Drivers of change in China’s energy-related CO2 emissions

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CO2 emissions are of global concern because of climate change. China has become the largest CO2 emitter in the world and presently accounts for 30% of global emissions. Here, we analyze the major drivers of energy-related CO2 emissions in China from 1978 when the reform and opening-up policy was launched. We find that 1) there has been a 6-fold increase in energy-related CO2 emissions, which was driven primarily (176%) by economic growth followed by population growth (16%), while the effects of energy intensity (−79%) and carbon intensity (−13%) slowed the growth of carbon emissions over most of this period; 2) energy-related CO2 emissions are positively related to per capita gross domestic product (GDP), population growth rate, carbon intensity, and energy intensity; and 3) a portfolio of command-and-control policies affecting the drivers has altered the total emission trend. However, given the major role of China in global climate change mitigation, significant future reductions in China’s CO2 emissions will require transformation toward low-carbon energy systems.

The largest absolute national contribution to global CO2 emissions now is from China (1, 2), which currently accounts for ~30% of global emissions (3). Like many other countries, the primary cause of anthropogenic CO2 emissions is energy-related fossil fuel combustion (4). China’s economy has increased rapidly, with an annual growth rate of 9.4% from 1978 to 2018 (5). There is a strong coupling relationship between the per capita gross domestic product (PCG) and the energy use per capita for China (SI Appendix, Fig. S1). A very strong positive correlation has been observed between the PCG and the energy consumption per capita (SI Appendix, Table S1). China’s energy consumption has increased along with the economy from 400 tons of oil equivalent (Mtoe) in 1978 to 3,248 Mtoe in 2018, with an annual growth rate of 5.4% (6). The increasing energy consumption has had a significant negative impact on China’s environment in terms of land use change; pollution of air, water, and soil; and biodiversity loss on land and in the ocean (7–9); it has also resulted in significant CO2 emissions, thereby strongly increasing the relative contribution from China to the global atmospheric CO2 concentration (10). There is also a strong coupling relationship between PCG and CO2 emissions per capita in China (Fig. 1A), and it has been demonstrated that the economic growth remains strongly coupled with CO2 emissions (11).

The Chinese authorities recognize China’s role in global CO2 emissions reduction and climate change mitigation and have accordingly strengthened their efforts to combat climate change: for example, by launching a “revolutionary strategy for energy production and
This strategy is aimed at enhancing energy conservation, optimizing the energy structure, and supporting the development of nuclear energy and renewables (12). With these efforts, the increase in energy-related CO2 emissions has been reduced. However, future emissions still need to be decreased significantly, and the drivers of emissions per se as well as the political and technological drivers of the reduced total and relative (per capita or gross domestic product [GDP]) CO2 emissions need to be explored, quantified, and better understood.

We applied the Kaya identity method to analyze the observed trends. This analytical tool allocates the contribution of the change in CO2 emissions into the product of 4 factors, namely population size (P), PCG, energy intensity (EI) per unit of GDP, and emission per unit of energy consumed (carbon intensity [CI]) (13). The contribution of each of these factors to CO2 emissions can be assessed by index decomposition analysis (IDA) (14–17). To the best of our knowledge, the major determinants over the past 40 y have not been fully identified and quantitatively assessed. Temporal trends in carbon emissions in China have only been analyzed over brief time spans (18–22), and therefore, we extended this study to a timescale of 40 y. Although China’s CO2 emissions have continued to rise, they have not increased at the same rate over time. Thus, analyzing the 4 factors that have affected CO2 emissions from 1978 to 2018 can help policy makers and stakeholders to understand the historical changes and determine how to curb increases in CO2. We applied the logarithmic mean divisia index (LMDI) method (15), which is a commonly used IDA approach, with the help of the Kaya identity and econometric analysis method to quantitatively assess the determinants driving China’s CO2 emissions growth since 1978. Details of the Kaya identity, LMDI methods, and data sources are provided in Methods.

**Results**

**Dynamic Changes in China’s Energy-Related CO2 Emissions.** An accurate account of energy-related emissions in China from 1978 to 2018 is the natural point of departure for a decomposition
matched well with those of BP. To this end, China reports on China indicators Tool, as well as British Petroleum (BP) have published Dioxide Information Analysis Center, and the Climate Access Database for Global Atmospheric Research (EDGAR), the Carbon (23). Nevertheless, several international organizations and data-

We also calculated the national CO2 emissions based on official energy consumption data and established emission factors (Methods).

A comparison between the data obtained from international databases and China’s official data from emission inventories showed that the IEA data had the best match (24). However, the CO2 emissions calculated in the current work (red curve in Fig. 2) matched well with those of BP. To this end, China’s CO2 emissions have increased rapidly from 1.37 Gt CO2 in 1978 to 9.64 Gt CO2 in 2018, with an average annual growth of 5.0%. The emission history can be roughly divided into 3 stages. The first stage began with the launch of reform and opening up and ended in 2000, during which time the CO2 emissions increased slowly at an average annual rate of 4.2%. The second stage started in 2001 when China joined the World Trade Organization (WTO) and ended in 2012, which had an average annual growth rate of 8.5%. The third stage was post-2012 when China’s economy entered a “new normal.” The growth of CO2 emissions slowed to an average annual growth rate of 0.81% between 2013 and 2018.

**Four Drivers of CO2 Emissions.** The amount of annual CO2 emission was calculated as the product of the CI, EI, PCG, and P. However, the historical changes in these 4 indicators were very different (Fig. 3; absolute numbers of the 4 indicators are listed in SI Appendix, Table S2). The CI declined by only 13.1% compared with that in 1978, despite efforts to optimize the energy structure. This was due to the high proportion of coal in primary energy consumption, which still constituted 59.0% in 2018 (11.7 percentage points lower than that in 1978). With the continuous improvement of economic and technical efficiencies, the EI also continued to decline. In 2018, the EI had decreased by 77.9% compared with that in 1978 but was still higher than the EI of major developed countries (Fig. 1B). The PCG displayed a significantly higher growth rate than population growth, and the PCG in 2018 was more than 25 times greater than that in 1978. China has implemented a family planning policy since 1978, and the population growth rate (PR) has been effectively controlled. In 2018, the total population had increased by 45.0% compared with that in 1978, while the CO2 emission per capita had increased by 387%.

**Decomposition Analysis through the Lens of Policy Changes.** By evaluating the relationship between macroeconomic policy change and carbon emissions during each 5-y planning period, it seemed plausible that national macroeconomic policies have affected the trend of carbon emissions by affecting the 4 drivers in different ways over time. The changes in emission regimes and contributions from the various contributors were closely linked to national policy programs over the various periods (Table 1). For instance, in 1978 the Chinese government began to comprehensively adjust the development direction of the national economy from a planned economy to a socialist market economy. As a result, China’s economic efficiency gradually improved from the restrictive economic system affected by the Cultural Revolution (11). During the first 3 y of reform (1978 to 1980), the economic growth rate was significantly higher than the growth rate of energy consumption. This caused the decline of both the EI and the CI. The reform and opening-up policy also increased domestic demand, leading to rapid economic growth and increasing CO2 emissions. Another example was China joining the WTO, which marked the start of the second stage of increase in CO2 emissions. After China joined the WTO in 2001, the international market was open to China without restriction, and investment was increased in energy-intensive industrial production, which led to a sharp increase in energy consumption and a significant rebound in EI (28). The effects of all of the 4 indicators were positive in the tenth 5-y plan (FYP period) (2001 to 2005).

**Further Analysis in Aggregate.** Temporal changes in the positive and negative contributions from the different drivers (SI Appendix, Table S3) revealed policy-driven dynamics. The PCG and P contributed significantly to carbon emissions over the entire period, while the EI and CI effects shifted between positive and negative and had a downward influence on CO2 emissions for most years. China’s CO2 emissions have increased since 1978 and increased by 6-fold between 1978 and 2018. Looking at this time span in aggregate (Fig. 4), the most significant contributor to increased CO2 emissions was PCG, which contributed 176% of the overall change in CO2 emissions between 1978 and 2018. The second most important factor was population growth, which contributed 16% of the overall change. The EI and CI effects displayed the opposite trend and caused reductions in CO2 emissions by 79 and 13%, respectively.

We also conducted an econometric analysis to further validate the relationships between CO2 emissions and the 4 driving factors. The Johansen cointegration test demonstrated that there was a long and stable cointegration between China’s CO2 emissions and the CI, EI, PCG, and PR, with elasticity coefficients for the 4 variables of 2.24, 1.16, 1.25, and 0.50, respectively, thereby implying that they all had a positive correlation with CO2 emissions. For example, when PCG, EI, and PR were kept unchanged, if the CI was reduced by 1%, then China’s CO2 emissions would
countries has been more than 41.0% since the early 1990s (33). Energy efficiency improvement was evident since 1978, and our analysis demonstrated that China’s opening-up policy as well as the adjustment of its industrial structure and reform of its economic system were major contributors to this trend (34). Further improvement of energy efficiency may originate from 2 drivers, namely technological improvement and industrial structure optimization (29). On one hand, energy efficiency from improvement in technology will gradually decrease because the energy consumption per unit of product for major energy-intensive industries has already been improving steadily over the past 40 y. For example, the EI of crude steel production in 2015 was 644 kgce/t, while the global advanced level was 602 kgce/t (6). On the other hand, China’s economic development still relies on energy-intensive industries, and the share of its secondary industry is significantly higher than that in other major developed countries. In 2017, the total energy use of 6 energy-intensive industries* accounted for 81.8% of the total industrial energy consumption (6); however, the added value of 6 energy-intensive industries accounted for only 29.7% of the total added value of industries (35). This means that the optimization of industrial structures will be important to reduce the EI in the future.

Discussion and Policy Implications

Our analysis suggested that, since the launch of the reform and opening-up policy, China has enacted, reinforced, or adjusted economic policies to satisfy developmental and environmental needs. Subsequently, the PCG and P have increased steadily with different growth rates, while the EI and CI have decreased but with some variability. Finally, these 4 drivers together influence the dynamic trend of China’s CO2 emissions. In addition, our analysis may be helpful in assessing the long-term trends and goals of CO2 emissions. The Chinese government pledged to continue with economic reform and an open market at the 40th anniversary of China’s reform and opening-up policy (36). This means that the policy environment for economic growth and energy efficiency improvement will exist for a long time, and a medium-high GDP growth rate is both possible and feasible (37–39). A less strict family planning policy did not trigger an increase in the fertility rate, but the adjustment of the family planning policy can boost labor resources and delay the process of population aging (40). In this context, many research institutes have predicted that China’s population will continue to grow until at least 2030 (29, 30, 41). Thereby, economic growth and population size will remain, driving the increase in CO2 emission in the long term.

There is still a significant gap in energy efficiency between China and developed countries. Thus, more attention should be paid to improving the efficiency of energy-intensive industries. China currently prioritizes energy conservation, energy saving, and emissions reduction, and this will eventually promote a downward trend in CO2 emissions. China has also formulated and started to implement a more proactive policy on renewable energy development. The development of renewable energy will gradually accelerate, and the energy structure will also be further

*Six energy-intensive industries are 1) smelting and pressing of ferrous metals; 2) manufacturing of raw chemical materials and chemical products; 3) manufacturing of nonmetallic mineral products; 4) processing of petroleum and coking and processing of nuclear fuel; 5) smelting and pressing of nonferrous metals; and 6) producing and supplying of electric power and heat power.
Table 1. Key policies and cumulative determinant effects from 1978 to 2018 (million tons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Policies or events</th>
<th>Net effect</th>
<th>Cl effect</th>
<th>Ei effect</th>
<th>PCG effect</th>
<th>P effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978–1980 (5th)</td>
<td>1) Started reform and opening up; 2) started socialist market economy; 3) implemented executive orders on control over energy use; 4) launched family planning policy</td>
<td>73</td>
<td>-2</td>
<td>-133</td>
<td>173</td>
<td>35</td>
</tr>
<tr>
<td>1981–1985 (6th)</td>
<td>1) Implemented household land contract-responsibility system; 2) established energy conservation management system</td>
<td>396</td>
<td>5</td>
<td>-413</td>
<td>695</td>
<td>109</td>
</tr>
<tr>
<td>1986–1990 (7th)</td>
<td>1) Dual-pricing system-driven inflation; 2) political turmoil; 3) enacted interim regulations on energy conservation management</td>
<td>525</td>
<td>-3</td>
<td>-267</td>
<td>631</td>
<td>164</td>
</tr>
<tr>
<td>1991–1995 (8th)</td>
<td>1) Strengthened reform and opening-up policy in 1992; 2) started to establish energy-saving standards</td>
<td>739</td>
<td>-34</td>
<td>-790</td>
<td>1,409</td>
<td>155</td>
</tr>
<tr>
<td>1996–2000 (9th)</td>
<td>1) Shut down 15 major categories of small heavy-pollution enterprises; 2) enacted Energy Conservation Law; 3) Southeast Asia financial crisis and severe flood disasters</td>
<td>274</td>
<td>-86</td>
<td>-968</td>
<td>1,182</td>
<td>146</td>
</tr>
<tr>
<td>2001–2005 (10th)</td>
<td>1) China joined the WTO; 2) Enacted medium- and long-term special plans for energy conservation; 3) launched Population and Family Planning Law</td>
<td>2,692</td>
<td>50</td>
<td>557</td>
<td>1,949</td>
<td>135</td>
</tr>
<tr>
<td>2006–2010 (11th)</td>
<td>1) Launched a policy package to expand domestic demand, addressing the global financial crisis; 2) listed EI as binding target for the FYP; 3) addressed Copenhagen pledge</td>
<td>2,063</td>
<td>-221</td>
<td>-1,540</td>
<td>3,644</td>
<td>181</td>
</tr>
<tr>
<td>2010–2015 (12th)</td>
<td>1) China’s economy enters new normal stage; 2) 12th FYP for energy conservation and emission reduction; 3) implemented national plan on climate change (2014–2020); 4) work plan for controlling greenhouse gas emissions during 12th FYP; 5) launched 2 children per household policy</td>
<td>1,150</td>
<td>-403</td>
<td>-1,853</td>
<td>3,183</td>
<td>224</td>
</tr>
<tr>
<td>2016–2018 (13th)</td>
<td>1) Launched supply-side structural reform; 2) 13th FYP for energy conservation and emission reduction; 3) enhanced actions on climate change: China’s nationally determined contributions; 4) work plan for controlling greenhouse gas emissions during 13th FYP</td>
<td>362</td>
<td>-356</td>
<td>-1,115</td>
<td>1,693</td>
<td>140</td>
</tr>
</tbody>
</table>

China has released an FYP for national economic and social development every 5 y. The annual decomposition results for the 4 indicators are provided in SI Appendix, Table S3. The cumulative determinant effects reflect the performances of the macroeconomic policies launched in the FYPs.

improved. It is expected that, by 2030 and 2050, the proportions of nonfossil fuel energy consumption will reach 20 and 50%, respectively (42).

Based on the discussion above, energy-related CO₂ emissions will continue to increase in the near future, but the growth rate of CO₂ emissions should remain at a relatively low level. Considering the 2030 CO₂ emissions peak target and the responsibility of helping the world achieve the Paris climate targets, the next 10 to 15 y will be critical for China to reach the carbon emission peak (29). Thus, China must make a transition toward a low-carbon economy and low-carbon energy systems and improve consumption behavior under the ongoing policy of reform and opening up.

First, the effective way to control CO₂ emissions is to promote the low-carbon transformation of economic growth (e.g., decoupling, which is where economic development occurs with less energy consumption). This strives to achieve long-term, high-quality development by optimizing the economic structure and transforming the drivers of economic growth. This includes strict control over the growth of energy-intensive industries as well as upgrading traditional industries through technological innovation and developing emerging industries that consume less energy. Furthermore, these measures can also help decrease the EI.

Second, a low-carbon transformation of energy systems should be implemented to improve energy efficiency and optimize the energy structure. Improving energy efficiency and increasing the share of renewable energy play a key role in decarbonizing the energy system around 2050 all over the world (43), especially in China. Regarding energy efficiency improvement, higher energy efficiency standards in the industry, building, and transportation sectors should be formulated and implemented. These standards would explore the energy conservation potential through economic structure optimization and energy management. With regard to optimizing energy structure, strong economic incentives to shift from fossil fuels to renewable energy will help to replace fossil fuels with nonfossil fuel alternatives in the dynamics of the energy transition. On one hand, it is important to strive for a fast reduction in coal consumption by setting a coal consumption cap and developing clean coal production and utilization technologies, such as coal cleaning technologies and carbon capture and storage technologies. On the other hand, it is imperative to speed up the development of nonfossil fuels, especially renewables, by increasing

Fig. 4. Cumulative determinant effects of 4 indicators from 1978 to 2018. The percentages above the y axis refer to the determinant’s contributions to the changes in CO₂ emissions.
renewable investment, setting more active and binding goals, giving priority to nonfossil fuels in gaining grid access, and establishing a carbon emission trade market (44).

Third, it is a public endeavor to change consumption behaviors to reduce the per capita energy consumption by advocating a low-carbon consumption culture but also, make efforts to influence the determinants driving China’s CO2 emission growth but also, provide useful perspectives to review policy changes in the long run. The formula can be expressed as Eq. 2:

\[ \Delta CO_2 = CO_2(t) - CO_2(t-1) = \Delta CI + \Delta EI + \Delta PCG + \Delta P. \]  

where \( \Delta CO_2 \) refers to the national or regional CO2 emissions of China and \( \Delta CI, \Delta EI, \Delta PCG, \) and \( \Delta P \) were defined as net effect, CI effect, EI effect, PCG effect, and P effect, respectively:

\[ \Delta CO_2 = CO_2(t) - CO_2(t-1) = \Delta CI + \Delta EI + \Delta PCG + \Delta P. \]  

The relative contribution of each indicator was calculated separately by Eqs. 4 to 7. If the \( \Delta CI \) is a positive value, then the CI effect is positive and promotes carbon emission growth; if the \( \Delta CI \) is a negative value, then the CI effect is negative and slows carbon emission growth. The same rule applies to the EI effect, the PCG effect, and the P effect:

\[ \Delta CI = \sum \frac{CO_2(t) - CO_2(t-1)}{\ln CO_2(t-1) - \ln CO_2(t-1)} \times \ln \left( \frac{CI(t)}{CI(t-1)} \right) \]  

\[ \Delta EI = \sum \frac{CO_2(t) - CO_2(t-1)}{\ln CO_2(t-1) - \ln CO_2(t-1)} \times \ln \left( \frac{EI(t)}{EI(t-1)} \right) \]  

\[ \Delta PCG = \sum \frac{CO_2(t) - CO_2(t-1)}{\ln CO_2(t-1) - \ln CO_2(t-1)} \times \ln \left( \frac{PCG(t)}{PCG(t-1)} \right) \]  

\[ \Delta P = \sum \frac{CO_2(t) - CO_2(t-1)}{\ln CO_2(t-1) - \ln CO_2(t-1)} \times \ln \left( \frac{P(t)}{P(t-1)} \right). \]  

**Methods**

**Approach for Calculating CO2 Emissions.** The reference approach is a top-down approach using the nation’s energy consumption data to calculate CO2 emissions from fossil fuel combustion when primary energy consumption data are easily available (23). We calculated the energy-related CO2 emissions using Eq. 1, and only 3 types of primary fossil fuels (coal, petroleum, and natural gas) were considered:

\[ CO_2 = \sum AD_i \times EF_i, \]  

where \( CO_2 \) refers to the national or regional CO2 emissions of China and \( AD_i \) and \( EF_i \) are the primary energy consumption and emission factors of fossil fuels, respectively.

**Kaya Identity.** The Kaya identity shows that the national or regional CO2 emissions are equal to the product of 4 indicators, namely CI, EI, PCG, and P. The Kaya identity was first proposed by Japanese scholar Yoichi Kaya at an Intergovernmental Panel on Climate Change (IPCC) seminar (13). The formula illustrates a relationship between macroeconomic indicators, such as CI, EI, P, and GDP. The 4 indicators in the formula cannot only be used to assess the determinants driving China’s CO2 emission growth but also, provide useful perspectives to review policy changes in the long run. The formula can be expressed as Eq. 2:

\[ CO_2 = \frac{CO_2}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} = CI \times EI \times PCG \times P, \]  

where \( E \) refers to the primary energy consumption of China, \( GDP \) refers to the GDP of China, and \( P \) refers to population size. \( \frac{CO_2}{E} \) refers to the CI, \( \frac{E}{GDP} \) refers to EI, and \( \frac{GDP}{P} \) refers to the PCG.

**LMDI Method.** We adopted the LMDI method to assess the contribution of different indicators to the overall change in the energy-related CO2 emissions in China from 1978 to 2018. The LMDI method has either an additive or multiplicative mathematical form, but the final decomposition results of the 2 forms are the same (14, 48). This study adopted the additive form, which decomposes the difference of the indicator form between time \( t \) and \( t - 1 \) into a number of determinant effects. We adopted the Kaya identity to separate the influences of the 4 indicators on the overall change in the CO2 emissions according to Eq. 2. According to the definition of the additive form of the LMDI method, the difference in China’s carbon emissions between 2 adjacent years (ΔCO2) is equal to the sum of the impacts from individual indicators, namely CI (ΔCI), EI (ΔEI), PCG (ΔPCG), and P (ΔP), as described in Eq. 3. For convenience, ΔCO2, ΔCI, ΔEI, ΔPCG, and ΔP were defined as net effect, CI effect, EI effect, PCG effect, and P effect, respectively:

\[ \Delta CO_2 = CO_2(t) - CO_2(t-1) = \Delta CI + \Delta EI + \Delta PCG + \Delta P. \]  

**Data Sources.** The GDP and population size data were taken from the China Statistical Yearbooks, and the nominal GDP in different years was adjusted to
Autocorrelation function (ACF) and partial autocorrelation function (PACF) were used to determine the appropriate lag length for the ARIMA model. The AIC, BIC, and SBC criteria were employed to select the optimal lag length, with lower values indicating a better fit. The Akaike information criterion (AIC) and the Bayes information criterion (BIC) were used to compare the goodness of fit of different models.

In the selected ARIMA model, the estimated coefficients were significant at the 5% level, indicating a strong relationship between the GDP and the key variables. The model was validated using the Ljung-Box Q test, which confirmed the absence of autocorrelation in the residuals.

The findings suggest that the GDP growth in China is highly influenced by the economic activity, investment, and technological advancements. These factors are expected to continue driving the economic growth in the future, but the potential challenges like environmental degradation and resource scarcity should be addressed.

References:


Appendix

Table A.1: Descriptive statistics for the variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP</td>
<td>1000</td>
<td>200</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Investment</td>
<td>30</td>
<td>5</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>0.5</td>
<td>0.1</td>
<td>0.3</td>
<td>0.7</td>
</tr>
</tbody>
</table>

This table presents the descriptive statistics of the key variables used in the analysis. The data are collected from the China Statistical Yearbooks for the period 1980-2010.
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