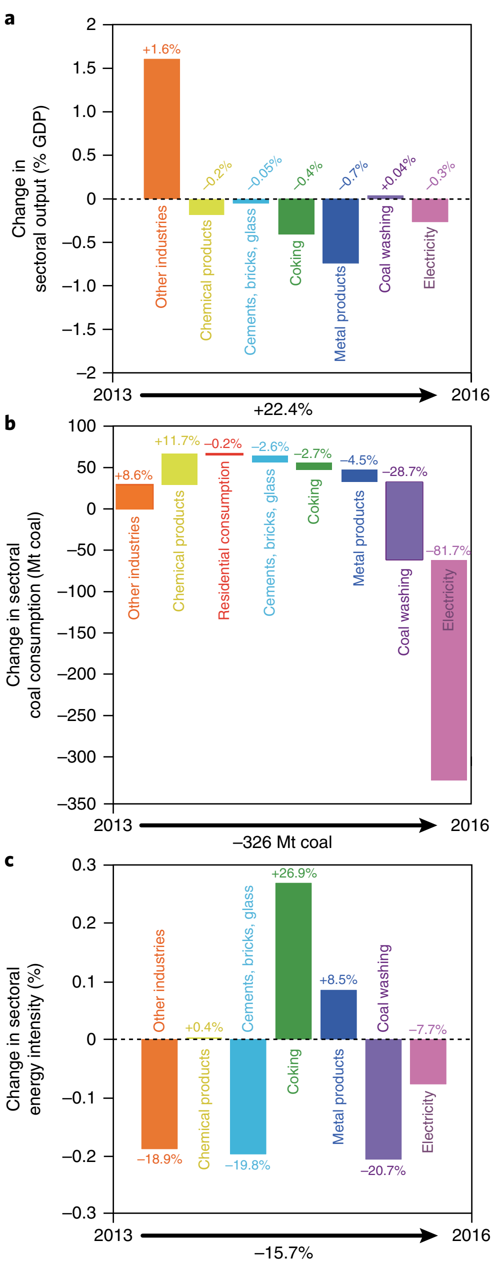

Fig. 3 | Sector-specific changes from 2013 to 2016 in China. a–c, Change in sectoral contribution to national GDP (**a**), coal consumption (**b**) and energy intensity (energy per unit of output, t per $) (**c**). Different coloured bars represent the main contributing sectors. Percentages above the bars in **b** are the sectoral contribution to the total change in coal consumption from 2013 to 2016.

decreasing energy intensity. Figure 3 shows some of the sectoral changes between 2013 and 2016. In particular, output from metal products, coking and chemical products sectors decreased, while 'other industries' (including the high technology and service industries) increased substantially (Fig. 3a). Also, the decreases in coal consumption over this timespan were largely in the electricity and coal washing sectors, with modest increases in consumption by the other industries and chemical products sectors (Fig. 3b). Finally, there were large decreases in energy per unit output of the other industries, cement, bricks and glass, coal washing and electricity sectors in 2013–2016, offset to some extent by increases in the energy intensity of coking and metal products (Fig. 3c).

Maintenance of lower emissions. After nearly two decades of rapidly rising emissions, a changing industrial structure, shifting energy mix, improving energy efficiency and economic deceleration caused Chinese emissions to peak at 9.53 Gt CO_2 in 2013 and decline by 4.2% in the years since. As the world's top emitting and manufacturing nation, this reversal is cause for cautious optimism among those seeking to stabilize the Earth's climate. Although some emissions inventories show the peak occurring a year earlier or later, the sensitivity testing of our decomposition analysis shows the relative contributions of the different drivers are consistent and robust (Fig. 2). Now, the important question is whether the decline in Chinese emissions will persist.

On the one hand, commentators have argued that the timetable of China's peak emissions pledge was not very ambitious[9,10]. For example, Green and Stern[11] argue 'China's international commitment to peak emissions "around 2030" should be seen as a highly conservative upper limit from a government that prefers to under-promise and over-deliver'. On the other hand, a 2013 peak is far sooner than anyone thought possible when Chinese President Xi Jinping first made the pledge in 2014.

Moreover, history suggests caution is warranted in concluding that the reversal in emissions will hold over the long term. Although the shift towards services and away from more energy-intensive manufacturing is unambiguous[11], China's economic growth has decelerated twice before. Most recently, after double digit growth from 1992 to 1996, China's economy slowed during the South-East Asian economic crisis, when growth fell to an average of 8% for the four years 1998–2001 before accelerating again by the mid-2000s. Similarly, rapid economic growth in the mid-1980s dropped dramatically to 4% between 1989 and 1991 before accelerating again in the 1990s[12]. Chinese emissions were essentially flat in 2016 (−0.4%), and—all other factors staying the same—a slight acceleration of economic growth (for example, from 6.7% in 2015 to 7.1% in 2016) would have caused an increase in total emissions (in reality, the Chinese economy grew by 6.7% in 2016).

The changes in China's economic structure that have led to the recent decline are the result of consistent and strategic policies to improve industry structure[9,13,14], especially after 2010, which is consistent with previous studies[15,16]. More efforts have been made in recent years. From 2012 to 2015, China eliminated outdated capacity in 16 energy-intensive industries. For example, coal-fired power generation capacity declined by 21.1 GW, and there were reductions of 520 Mt in coal production, 126 Mt in iron and steel processing, and 500 Mt in cement[17]. These structural changes have been reinforced by policies aimed at improving air quality and boosting the deployment of low-carbon energy sources[18]. For example, the Chinese government has strictly limited the development of new coal-fired power plants since 2013. Air quality policies have also encouraged more efficient use of coal, such as by phasing out older, smaller coal-fired power plants[18].

However, recent progress in China, such as the retirement of small, old and especially inefficient plants, offers a one-time decrease in emissions that is not easily repeated. The majority of coal-fired power plants now operating in China are large, modern power plants that have been built since the mid-1990s[19], and investments in coal-fired plants seem to have declined significantly from 2015 to 2017[20,21]. Thus, further emissions reductions may increasingly depend on overcoming considerable infrastructural inertia by replacing valuable, young generators that burn coal with non-fossil electricity. Escaping carbon lock-in may therefore test the political will of China's central government[22,23].

Nonetheless, government policies are a sign that the nascent decline in China's emissions will continue. China's seven local and regional pilot carbon market schemes will be replaced by a nationwide emissions trading scheme in 2018[24]. China has also pledged to improve national energy intensity during the period 2015–2020[25], which will further translate to emissions reduction in coming years[25]. Moreover, in response to the USA withdrawal from the Paris Agreement, China has increasingly assumed a leadership role in climate change mitigation, and its five-year progress reports under the agreement will be heavily scrutinized by the rest of the world.

Besides climate, energy security and public health goals will discourage coal consumption. Although China still produces almost 4 billion tons of coal a year (over three times that of the USA, the next largest producer), it also imports more coal than any other country, prompting concerns about energy independence and security[26]. At the same time, rising incomes in major cities and concerns about the health impacts of poor air quality can be expected to lead to the close of any remaining older coal-fired boilers and encourage a shift to natural gas, particularly in regions such as Southern and Eastern China, which are both more affluent and more reliant on imported coal[27].

Other policies cut in both directions. For example, the One Belt One Road policy emphasizes both public transport infrastructure and road transportation, and seeks to export coal technologies to neighbours such as Pakistan. As a result, growth in personal transportation could lead to large increases in emissions over the next decade (as evidenced by the growth in new and cheap sport utility vehicle (SUV) sales at recent low retail prices)[28]. However, over the longer term, electric vehicles may avoid such emissions, assuming the availability of low-carbon electricity[29].

China's emissions may fluctuate in the coming years and that may mean that 2013 may not be the final peak[30]. For example, extrapolating from data for the first six months of 2017, Jackson and colleagues argue that Chinese CO_2 emissions (including cement) may rise for all of 2017[31]. However, the changes in industrial activities, coal use and efficiency that have caused the recent decline have roots in the changing structure of China's economy and long-term government policies. The recent Chinese policy directive to cap coal at 4 billion metric tonnes per year requires its proportion in the energy mix to decrease from 64% in 2015 to around 58% by 2020. Such pressures suggest that the downward trend in emissions could persist as China's economy shifts from heavy and low-value manufacturing to high-technology and service industries. Both emissions and their underlying drivers will need to be carefully monitored, but the fact that China's emissions have decreased for several years—and more importantly the reasons why—give hope for further decreases going forward.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41561-018-0161-1.

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Author contributions

D.G., D.M.R and S.J.D. conceived the study. D.G. led the study. Y.S. and Z.M. provided energy and emission data. J.M. performed decomposition analysis. N.Z. and S.S. performed the econometric analysis. All authors (D.G., J.M., D.M.R., N.Z., Y.S., Z.M., S.S., Z.L., Q.Z. and S.J.D.) interpreted the data and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Emissions estimates and data sources. The national CO_2 emissions used in this study include two parts: energy-related emissions (emissions from fossil fuel combustion), and process-related emissions (emissions from cement industry processes). According to the IPCC guidelines[7], energy-related CO_2 emissions (CE) equals activity data (AD, fossil fuel consumption) multiplied by the parameters net calorific value (NCV), emission factor of CO_2 (EF) and oxygenation efficiency (O):

$$CE_{ij} = AD_{ij} \times NCV_i \times EF_i \times O_{ij} \tag{1}$$

Here, CE_{ij} refers to the CO_2 emissions by energy type (i) and sector (j). The emissions are calculated for 17 different energy types (Supplementary Table 1) and 47 socioeconomic sectors (Supplementary Table 2) in this study.

AD_{ij} represents the fossil fuel consumption by the corresponding energy types and sectors. Energy loss during transportation, energy processes and input as a raw material in a chemical process are excluded from the consumption as these parts of the energy use will not emit any CO_2 (ref. [33]). All data were collected from the most up-to-date energy balance tables and energy consumption by sectors published in Energy Statistical Yearbooks[34].

NCV_i in equation (1) refers to the net caloric value, which is the heat value produced per physical unit of fossil fuel combusted. EF_i is the CO_2 emissions per net caloric value produced for different fossil fuel types. O_{ij} is the oxygenation efficiency, which refers to the oxidation ratio when burning fossil fuels. We consider different oxygenation efficiencies for fossil fuels used in different sectors, as the combustion technology levels differ by sector in China.

All three parameters were collected based on our previous survey of China's fossil fuel quality[35] and are assumed to be unchanged throughout the study period[33,36]. The emission factors of coal-related fuels are approximately 40% lower than the IPCC default value, while the oil- and gas-related fuels' emission factors are close to the IPCC values. The oxygenation efficiencies are calculated based on the different combustion levels of China's industrial sectors. The average oxygenation efficiency for coal-related fuels is 92%, lower than the values of 100% and 98% used by the United Nations (UN) and IPCC. China Emission Accounts and Datasets (CEADs) also employs the latest energy consumption data adjusted by National Bureau of Statistics (NBS) in 2014. The data adjustment in 2014 brings a 5% increase to the total CO_2 emissions. The parameters in this study are now being widely used by the Chinese Government in its recently released report on climate change[37].

We calculate the process-related CO_2 emissions (cement production) in equation (2): CE_t refers to CO_2 emission from cement production in China. The activity data (AD_t) refer to cement production, and are collected from China's Statistical Yearbook 2001–2017[8]. The emission factor for cement production (EF_t) is also collect from our previous research[35].

$$CE_t = AD_t \times EF_t \tag{2}$$

Decomposition analysis. Decomposition analysis (DA) methods have been used extensively to quantify the contribution of socioeconomic drivers to changes in environmental pressures[6,38,39]. Two decomposition approaches are by far the most popular: index decomposition analysis (IDA) and structural decomposition analysis (SDA). Compared with SDA, which is based on input–output coefficients and final demands from input–output tables, IDA is more suitable for time-series analysis using data with sufficient temporal and sectoral detail[40,41]. The advantage of the IDA approach is that it can be easily applied to any data at any level of aggregation[42].

Among specific IDA methodologies, the Logarithmic Mean Divisia Index (LMDI) has been shown by past studies to be favourable because of its path independence, consistency in aggregation, and ability to handle zero values[43–45]. As a result, many studies have used LMDI to provide policy-relevant insights, for instance by identifying the driving forces of energy consumption[42,46,47] and changes in CO_2 emissions[48–51]. The LMDI analysis compares a set of indices between the base and final year of a given period, and explores the effects of these indices on the trend of emissions over that period[42]. See Supplementary Information for detailed calculation.

In this study, we decompose the national energy-related industrial CO_2 emissions (C) as

$$C = \sum_i \sum_j C_{ij} = \sum_i \sum_j P \times \frac{G}{P} \times \frac{G_j}{G} \times \frac{E_j}{G_j} \times \frac{E_{ij}}{E_j} \times \frac{C_{ij}}{E_{ij}} = \sum_i \sum_j P \times Y \times S_j \times I_j \times M_{ij} \times T_{ij} \tag{3}$$

where C represents national energy-related industrial CO_2 emissions, C_{ij} is the CO_2 emissions in sector j (where sector $j = 1,2,3,4$ represents light industries, heavy industries, high-technology industries and agricultural & service industries; see Supplementary Table 2 for sector definitions) by fuel type i (where $i = 1,2,3$ represents coal, oil and natural gas, respectively), G_j is GDP of sector j, E_{ij} is the consumption of fuel type i in sector j. Thus, according to equation (1), C is represented by six factors:

P is population;

$Y = G/P$ stands for GDP per capita and measures economic growth;

$S_j = G_j/G$ is sector j's share of total GDP, representing the industrial structure;

$I_j = E_j/G_j$ is the energy intensity in sector j and measures the energy consumption per unit of GDP, which indicates the energy efficiency;

$M_{ij} = E_{ij}/E_j$ is the proportion of fuel type i in sector j and represents the energy mix effect; M_1, M_2 and M_3 in equation (4) describe the proportion of coal, oil and natural gas in the entire economy. The effect of non-fossil energy proportion is assessed to be zero.

$T_{ij} = C_{ij}/E_{ij}$ is the emission intensity of fuel type i in sector j, reflecting changes in fuel carbon content upgrades (for example, replacing brown coal with anthracite) within any broad fuel type (that is, coal consumption). Seventeen types of fossil fuel are included in this study (Supplementary Table 1), which is aggregated into three categories (coal, oil and gas).

Thus, the change of energy-related industrial CO_2 emissions in year t compared with the year $t-1$ is calculated as

$$\begin{aligned}\Delta C_{\text{tot}} = {} & \sum_i^3 \sum_j^4 L(w_{ij}^t, w_{ij}^{t-1}) ln\left(\frac{P^t}{P^{t-1}}\right) + \sum_i^3 \sum_j^4 L(w_{ij}^t, w_{ij}^{t-1}) ln\left(\frac{Y^t}{Y^{t-1}}\right) \\ & + \sum_i^3 \sum_j^4 L(w_{ij}^t, w_{ij}^{t-1}) ln\left(\frac{S_j^t}{S_j^{t-1}}\right) + \sum_i^3 \sum_j^4 L(w_{ij}^t, w_{ij}^{t-1}) ln\left(\frac{I_j^t}{I_j^{t-1}}\right) \\ & + \sum_j^4 L(w_{1j}^t, w_{1j}^{t-1}) ln\left(\frac{M_{1j}^t}{M_{1j}^{t-1}}\right) + \sum_j^4 L(w_2^t, w_2^{t-1}) ln\left(\frac{M_{2j}^t}{M_{2j}^{t-1}}\right) \\ & + \sum_j^4 L(w_3^t, w_3^{t-1}) ln\left(\frac{M_{3j}^t}{M_{3j}^{t-1}}\right) + \sum_i^3 \sum_j^4 L(w_{ij}^t, w_{ij}^{t-1}) ln\left(\frac{T_{ij}^t}{T_{ij}^{t-1}}\right) \\ = {} & \Delta C_{\text{P}} + \Delta C_{\text{Y}} + \Delta C_{\text{S}} + \Delta C_{\text{I}} + \Delta C_{\text{coal}} + \Delta C_{\text{oil}} + \Delta C_{\text{gas}} + \Delta C_{\text{T}}\end{aligned} \tag{4}$$

Here, $L(w_{ij}^t, w_{ij}^{t-1}) = (C_{ij}^t - C_{ij}^{t-1}) / (\ln(C_{ij}^t) - \ln(C_{ij}^{t-1}))$, is a weighting factor called the logarithmic mean weight. ΔC_{P}, ΔC_{Y}, ΔC_{S}, ΔC_{I}, ΔC_{coal}, ΔC_{oil}, ΔC_{gas} and ΔC_{T} are CO_2 emission changes owing to population variation, economic growth, industrial structure adjustment, energy intensity effect, changes in the proportion of coal, oil and natural gas consumption, and emission intensity change, respectively. The decomposition analysis with CO_2 emissions estimated in this study is defined as the base decomposition.

Sensitivity test. To assess the extent to which different factors' contributions are affected by national CO_2 emissions, we conduct a sensitivity analysis that decomposes the emissions from the BP, IEA and EIA databases (Fig. 1a). CO_2 emissions from other data sources were obtained from the Carbon Dioxide Information Analysis Centre (CDIAC)[1], the Emissions Database for Global Atmospheric Research (EDGAR)[52], the United Nations Framework Convention on Climate Change (UNFCCC)[1,53], the US Energy Information Administration (EIA, https://www.eia.gov/), the International Energy Agency (IEA, https://www.iea.org/statistics/topics/CO2emissions/) and British Petroleum (BP)[32].The national fossil fuel emissions for the different data sources are given by C_{BP}, C_{IEA} and C_{EIA}, respectively. They are then split into different fuel types in different sectors (C_{ij}) with the share (C_{ij}/C) in the base decomposition. Decomposition 1(C_{BP}), decomposition 2 (C_{EIA}) and decomposition 3 (C_{IEA}) are conducted with the same E_{ij}, E_j and P in the base decomposition. The range of results for decompositions 1, 2 and 3 are shown as error bars in Fig. 2.

Cumulative sum test. We use an econometric approach to investigate whether a structural break of energy-related carbon emissions occurred in the industrial sector over the period 2000–2016. The occurrence of a structural break is examined using the cumulative sum (cusum) test introduced by Brown and colleagues[54] and Ploberger and Krämer[55].

We model the total energy-related CO_2 emissions as a function of its first-order lag as follows:

$$\text{CO2}_t = \beta_t \text{CO2}_{t-1} + e_t \quad t = 1, \dots, T \tag{5}$$

where β_t is a vector of time-varying parameters and e_t is an independent and identically normally distributed error term. The null hypothesis for the test of parameter stability is H_0: $\beta_t = \beta$, which is interpreted as the parameter β being constant over time. Under the null hypothesis, the recursive residuals are assumed to be independent and identically distributed as $N(0, \sigma_e^3)$, and the cumulative sum of the recursive residuals also has a mean of zero. The formula for the cumulative sum of the recursive residuals can be found in ref. [54].

The null hypothesis can be rejected if the cusum statistic is larger than a critical value at 90%, 95% or 99%. Once the null hypothesis is rejected, it implies that there is a structural break during this period.

Data availability. The original data that support the findings of this study can be freely downloaded from the China Emission Accounts and Datasets (CEADS) website (http://www.ceads.net/). The data descriptor has been published on *Scientific Data* to facilitate reuse[36,56].

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