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

Dabo Guan[1,2,*], Jing Meng[2,3,*], David M. Reiner[4], Ning Zhang[5], Yuli Shan[2], Zhifu Mi[6], Shuai Shao[7], Zhu Liu[1,8], Qiang Zhang[1] and Steven J. Davis[9]

[1] Department of Earth System Science, Tsinghua University, Beijing, 150080, China

[2] Water Security Research Centre, School of International Development, University of East Anglia, Norwich NR4 7JT, UK

[3] Department of Politics and International Studies, University of Cambridge, Cambridge CB3 9DT, UK

[4] Judge Business School, University of Cambridge, Cambridge CB2 1AG UK

[5] College of Economics, Jinan University, Guangzhou 510632, China

[6] The Bartlett School of Construction and Project Management, University College London, WC1E 7HB, London, UK

[7] School of Urban and Regional Science, Shanghai University of Finance and Economics, Shanghai 200433, China

[8] Tyndall Centre for Climate Change Research, School of International Development, University of East Anglia, Norwich NR4 7JT, UK

[9] Department of Earth System Science, University of California, Irvine, Irvine, California 92697, USA

* These authors contributed equally to this work.

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 declined in each year from 2014 to 2016. However, the prospect for maintenance of the continued reductions depend 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 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 GDP) 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 from 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 a third (29.5%) of the global total in 2015 [1]. For this reason, international efforts to stabilize the Earth's climate depend heavily upon 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 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 are have fallen primarily as a result of slowing economic activity, as happened in the U.S. during the global financial crisis [4], renewed economic growth could reverse the decrease [5,6].

Here, we assess the drivers of Chinese emissions from 2007-2016. Details of the analytical approach and data sources are provided in the *Methods* section below and Supplementary Information (SI). In summary, we update 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 Chinese government Yearbooks. This was necessary to ensure consistency and sufficient sectoral detail, and because the underlying Chinese data has 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, energy consumption and economic activity. The red curve in Fig.1a shows our estimates of Chinese emissions from 2000-2016, with other curves exhibiting similar emissions similar 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 9.5 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).

Fig.1b shows contemporaneous trends in China's economic growth (green curve) and carbon intensity (purple curve): 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 2000-2016 (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, Figure 1C shows that China's energy consumption has continued to increase over the same period, but at a decelerated rate after 2011. Moreover, energy 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 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 (i.e. fuel-specific changes in CO_2 emissions per unit energy; orange); (7) changes in energy intensity (i.e. energy consumed per unit of GDP; red); and (8) changes in industrial structure (i.e. the relative contributions of different types of industry to GDP). In order to facilitate presentation and discussion, we subdivide the results from 2007-2016 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 fuels, and particularly coal, being burned in China (Fig. 2, orange bars). Higher quality coal (i.e., anthracite) contains greater carbon by mass, which results in more CO_2 emissions per ton of fuel burned than does lower quality coal (i.e., 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 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 2007-2010, the most important of these was changes 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 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 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 examined the energy related industrial emissions from 2000 to 2016. Although the emissions show turning points around both 2008 and 2013, the cusum test suggests that only the change from 2015 (at 95% condifence intervel) 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 over 2013-2016 to decrease by 10.0%, 7.8%, and 5.1%, respectively (22.9% in total). In addition, Chinese economic growth 2013-2016 was somewhat slower than in the previous analyzed periods, driving emissions up by 18.2% (6.4% less than in the period 2010-2013; green bars in Fig. 2). 2013-2016 population growth continued to push emissions upward at the same pace as in the two previous 3-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).

Fig. 3 reveals further details underlying the decreases due to changes in industrial structure, coal consumption, and energy intensity during 2013-2016. Fig. 3a highlights the shift in China's industrial outputs over 2013-2016, away from energy- and emissions-intensive manufacturing towards higher value-added (e.g., 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% 2013-2016 [8].

Fig. 3b reveals the sectors that have accounted for the drop in Chinese coal consumption over 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 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 rapid growth of renewable and nuclear energy, which increased at an average annual rate of 10.5% per year 2007-2013, and 11% 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% 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 decreasing energy intensity. Fig. 3 shows some of the sectoral changes between 2013 and 2016. In particular, output from the metal products, coking, and chemical products sectors decreased while "other industries" (including the high technology and service industries) increased substantially (Fig. 3a). Also shown, 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 2013-2016, offset to some extent by increases in the energy intensity of coking and metal products (Fig. 3c).

Maintenance of the 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 9.5 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, 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 (2016) [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." But 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 1992-1996, China's economy slowed during the 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 (e.g., 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 (gigawatts), as well as reductions of 520 Mt (million tonnes) in coal production, 126 Mt in iron and steel processing and 500 Mt of cement [17]. These structural changes have been reinforced by policies aimed at improving air quality and boosting deployment of low-carbon energy sources [18]. For example, the Chinese government has strictly limited 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 plant seem to have declined significantly from 2015 to 2017 [20,21]. Thus, further emissions reductions may increasingly depend on overcoming consider able 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 2015-2020 [25], which will further translate to emissions reduction in coming years [25]. Moreover, in response to the U.S. 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 United States, the next largest producer), it also imports more coal than any other country, prompting concerns of 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 close any remaining older coal-fired boilers and encourage a shift to natural gas, particularly in regions such as Southern and Eastern China that 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 neighbors 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 produced SUV sales at recent low retailing 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 et al. 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.

References

1. Boden, T. A., Marland, G. & Andres, R. J. *Global, Regional, and National Fossil-Fuel CO_2 Emissions.* Oak Ridge National Laboratory, U.S. Department of Energy. http://cdiac.ornl.gov/CO2_Emission/timeseries/national (2016).
2. Liu, Z. *et al.* Steps to China's carbon peak. *Nature* **522**, 279-281 (2015).
3. Wang, X. & Zhang, S. Exploring linkages among China's 2030 climate targets. *Clim Policy* **17**, 458-469 (2017).
4. Feng, K., Davis, S. J., Sun, L. & Hubacek, K. Drivers of the US CO_2 emissions 1997–2013. *Nature Communications* **6**, 7714 (2015).

5. Jackson, R. B. *et al.* Reaching peak emissions. *Nature Climate Change* **6**, 7-10 (2015).

6. Peters, G. P. *et al.* Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Clim. Change* **7**, 118-122 (2017).

7. IPCC. *IPCC Guidelines for national greenhouse gas inventories*. (Institute for Global Environmental Strategies (IGES), 2006).

8. National Bureau of Statistics of the People's Republic of China. *China Statistical Yearbook 1998-2016* (China statistics press, 1998-2017).

9. Mi, Z. *et al.* Pattern changes in determinants of Chinese emissions. *Environ. Res. Lett.* **12**, 074003 (2017).

10. He, J. Analysis of CO_2 emissions peak: China's objective and strategy. *Chinese Journal of Population Resources and Environment* **12**, 189-198 (2014).

11. Green, F. & Stern, N. China's changing economy: implications for its carbon dioxide emissions. *Climate Policy*, 1-15 (2016).

12. Hubacek, K., Guan, D. & Barua, A. Changing lifestyles and consumption patterns in developing countries: A scenario analysis for China and India. *Futures* **39**, 1084-1096 (2007).

13. West, J. J. *et al.* Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature climate change* **3**, 885 (2013).

14. Mi, Z. *et al.* Chinese CO_2 emission flows have reversed since the global financial crisis. *Nature communications* **8**, 1712 (2017).

15. Qi, Y., Stern, N., Wu, T., Lu, J. & Green, F. China's post-coal growth. *Nat. Geosci.* **9**, 564-566 (2016).

16. Guan, D., Peters, G. P., Weber, C. L. & Hubacek, K. Journey to world top emitter: An analysis of the driving forces of China's recent CO_2 emissions surge. *Geophys. Res. Lett.* **36**, L04709 (2009).

17. National Bureau of Statistics of the People's Republic of China. New Pattern of energy development, new achievement of energy saving. http://www.stats.gov.cn/tjsj/sjjd/201707/t20170707_1510973.html. (2017).

18. Zhang, Q., He, K. & Huo, H. Policy: cleaning China's air. *Nature* **484**, 161 (2012).

19. Minx, J. C. *et al.* A "carbonizing dragon": China's fast growing CO_2 emissions revisited. *Environmental science & technology* **45**, 9144-9153 (2011).

20. Edenhofer, O., Steckel, J. C., Jakob, M. & Bertram, C. Reports of coal's terminal decline may be exaggerated. *Environ. Res. Lett.* **13**, 024019 (2018).

21. Shearer, C., Ghio, N., Myllyvirta, L., Yu, A. & Nace, T. *Boom and Bust: Tracking the Global Coal Plant Pipeline* (CoalSwarm, Greenpeace USA, Sierra Club, 2017).

22. Davis, S. J. & Socolow, R. H. Commitment accounting of CO_2 emissions. *Environ. Res. Lett.* **9**, 084018 (2014).

23. Seto, K. C. *et al.* Carbon lock-in: Types, causes, and policy implications. *Annual Review of Environment and Resources* **41**, 425-452 (2016).

24. Guan, D., Shan, Y., Liu, Z. & He, K. Performance Assessment and Outlook of China's Emission-Trading Scheme. *Engineering* **2**, 398-401 (2016).

25. Hu, A.-G. The Five-Year Plan: A new tool for energy saving and emissions reduction in China. *Advances in Climate Change Research* **7**, 222-228 (2016).

26. International Energy Agency. Coal Information 2016. http://www.iea.org/bookshop/722 Coal_Information_2016. (2016).

27. Sheehan, P., Cheng, E., English, A. & Sun, F. China's response to the air pollution shock. *Nature Climate Change* **4**, 306-309 (2014).

28. Wiedenhofer, D. *et al.* Unequal household carbon footprints in China. *Nature Clim. Change* **7**, 7580, 2017).

29. Hofmann, J., Guan, D., Chalvatzis, K. & Huo, H. Assessment of electrical vehicles as a successful driver for reducing CO_2 emissions in China. *Appl. Energy* (2016).

30. Zheng, H. *et al.* How modifications of China's energy data affect carbon mitigation targets. *Energy Policy* **116**, 337-343 (2018).

31. Jackson, R. *et al.* Warning signs for stabilizing global CO_2 emissions. *Environ. Res. Lett.* **12**, 110202 (2017).

Acknowledgments. This work was supported by the National Natural Science Foundation of China (41629501), National Key R&D Program of China (2016YFA0602604 and 2016YFC0206202), National Natural Science Foundation of China (71373153, 91746112, 71773075, 71761137001 and 71503168), National Social Science Foundation of China (15ZDA054), the UK Natural Environment Research Council (NE/N00714X/1 and NE/P019900/1) and Economic and Social Research Council (ES/L016028/1), British Academy Grant (AF150310) and the Philip Leverhulme Prize.

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 interpreted the data results and wrote the paper.

Author Information Correspondence and requests for materials should be addressed to J.M. (jm2218@cam.ac.uk), N.Z (zn928@naver.com), S.S (shao.shuai@sufe.edu.cn), and S.J.D. (sjdavis@uci.edu).

Competing interests: The Authors declare no Competing Financial or Non-Financial Interests.

Figure captions

Figure 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[32], IEA[33] and BP[34] 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* is the result of energy-related CO_2 emissions. If the plot of the recursive cusum process crosses the confidence bands, indicating a significant structural break in that period.

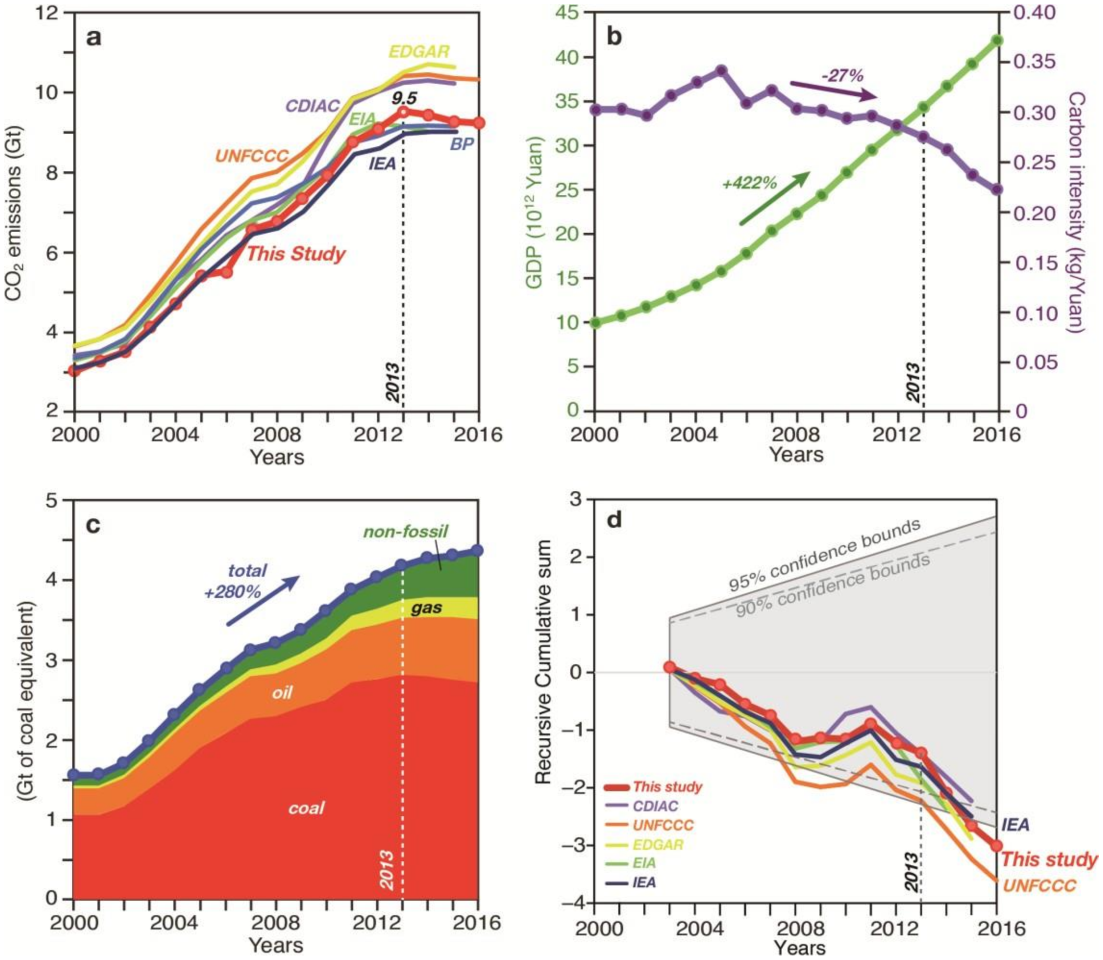


Figure 2. **Contribution of each driver to the change in national CO_2 emissions in the periods 2007-2010, 2010-2013 and 2013-2016.** The length of the bar reflects the contribution of each factor per year. The error bar of each column is based on the range of the decomposition results of emissions from EIA, IEA and BP statistics.

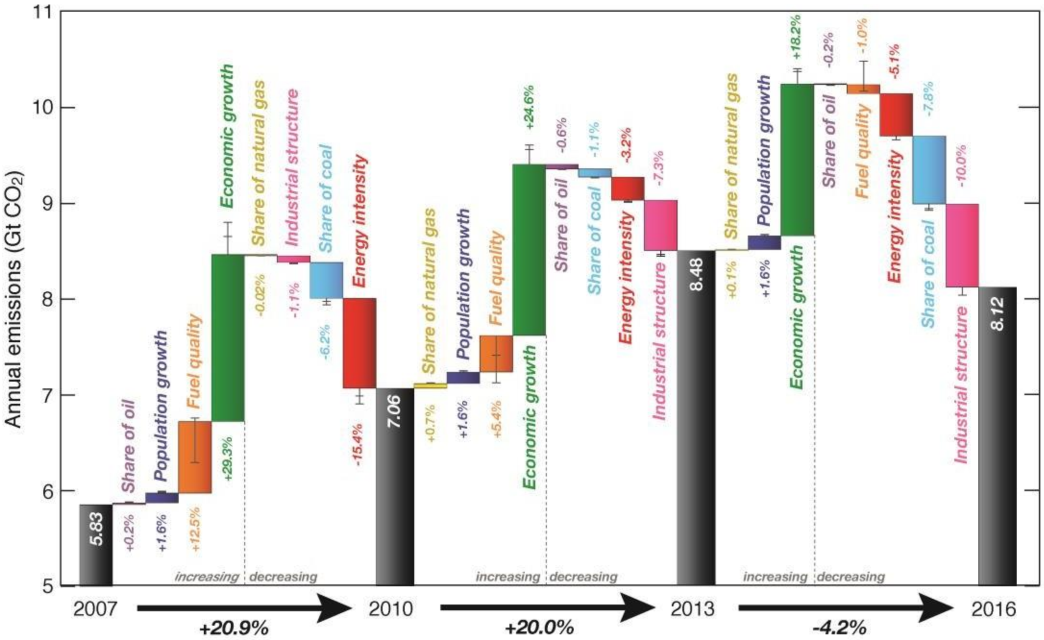
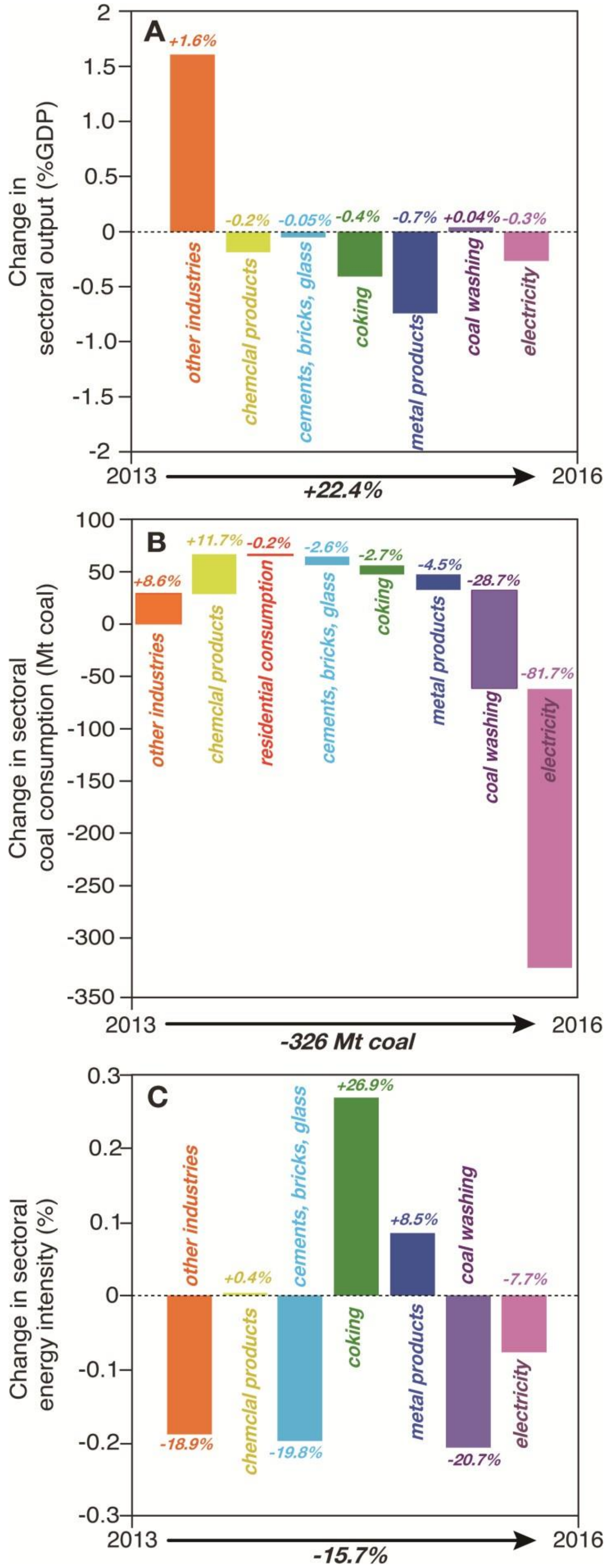


Figure 3. **Sector-specific changes from 2013 to 2016 in China.** (a) change in sectoral contribution to national GDP, (b) coal consumption and (c) energy intensity (energy per unit of output, unit: t/$). Different color bars represent the main contributing sectors. Percentage above each bar in (b) is the sectoral contribution to the total change in coal consumption from 2013 to 2016.


A
Change in sectoral output (%GDP)
2
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
-2
+1.6%
other industries
-0.2%
chemclal products
-0.05%
cements, bricks, glass
-0.4%
coking
-0.7%
metal products
+0.04%
coal washing
-0.3%
electricity
2013
+22.4%
2016
B
Change in sectoral coal consumption (Mt coal)
100
50
0
-50
-100
-150
-200
-250
-300
-350
+8.6%
other industries
+11.7%
chemclal products
-0.2%
residential consumption
-2.6%
cements, bricks, glass
-2.7%
coking
-4.5%
metal products
-28.7%
coal washing
-81.7%
electricity
2013
-326 Mt coal
2016
C
Change in sectoral energy intensity (%)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
other industries
-18.9%
+0.4%
chemclal products
cements, bricks, glass
-19.8%
+26.9%
coking
+8.5%
metal products
coal washing
-20.7%
-7.7%
electricity
2013
-15.7%
2016

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 equals to activity data (fossil fuel consumption) multiplied by parameters NCV, EF , and O , see equation (1) below.

$$CE_{ij} = AD_{ij} \times NCV_i \times EF_i \times O_{ij} \qquad (1)$$

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

AD_{ij} (activity data) means to fossil fuel consumption by the corresponding energy types and sectors. Energy loss during transportation, energy processes, and input as raw materials in chemical process are exclude from the consumption as these part of energy use will not emit any CO_2[35]. All the data are collected from the most up-to-date energy balance tables and energy consumption by sectors published in Energy Statistical Yearbooks[36].

NCV_i in equation (1) refers to net caloric value, which is the heat value produced per physical unit of fossil fuel combusted. EF_i (emission factor) is the CO_2 emissions per net caloric value produced for different fossil fuel types. O_{ij} is 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 are collected based on our previous survey of China's fossil fuel quality[37] and assumed to be unchanged throughout the study period[35,38]. 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 UN and IPCC. CEADs also employs the latest energy consumption data adjusted by 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 [39].

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) refers to cement production, which 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[37].

$$CE_t = AD_t \times EF_t \qquad (2)$$

Decomposition analysis. Decomposition analysis (DA) methods have been used extensively to quantify the contribution of socioeconomic drivers to change in environmental pressures [6,43-44]. Two decomposition approaches are by far the most popular, namely, 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 [45,46]. The advantage of the IDA approach is that it can be easily applied to any data at any level of aggregation [47].

Among specific IDA methodologies, the Logarithmic Mean Divisia Index (LMDI) has been shown by past studies to be preferable by virtue of its path independence, consistency in aggregation, and ability to handle zero values [48-50]. As a result, many studies have used LMDI to provide policy-relevant insights, for instance by identifying driving forces of energy consumption [47,51,52] and changes in CO_2 emissions [53-56]. 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 [47]. See supplementary information for detailed calculation.

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

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

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 definition) by fuel type *i* (where *i*=1,2,3 represents coal, oil, and natural gas, respectively), G_j is Gross Domestic Product (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 mentioned above:

1）P is population；

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

3) $S_j = G_i / G$ is the sector *j*'s share of total GDP, represents the industrial structure;

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

5) $M_{ij} = E_{ij}/E_j$ 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.

6) $T_{ij} = C_{ij} / E_{ij}$ is the emission intensity of fuel type *i* in sector *j*, reflecting changes of fuel carbon content upgrades (e.g. replacing brown coal by anthracite) within any broad fuel type (i.e. coal consumption). 17 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 national CO_2 emissions in year *t* compared with the year *t-1* is calculated as

$$
\begin{aligned}
\Delta C_{tot} &= \sum_{i}^{3}\sum_{j}^{4} L(w_{ij}^{t}, w_{ij}^{t-1}) \ln\left(\frac{P^{t}}{P^{t-1}}\right) + \sum_{i}^{3}\sum_{j}^{4} L(w_{ij}^{t}, w_{ij}^{t-1}) \ln\left(\frac{Y^{t}}{Y^{t-1}}\right) + \sum_{i}^{3}\sum_{j}^{4} L(w_{ij}^{t}, w_{ij}^{t-1}) \ln\left(\frac{S_{j}^{t}}{S_{j}^{t-1}}\right) \\
&+ \sum_{i}^{3}\sum_{j}^{4} L(w_{ij}^{t}, w_{ij}^{t-1}) \ln\left(\frac{I_{j}^{t}}{I_{j}^{t-1}}\right) + \sum_{j}^{4} L(w_{1j}^{t}, w_{1j}^{t-1}) \ln\left(\frac{M_{1j}^{t}}{M_{1j}^{t-1}}\right) + \sum_{j}^{4} L(w_{2j}^{t}, w_{2j}^{t-1}) \ln\left(\frac{M_{2j}^{t}}{M_{2j}^{t-1}}\right) \\
&+ \sum_{j}^{4} L(w_{3j}^{t}, w_{3j}^{t-1}) \ln\left(\frac{M_{3j}^{t}}{M_{3j}^{t-1}}\right) + \sum_{i}^{3}\sum_{j}^{4} L(w_{ij}^{t}, w_{ij}^{t-1}) \ln\left(\frac{T_{ij}^{t}}{T_{ij}^{t-1}}\right) \\
&= \Delta C_{P} + \Delta C_{Y} + \Delta C_{S} + \Delta C_{I} + \Delta C_{coal} + \Delta C_{oil} + \Delta C_{gas} + \Delta C_{T}
\end{aligned} \tag{4}
$$

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 which decomposes the emissions from the BP, IEA and EIA databases (Fig.1a). CO_2 emissions from other data source are obtained from Carbon Dioxide Information Analysis Centre (CDIAC)[1]; Emissions Database for Global Atmospheric Research (EDGAR)[41]; United Nations Framework Convention on Climate Change (UNFCCC)[1,42]; U.S. Energy Information Administration (EIA)[32], International Energy Agency (IEA)[33] and British Petroleum (BP)[34].The national fossil fuel emissions for the different data sources are given by C_{BP}, C_{IEA} and C_{EIA} respectively. Then they were split into different fuel types in different sectors (C_{ij}) with the share (C_{ij}/C) in the base decomposition. The 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 of decompositions 1, 2 and 3 are shown as error bars in Fig.2.

Cumulative sum (cusum) test. We use an econometric approach to investigate whether a structural break of energy- related carbon emissions had occurred in the industrial sector over 2000-2016. The occurrence of structural break is examined using the cumulative sum (cusum) test introduced by Brown et al.[57] and Ploberger and Krämer[58]

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

$$□□2_{□} = □_{□}\,□□2_{□-1} + □_{□} \qquad □ = 1, \dots, □ \tag{3}$$

Where □□ is a vector of time-varying parameters and □□ is an independent and identically normally distributed error term. The null hypothesis for the test of parameter stability is H_0: □□ = □, which is interpreted as the parameter □ is constant over time. Under the null hypothesis, the recursive residuals are assumed to be independent and identically distributed as $N(0, \sigma^{3}_{e})$, 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 Brown et al.[57].

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 exists 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 [40].

References

32. U.S. Energy Information Administration (EIA). *https://*www.eia.gov/.

33. International Energy Agency. https://www.iea.org/statistics/topics/CO2emissions/.

34. British Petroleum. Statistical Review of World Energy 2016 (London: British Petroleum , 2016).

35. Shan, Y. *et al.* Methodology and applications of city level CO_2 emission accounts in China. *Journal of Cleaner Production* **161**, 1215-1225 (2017).

36. National Bureau of Statistics of the People's Republic of China. *China Energy Statistical Yearbook* (China statistics press, 2001-2017).

37. Liu, Z. *et al.* Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **524**, 335-338 (2015).

38. Shan, Y. *et al.* China CO 2 emission accounts 1997–2015. *Scientific data* **5**, 170201 (2018).

39. National Development and Reform Commission. The People's Republic of China First Biennial Update Report on Climate Change." from http://qhs.ndrc.gov.cn/dtjj/201701/W020170123346264208002.pdf. (2016).

40. Shan, Y. *et al.* New provincial CO2 emission inventories in China based on apparent energy consumption data and updated emission factors. *Appl. Energy* **184**, 742-750, (2016).

41. Olivier, J. G. J., Janssens-Maenhout, G., Muntean, M. & Peters, J. A. H. W.. *Trends in global CO2 emissions: 2016 Report*. European Commission, Joint Research Centre (JRC), Directorate C—Energy, Transport and Climate; PBL Netherlands Environmental Assessment Agency, The Hague., (2016).

42. United Nations Framework Convention on Climate Change (UNFCCC). 2016 http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php; accessed June 2017.

43. Guan, D., Hubacek, K., Weber, C. L., Peters, G. P. & Reiner, D. M. The drivers of Chinese CO_2 emissions from 1980 to 2030. *Global Environmental Change* **18**, 626-634 (2008).

44. Feng, K., Davis, S. J., Sun, L. & Hubacek, K. Drivers of the US CO_2 emissions 1997-2013. *Nature communications* **6** (2015).

45. Hoekstra, R. & Van den Bergh, J. C. Comparing structural decomposition analysis and index. *Energy economics* **25**, 39-64 (2003).

46. Zhang, M., Mu, H., Ning, Y. & Song, Y. Decomposition of energy-related CO_2 emission over 1991–2006 in China. *Ecological Economics* **68**, 2122-2128 (2009).

47. Ma, C. & Stern, D. I. China's changing energy intensity trend: A decomposition analysis. *Energy Economics* **30**, 1037-1053 (2008).

48. Ang, B. W. The LMDI approach to decomposition analysis: a practical guide. *Energy policy* **33**, 867-871 (2005).

49. Ang, B. W. & Liu, F. A new energy decomposition method: perfect in decomposition and consistent in aggregation. *Energy* **26**, 537-548 (2001).

50. Ang, B., Zhang, F. & Choi, K-H. Factorizing changes in energy and environmental indicators through decomposition. *Energy* **23**, 489-495 (1998).

51. Ou, Y.H., Liu, Y.F. & Man, J.Y. Decomposition research of the total energy consumption of China based on LMDI. *Economic Management* **7**, 021 (2007).

52. Zhang, M. & Guo, F. Analysis of rural residential commercial energy consumption in China. *Energy* **52**, 222-229 (2013).

53. Kyonghwa, J. & Suyi, K. LMDI decomposition analysis of greenhouse gas emissions in the Korean manufacturing sector. *Energy Policy* **62**, 1245-1253, doi:10.1016/j.enpol.2013.06.077 (2013).

54. Liu, L., Fan, Y., Wu, G. & Wei, Y.M. Using LMDI method to analyze the change of China's industrial CO_2 emissions from final fuel use: An empirical analysis. *Energy Policy* **35**, 5892-5900 (2007).

55. Kang, J. *et al.* A multi-sectoral decomposition analysis of city-level greenhouse gas emissions: case study of Tianjin, China. *Energy* **68**, 562-571 (2014).

56. Wang, Y., Zhu, Q. & Geng, Y. Trajectory and driving factors for GHG emissions in the Chinese cement industry. *Journal of Cleaner Production* **53**, 252-260 (2013).

57. Brown, R. L., Durbin, J. & Evans, J. M. Techniques for testing the constancy of regression relationships over time. *Journal of the Royal Statistical Society. Series B (Methodological)*, 149-192 (1975).

58. Ploberger, W. & Krämer, W. The CUSUM test with OLS residuals. *Econometrica: Journal of the Econometric Society*, 271-285 (1992).