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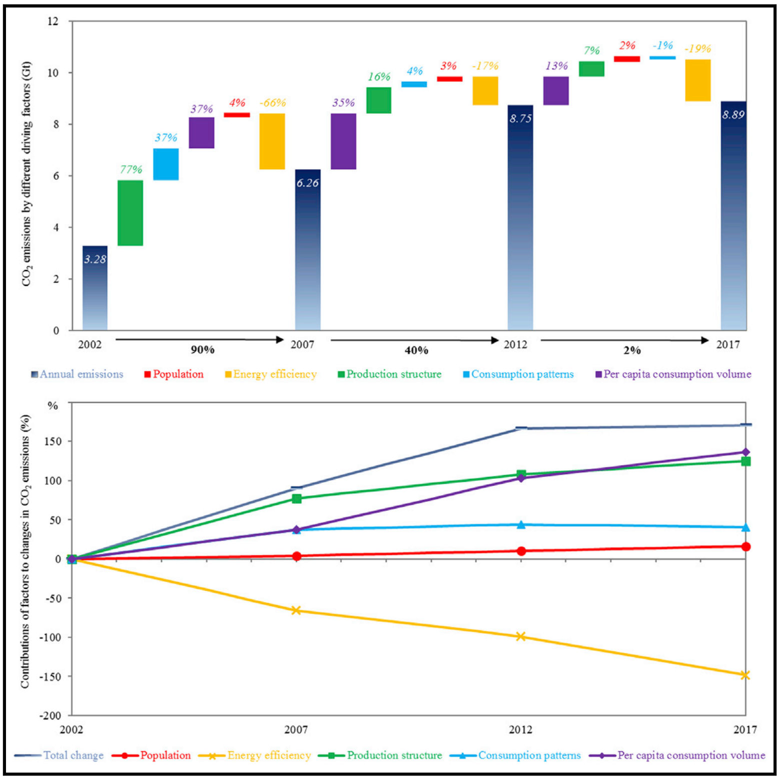
The Slowdown in China's Carbon Emissions Growth in the New Phase of Economic Development

Graphical Abstract



Highlights

- We explore the role of socioeconomic drivers in China's CO$_2$ emission changes
- The growth rate of China's emissions decelerated from 2012 to 2017 in the new normal
- Gains in energy efficiency is the biggest cause of the emissions deceleration
- Slowing GDP growth and changing consumption patterns also make large contributions

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In Brief

China's CO$_2$ emissions have plateaued under its commitment to peaking carbon emissions before 2030 to mitigate global climate change. It is closely linked to the fact that China's economic development has entered a stage named "the new normal," characterized by more inclusive and sustainable development patterns. This study shows that gains in energy efficiency, deceleration of economic growth, and changes in consumption patterns are the main causes of the deceleration of China's emissions growth from 2012 to 2017.

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3 tons of
CO_2 offset

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The Slowdown in China's Carbon Emissions Growth in the New Phase of Economic Development

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SCIENCE FOR SOCIETY It is widely known that China is the world's largest emitter of carbon dioxide. This is largely attributed to its emerging and rapidly growing economy. In light of these emissions and the destabilizing effect they have on global climate, and as economic growth has begun to slow (an economic phase referred to as the "new normal"), China has committed to achieving peak CO_2 emissions by 2030, after which emissions will be reduced. However, the socioeconomic drivers of CO_2 emissions are complex, and only through developing a clear understanding of these drivers and how they interact will China be able to successfully chart a course that both enables continued economic growth and CO_2 emission reductions. This research shows that patterns of carbon emissions have changed dramatically upon entering the new normal phase. It is found that gains in energy efficiency and changes in consumption patterns are crucial in achieving a low-carbon transition and long-term sustainability in China.

SUMMARY

China's CO_2 emissions have plateaued under its commitment to reaching peak carbon emissions before 2030 in order to mitigate global climate change. This commitment is aligned with China's turn toward more sustainable development, named "the new normal" phase. This study aims to explore the role of possible socioeconomic drivers of China's CO_2 emission changes by using structural decomposition analysis (SDA) for 2002–2017. The results show deceleration of China's annual emissions growth from 10% (2002–2012) to 0.3% (2012–2017), which is mainly caused by gains in energy efficiency, deceleration of economic growth, and changes in consumption patterns. Gains in energy efficiency are the most important determinants, offsetting the increase by 49% during 2012–2017. The recent moderation of emission growth is also attributed to China's decelerating annual growth rate of gross domestic product (GDP) per capita from 12% (2002–2012) to 6% (2012–2017) and to the economic transformation to consumption-led patterns in the new normal phase.

INTRODUCTION

Climate change is a global environmental challenge for humanity. Therefore, greenhouse gas (GHG) emission reduction has become a central issue in the international environmental dialog. It is predicted that the global average temperature may rise by 3°C by the end of the 21st century from its level at the end of the 20th century.[1] With the rapid growth of China's economy in recent decades, China's GHG emissions, as represented by CO_2, have skyrocketed.[2–4] In 2006, China surpassed the United States to become the largest carbon emitter worldwide.[5–7] Despite significant challenges to reducing emissions as an emerging economy with a huge population, China has formulated a series of effective policies to mitigate climate change through analyzing the forces driving its rapidly increasing emissions.[8] Thus, China's CO_2 emissions have plateaued since 2012,[9–11] as its economic development has entered a stage named "the new normal."[12] Development patterns are shifting from rapid growth to sustained growth in this new stage with a more inclusive and sustainable economic structure, including higher living standards, cleaner energy industries, and more knowledge-based services.[13] Through industrial upgrading and economic restructuring, the new development pattern under the new normal is playing an important role in effective emission reductions.[14] Currently, China is continuously improving its development patterns toward low-carbon transitions,[15] thereby achieving emission reductions on track before 2030 in alignment with its commitment at the Paris Climate Change Conference in November 2015.[10,11] With an appropriate path for implementing emission reductions, China's economic growth and social development will not be restricted by this emission-reducing target.[16] Better still, choosing the appropriate path would in turn improve China's economic development pattern through the shift to low-carbon, sustainable growth measured by a green economy.[17]

To reduce CO_2 emissions, effective policies are required. However, the driving forces underlying emission trends are complex and closely related to socioeconomic development. A restructured development model is necessary to achieve emission reductions. We therefore analyze and understand the driving factors, including efficiency gains and consumption improvements. While previous studies have approached the driving force by decomposing contributions and assessing impacts,[18–20] most of them analyze changes in emissions by considering multiple driving factors, including energy efficiency, energy mix, economic development, production process, industrial structure, technological progress, openness, and population. CO_2 emissions can be reduced by a model that improves energy efficiency and adjusts energy mix through the Kaya components, i.e., GDP, energy divided by GDP, and CO_2 divided by energy.[12] By using either an adaptive weighting divisia index or structural decomposition analysis (SDA), the driving force can be decomposed from the perspective of carbon intensity adjusted by China's energy structure.[21,22] SDA shows that improved energy efficiency has greatly offset the growth of China's CO_2 emissions despite China's rapid economic growth.[23,24] Changes in economic development also play an important role in affecting carbon intensity, which can be demonstrated with econometric approaches.[25] The transformation from heavy industry to high tech and services is identified as one of the main drivers in reducing CO_2 emissions by the Kaya components.[11] The industrial structure, technological level, and proportions of goods traded in domestic and foreign markets are key factors in evaluating the development patterns of a country, and thus contribute to driving emissions, shown by dual multiple factor analysis.[26] By focusing on multiple factors simultaneously, the aforementioned studies obtain similar findings showing emissions reduction contributed by energy efficiency and energy mix, positive potentials from industrial structure and technological progress, and slowing increase of emissions caused by economic development and population, while the impact level of each specific factor varies.

However, most current research focuses only on CO_2 emissions factors and their constituent patterns within the driving force for emissions, while the dynamic effects of drivers are generally ignored. According to the Global Carbon Budget 2018, China's CO_2 emissions in 2018 slightly rebounded by 4.7%, which may indicate this lack of understanding. Specifically, the constituent patterns of the driving force are usually given under static conditions. Likewise, most current studies that identify driving factors state whether they are positive or negative and estimate the magnitude. However, the dynamic effects are vigorously active forces affecting both the stability and the development of the factors themselves over time,[27] and thus demand further exploration. Research on changes in drivers from a dynamic perspective is limited; for example, by identifying the effects of each driver over time through sequence decomposition and extending this dataset, one can obtain more accurate and useful results.[28] This is of particular importance because changes in drivers have become a determinant in offsetting the increase in China's CO_2 emissions under the new normal. This paper fills the knowledge gap by analyzing changes in the drivers of emission reductions from 2002–2017.

Here, we use SDA to analyze how China's CO_2 emission reductions benefit from retentive efficiency gains and improved consumption patterns by expanding the dataset to include the stage of the new normal. This paper fills research gaps by considering the following aspects. First, the paper dynamically analyzes the combined effect of the driving factors and their changing trends on China's ability to realize its goal for emission reductions. The trend of changes in CO_2 emissions has plateaued in the new normal because the trend of changes in drivers has positively shifted, and this is represented by efficiency gains and consumption improvements. Second, this paper studies in detail the positive change in drivers resulting from their core engine and their underlying mechanisms, which is the key to understanding the slowing growth of CO_2 emissions under the new normal. In order to study how various drivers work to reduce emissions, further analysis is needed to understand how efficiency is improved and consumption is upgraded, as dynamic processes illuminate the changing paths of efficiency gains and consumption improvements. Third, since SDA is a widely used, well-developed, and robust method, this paper employed SDA as a basis for exploring an expanded dataset to analyze recent changes in China's development patterns and drivers of CO_2 emissions under the new normal. The expanded dataset uses the latest published energy and emission data and the newest IO tables. With timely incorporation of crucial data for 2017, this research can provide practical policy recommendations to help China continue its current promising trend of emission reductions. More importantly, with regard to the changes in drivers behind China's CO_2 emissions, important benefits and implications can be gleaned from the dynamic perspective. For example, the dynamic changes in energy efficiency showcase previous achievements of efficiency-related policies, implying continued orientation and future potentials. Simultaneously, the dynamic changes in consumption patterns reflect current conditions during China's shifting development stage, thereby indicating the ongoing transition and pointing toward future improvements.

RESULTS

Trends and Drivers of China's CO_2 Emissions

From 2002 to 2017, production-based CO_2 emissions in China dramatically increased from 3,003 million tons (Mt) in 2002 to a high point of 9,534 Mt in 2013, while total emissions have plateaued since 2013, decreasing to 9,339 Mt in 2017 (Figure 1A). Direct household CO_2 emissions are mainly derived from the energy consumption of urban and rural residents (Figure S1). In general, during the period of rapid economic growth before the financial crisis, total household emissions from the three fuels fluctuated with an increase from 173 Mt to 291 Mt, while a decrease occurred in 2008, mainly caused by the financial crisis.

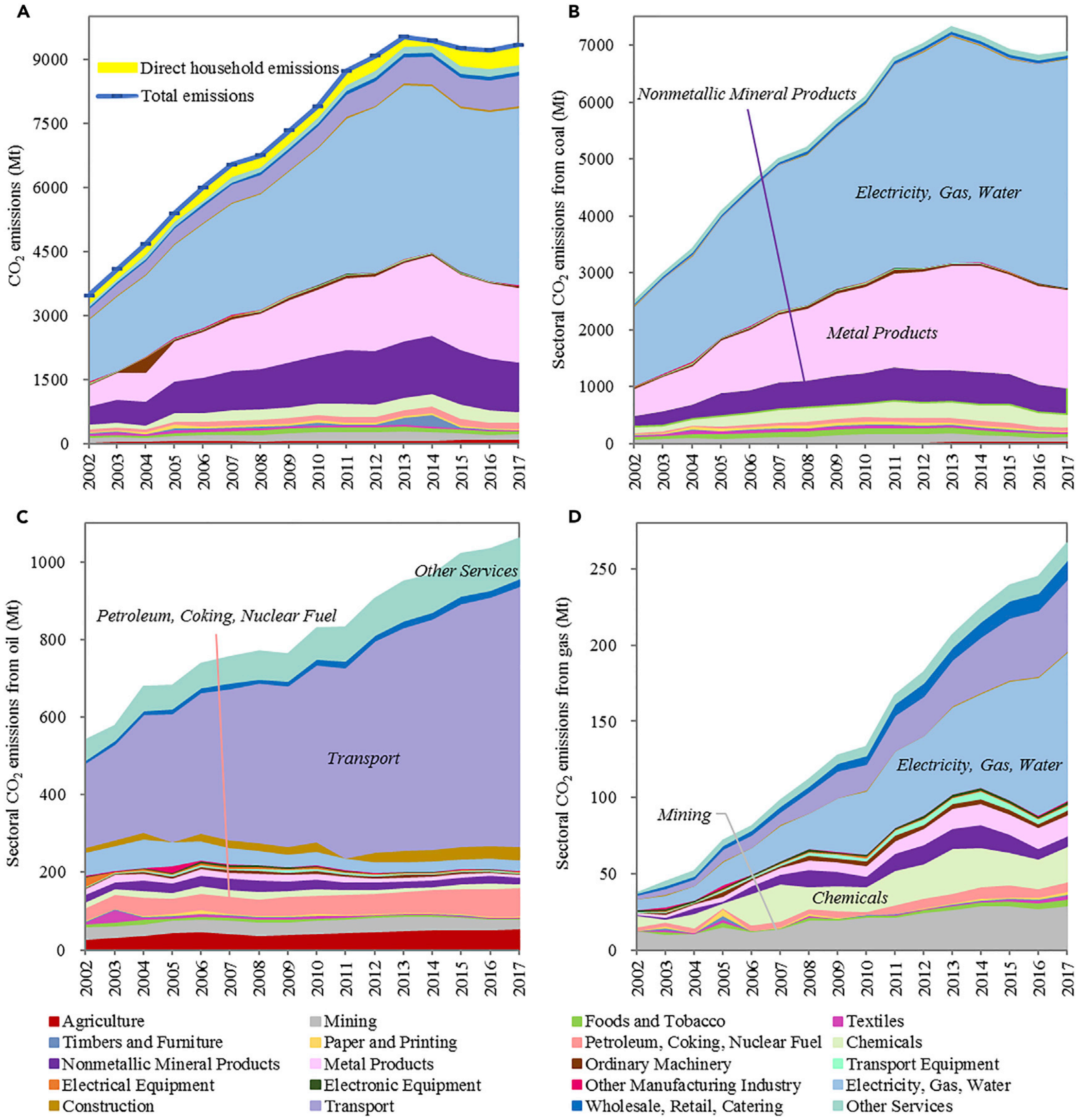

Figure 1. Trends in CO_2 Emissions from 2002–2017 in China

(A) Total CO_2 emissions and household CO_2 emissions by urban and rural residents.

(B) Industrial CO_2 emissions from coal by sector.

(C) Industrial CO_2 emissions from oil by sector.

(D) Industrial CO_2 emissions from gas by sector.

Since 2008, emissions from coal have stabilized to 136 Mt in 2017, while emissions from oil and gas have steadily risen to 219 Mt and 91 Mt, respectively. More specifically, the trend of CO_2 emissions from rural coal has grown slightly, while emissions from urban coal represents the only decline seen among household emissions. In terms of emissions from oil and gas, household emissions by urban and rural residents increased significantly. Each group emitted more than twice as much in 2017 than it did in 2008. For urban household emissions, in 2002, the greatest proportion of emissions was from coal (51%) and the smallest was from gas (10%). However, in 2017, emissions from oil (58%) were ranked first, followed by gas (34%). In rural household emissions, the ranking of coal, oil, andgas remained the same for 2002–2017, but the increments of emissions from oil and gas were significantly greater than that of coal.

From the perspective of identifying the sources, we analyzed CO_2 emissions from different fuel types (i.e., coal, oil, and gas) at the sectoral level. Emissions from coal by sector account for an average of approximately 75% of total emissions over this 15-year period; thus, the trend of coal-caused sectoral emissions is closest to the trend of total emissions (Figure 1B). Sectoral emissions from coal shift from a steady growth trend to an overall decline; the highest point was 7,321 Mt in 2013, followed by a drop to 6,888 Mt in 2017. More specifically, the "electricity, gas, and water" sector (53%) is the largest sector contributing to coal-caused emissions; one possible reason for this is the irreplaceable status of thermal power generation in China.[29] Metal (24%) and non-metallic mineral products (8%), two sectors with high energy consumption and emission pollution, contribute to high coal-caused emissions as well. In contrast to coal-caused emissions, CO_2 emissions from oil have been rising steadily, from 540 Mt in 2002 to 1,061 Mt in 2017, but there are divergent trends by sector (Figure 1C). Most oil-caused emissions by the agricultural and industrial sectors have been stable, have fallen, or have only increased slightly, with the increase mostly present in the energy sectors represented by the third-largest emitter, "petroleum, coking, and nuclear fuel" (6%). However, emissions from oil by service sectors have generally increased considerably, with the largest emissions coming from transport (54%), followed by other services (10%). Similar to oil-caused emissions, sectoral CO_2 emissions from gas also show an upward trend, with a sharp increase of more than seven times, from 37 Mt in 2002 to 267 Mt in 2017 (Figure 1D). Gas-caused CO_2 emissions have increased in almost all sectors but vary in growth rate. A comparison between this trend and the downward trend in coal-caused emissions in recent years clearly indicates that CO_2 emissions have been well controlled by using clean energy rather than fossil fuels. Similar to the largest emitter in coal-caused emissions, electricity, gas, and water (29%) is the sector with the greatest gas-caused emissions, followed by the "mining" (15%) and "chemical" (12%) sectors. These latter two sectors are classified as heavy industries, while the second and third largest industrial CO_2 emitters from coal are in the manufacturing industry.

Based on SDA, the contributions of five socioeconomic drivers to China's CO_2 emissions are analyzed, including population, production structure, energy efficiency, per capita consumption volume, and consumption patterns. Given the availability of China's IO tables, we perform calculations for four years (i.e., 2002, 2007, 2012, and 2017) with survey-based published IO tables. Hence, the results from 2002–2017 are presented and discussed, and this 15-year period can be divided into three stages, with one stage every five years. The first stage, as the extensive growth period, benefits from the World Trade Organization (WTO) accession (2002–2007) with high growth. The next stage is negatively affected by the financial crisis (2007–2012) successively.[30] The last stage (2012–2017), called the new normal, is a new stage of development characterized by a change from high-quantity development with rapid growth to high-quality development with inclusive and sustainable growth.

From the perspective of stages, the growth trend of China's CO_2 emissions, which slows during the first two stages, plateaus upon entering the new normal (Figure 2A). After the WTO accession, China's economy grows rapidly under the dividend of global trade and international standards, with a significant increase in production capacity and rapid growth in consumption. Therefore, the growth rate of China's CO_2 emissions reaches 90% during 2002–2007, gradually falling to 40% during 2007–2012. In the new normal, to achieve an intensive and sustainable transition, China's economic development pattern has made supply-side adjustments by eliminating backward production capacity, upgrading industrial structures, improving resource utilization efficiency, and promoting clean energy. Consequently, emissions slightly increase by 2% during 2012–2017, with an increment of 148 Mt. The population, a relatively stable driver, contributes to a growth rate of emissions of approximately 3% in each stage. Additionally, the production structure and per capita consumption volume are two important factors in increasing emissions throughout the entire period, although the increments vary from stage to stage.

During the three stages, energy efficiency and consumption patterns are two drivers that play important roles in emission reductions. The only driver bringing continuous reductions in China's CO_2 emissions is energy efficiency, and it contributes to the greatest emission reductions. Energy efficiency improvement means a significant drop in emissions per unit of output. Because advanced energy-saving and emission-reducing technologies are actively promoted, technical levels and efficient applications of the whole energy industry have substantially improved. Simultaneously, with the elimination of backward production capacity, the improved capacity utilization rate leads to positive and significant effects on the internal efficiency of every industry. Therefore, the energy consumed per unit of output is gradually decreasing. Another important factor driving emission mitigation is changing consumption patterns; this factor has led to gradual reductions. The shift in and optimization of consumption patterns makes contributions to increases in slowing emissions. Affected by the global financial crisis, China has been actively seeking new economic growth patterns, from the export-oriented growth that followed participation in global trade[31,32] and the investment-led growth that emerged in response to the financial crisis[33,34] to an economic transformation based on domestic consumption demands under the new normal.[27,35] Changes in emissions driven by final use are shifting from exports under trade dividends and investments under policy stimulus to domestic consumption in the new normal.

In terms of drivers, four main factors—production structure, per capita consumption volume, consumption patterns, and population—contribute to the increase in China's CO_2 emissions, while energy efficiency offsets emissions with a reduction of 148% during this 15-year period, taking 2002 as the base year (Figure 2B). The increment of CO_2 emissions is predominantly driven by rapid growth in the production structure, which saw a 158% shift in its relative proportion in the change, making it the closest to the percentage in the total change of emissions (171%) from 2002–2017. Another major factor causing increased emissions is consumption, which is composed of per capita consumption volume and consumption patterns. The growth trend of per capita consumption (145%) is similar to the total trend, while the contribution of consumption patterns (51%) to the percentage change in emissions is relatively smaller. Although population growth leads to an increase in emissions, its trend is stable, with a slight increase in emissions of only 17%. In the period of 2002–2012, the contribution of each driver to changes in emissions shows a regular increasing or decreasing trend with a relatively stable rate of change. Hence, China's total CO_2 emissions gradually increase during the first two growth stages through open-market gains (2002–2007) and stimulus-policy effects (2007–2012).

Among the noteworthy drivers mentioned above, the last stage shows a major contribution to emission reductions by shifting to an industry focus on inclusivity and sustainability in the new normal stage (2012–2017). The contributions from

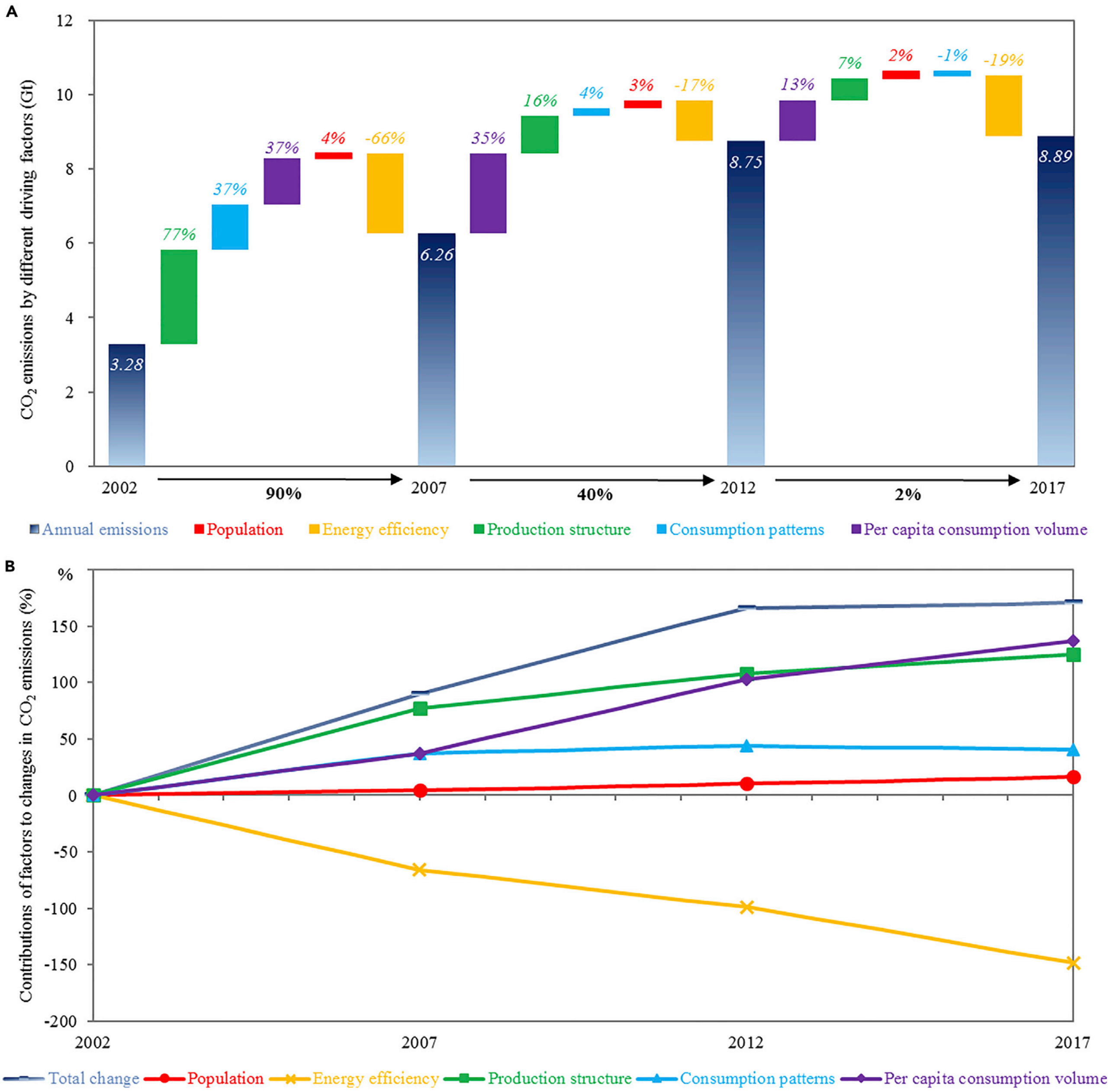

Figure 2. Drivers of CO$_2$ Emissions from 2002–2017 in China

(A) Absolute changes in CO$_2$ emissions caused by the five driving factors for 2002–2007, 2007–2012, and 2012–2017. The length of the bars reflects emissions and changes per stage.

(B) Relative contributions of five driving factors to percentage changes in CO$_2$ emissions in the 2002–2017 period using 2002 as the base year.

energy efficiency to emission reductions in recent stages have more than doubled: from −66% in 2007 to −148% in 2017 when taking 2002 as the base year. In the new normal, energy efficiency is being improved through the control of emissions from high-energy-consuming enterprises by policies of eliminating backward production. Simultaneously, heavy industry is decelerating, while the service industry is being encouraged. Consequently, the efficiency of energy utilization has been improved by the increasing proportion of tertiary industries, including service industries and high-tech industries, in the overall output. The transformation of development patterns has adjusted the economic output structure, thus helping China to improve energy efficiency. The trend of mitigating emissions through consumption patterns since the crisis has continued in the new normal, from 44% in 2012 to 40% in 2017 with 2002 as the base year. First, urban households can be covered by clean energy, while most of the rural households only have access to traditional fossil fuels; second, emissions change with the output adjustment of sectors based on capital formation; additionally, the emissions embodied in domestic and export products vary. Therefore,

CO_2 emissions are closely related to consumption patterns in the final-use categories. Transformations in consumption patterns have become an important step in the improvement of both the energy structure and the entire economic structure. With China's rapid economic growth in the early 21st century, the production and consumption of high-energy-consuming and high-carbon-emitting products caused serious damage to the ecological environment. However, by emphasizing the green economy in recent years, changes in consumption patterns, such as shifts to low-carbon products and clean energy, have contributed to the gradual moderation of emission growth. In addition to consumption patterns, per capita consumption volume (the other key component of consumption improvements) contributes to slowing emission increases during the new normal, from 103% in 2012 to 137% in 2017 with 2002 as the base year. Consumption volume equals GDP measured by total expenditure. Hence, per capita consumption volume with decelerating growth represents a moderating economic growth rate. By emphasizing quality and efficiency, China's economic restructuring aims to save energy and reduce emissions to achieve sustainability. In summary, China's CO_2 emission reductions have benefited from the changes in drivers, especially efficiency gains and consumption improvements, in the new normal.

Efficiency Gains and Consumption Improvements

China's CO_2 emissions have plateaued in the new normal mainly because energy efficiency, measured by carbon intensity (i.e., CO_2 emissions per unit of economic output), has changed. Taking 2002 as the base year, efficiency gains have greatly contributed to offsetting CO_2 emissions by 66% in the first rapid-development stage (2002–2007), which is consistent with previous studies.[32,34] The contributions of energy efficiency have continued by -17% (2007–2012) during the second post-crisis stage. Existing findings show that the efficiency advantage was lost during this period,[27] while results in this study, by using the latest decisive data, indicate that the weakened efficiency advantage has gradually recovered by -19% (2012–2017) upon entering the new normal stage. From the dynamic perspective, efficiency gains have changed from the maximum in the market-led context to a smaller value under the demand-stimulus intervention and then back to a relatively large level via the supply-side policies.

Compared with the level in 2002, the national carbon intensity trend increases from 2002 to 2007 and then decreases continuously, where the largest decline of -2% during the new normal stage in 2017 greatly contributes to gains in energy efficiency (Figure 3A). Similarly, the change in carbon intensity of the mining sector shows a considerable drop, bottoming out at -50% in the new normal. The mining industry is an area of focus when implementing policies that eliminate backward production capacity in the new normal; as a result, the mining sector has the maximum downward change in carbon intensity from among 20 sectors in the last stage. Because the mining sector consumes substantial energy and emits many tons of CO_2, it has a significant impact on national carbon intensity. Similar to the changes in the mining sector, changes in the carbon intensity of heavy-industry-related sectors turn from incremental growth in the second stage during the crisis to reductions in the new normal under regulatory policies. The carbon intensities of the petroleum, coking, and nuclear fuel sector and the "other manufacturing industry" sector, which show similar trends, dramatically decrease in the last stage while fluctuating in previous stages. The heavy industry with high industrial concentrations and heavy assets, located in inland areas due to the distribution of resources, is more susceptible to policy. Thus, the policy responses of these sectors vary across different stages. Affected by stimulus policies from the demand side during the crisis, government spending (represented by infrastructure investment) drives the extensive development of capital-intensive industries with heavy assets; thus, carbon intensity rebounds. In the new normal, policies of eliminating backward production from the supply side have controlled the upstream industries with high pollution; therefore, carbon intensity has rapidly shifted to a decreasing trend. Declines in the carbon intensity of these sectors have greatly reduced total emissions per unit output, thereby improving energy efficiency, especially after China entered the new normal.

The overall trends in the carbon intensity of the "agriculture" and "light-industry-related" sectors decline (Figure 3B). The carbon intensity of agriculture shows positive performance, declining in the previous stages, while the trend slightly turns upward in the last stage, from -18% to -4%. Under the new normal, agricultural policy emphasizes the transformation of agricultural development patterns through the construction of modern agriculture. Although aiming at improving agricultural efficiency, the policy effect of reducing agricultural carbon intensity has been weakened in recent years; policies have been subject to exogenous factors that create exorbitant costs, including the rising cost of production, the domestic and foreign price spread, the import surge, and disruptive tariffs. Slightly different from agriculture, the light-industry-related sectors are mostly concentrated in coastal areas with relatively developed foreign trade and are thus able to react to changes in international demand in a timely manner. With few policy regulations, these light-industry-related sectors, including "foods and tobacco," "textiles," "timbers and furniture," "paper and printing," "chemicals," and "metal products," are mainly affected by market factors. Since the deepening of the crisis, these sectors have started to spontaneously reduce their capacity. Policy-led capacity reduction from the supply side has been implemented in-depth in the new normal, thereby continuing downward trends through the last stage. However, those light industries using agricultural and non-agricultural products vary in their sensitivity to the market or to policy, resulting in different reductions during the latter two stages.

The trends of the "energy" and the "manufacturing and processing" sectors show positive performance because changes in their carbon intensities remain less than zero compared with the base-year levels and are continuing downward (Figure 3C). Although there are small fluctuations in the intermediate stages, the trends all show dramatic drops in the last stage, reflecting an increase in energy efficiency gains. Large-scale products and the machinery processing and equipment manufacturing sectors, including "nonmetallic mineral products," "ordinary machinery," and "transport equipment," are characterized by sharp declines in the first and last stages. The overall falling trends of the "electronic equipment" and "electrical equipment" sectors, as representatives of high-tech sectors, are similar to those of the aforementioned "manufacturing and processing" sectors,

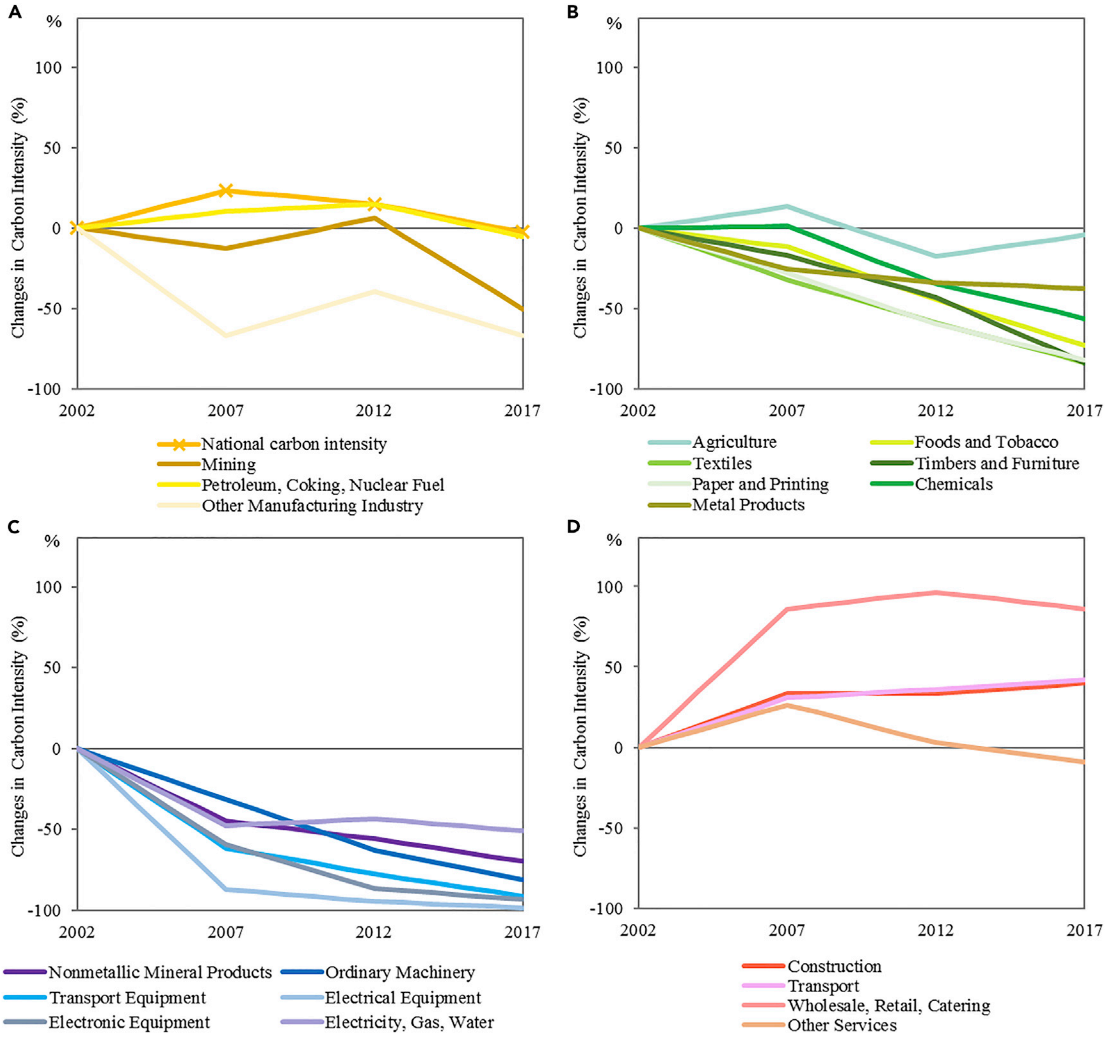

Figure 3. Changes in Carbon Intensity Levels for All Sectors from 2002–2017 in China

(A) Trends in carbon intensity for the nation and for "heavy-industry-related" sectors.

(B) Trends in carbon intensity for the "agriculture" and "light-industry-related" sectors.

(C) Trends in carbon intensity for the "energy" and "manufacturing and processing" sectors.

(D) Trends in carbon intensity for the tertiary industry sectors. According to the standard (National Bureau of Statistics of China [NBSC]) combined with the trend, sectors are roughly divided into the above four categories (Table S2).

but their downward trends are slowing in the new normal. First, the manufacturing and processing industry, which produces the leading and fastest-growing commodities in world trade, quickly achieved a sharp decline in carbon intensity and remarkable gains in energy efficiency after China's accession to the WTO. Machinery equipment, the most in-depth and influential industry (because it is where scientific technology and knowledge are transformed into productive forces), covers sectors with high technological content, high added value, strong industrial relevance, and major export benefits. Second, China is in a period of transition from extensive to intensive economic growth patterns, focusing on efficiency and quality while also considering resource conservation and pollution reduction in the new normal. Because the basis of intensification is the development of advanced and efficient technical equipment, transforming traditional industries through advanced equipment is a practical way to achieve industrial structure upgrading. Therefore, the manufacturing and processing industry plays a vital role in the transformation of economic growth patterns. In response to changes in domestic and overseas market demand in the new normal, equipment manufacturing and machinery processing companies have actively strengthened independent innovation and adjusted their product mix toward green, knowledge-based, and high-end goals, leading to progress in the field of energy-saving and environmentally friendly products. The energy sector causes the greatest industrial emissions, which come from both coal and gas. Therefore the electricity, gas, and water sector has experienced a trend of changes in carbon intensity characterized by significant declines in the first and last stages, similar to the equipment sectors. According to the earlier analysis of CO_2 emissions from different fuel types, gas-caused industrial emissions in this sector have increased significantly, while coal-caused emissions have decreased since 2013. This indicates that emissions are being well controlled by the shift from fossil fuel to clean energy. The above structural adjustment of energy use in the energy sector reduces carbon intensity to improve energy efficiency.

In contrast to the ''energy'' and the ''manufacturing and processing'' sectors, changes in the carbon intensity of tertiary sectors almost remain above zero compared to base-year levels; however, after the first stage, the trends of these sectors have plateaued (Figure 3D). Even if the carbon intensity of the tertiary sector has a positive value, its impact on the environment is small due to its low emissions; therefore, the tertiary sector is strongly promoted within the development of a green economy. The trends of the ''construction'' sector and the ''transport'' sector are similar, with sharp increases after China first opened up to the global market that gradually stabilized with slight fluctuations. Additionally, the fluctuation of the ''wholesale, retail, and catering'' sector is more strongly affected by market consumption demand, while the carbon intensity of the construction sector generally fluctuates under policy stimulus or regulation because this investment-driven industry is volatile and highly sensitive to policies. The trends of the ''transport'' and ''other services'' sectors are similar at first, but they diverge after 2007. With its continuous decline, the other services sector maintains the advantage of a downward trend in the new normal, even dropping below its base-year level (−9%). However, the carbon intensity of the transport sector continues to slightly increase in the last stage, and the increment eventually reaches a level of 42%. The increase in carbon intensity of tertiary industry can be attributed to its accelerating growth and vigorous development. Due to advantages stemming from improvements in technology and efficiency, the modern service industry is becoming a new growth engine for economic development. Hence, this industry has played an important role in the national economy, representing a key step for optimizing economic development patterns in the new normal.

With slowing total demand and through policies designed to optimize consumption structure, changes in consumption, based on the five components representing end use, have offset the growth of China's CO_2 emissions in the new normal. With 2002 as the base year, the increment of emissions induced by consumption patterns is 37% in the first stage, contributing 4% in the second stage (2007–2012), and continuing with −1% in the new normal (2012–2017). Limited by the data available, previous studies mostly focus on the consumption volume as an emission-driving force, showing similar findings to those in this study.[24,27] However, by analyzing dynamic changes in patterns, this study pays more attention to the consumption structure, especially the comparative analysis under the development model of the new normal.

For consumption-induced emissions, the growth rate of total volume has slowed by stages, and there have been changes in the structural proportions of the five final-use components as follows: a significantly increasing proportion of capital formation and inventory, a gradually and steadily increasing proportion of rural and urban consumption, a relatively stable proportion of government spending, and a considerably decreasing proportion of exports (Figure 4A). After China's accession to the WTO, followed by a period of high economic growth, the proportion of exports has increased from 23% to 30% by squeezing a large share of consumption, leading to an increase in export-induced emissions by 1,098 Mt during 2002–2007. The proportion of capital formation and inventory has significantly increased to 42% by 1,386 Mt. Government participation has weakened in this market-driven stage, with the proportion decreasing to 5% (Figure 4B). In response to the 2007 financial crisis, government stimulus policies have partly replaced exports by capital formation and inventory, and the embodied emissions have soared by 1,657 Mt, accounting for a large increase to 49%, while that of exports has been dramatically affected by weak global demand under the crisis, representing a proportion decline to 22%. Although induced emissions from rural, urban, and government consumption have changed slightly, their proportions have remained almost unchanged at 5%, from 18% to 19% and 5% during 2007–2012 (Figure 4C). However, upon entering the new normal, the proportion of urban consumption has increased dramatically, rising to 21%. Government consumption has almost retained its share at 6%, while the proportion of exports has further dropped to 19%, with a −243 Mt contribution to emission reductions (Figure 4D).

At the sector level, the changes in emissions induced by the five final-use categories are analyzed individually. First, the emissions embodied in rural and urban consumption, which are concentrated in the ''energy sector'' and ''other services,'' first accelerated and then decelerated under the new normal. Second, government-induced emissions have significantly increased given the policy dividend after WTO accession and the stimulus policies implemented during the crisis; this increase thus results from intervention and regulation. However, government has played an important role by only increasing 67 Mt in the new normal through reforms from the supply side rather than the demand side. Emissions caused by government consumption have concentrated on the other services sector, which has greatly affected the overall contribution of government to emissions. Third, the recent and noticeably slowing increase of emissions induced by capital formation and inventory has mainly resulted from decelerating investment in secondary industry in the post-crisis era with the absence of a government stimulus policy. By aiming at infrastructure, including high-speed rail, roads, and bridges, capital was heavily invested, largely in transportation-related industries, during the government stimulus plan from 2007–2012. However, the construction period of the infrastructure cycle is relatively long. Therefore, the increments of emissions induced by capital formation and inventory were first accumulated and reflected in the upstream ''transportation equipment'' sector during the initial period of the stimulus policy from 2007–2012. In terms of increased emissions, the construction sector has consistently ranked first in each stage, and most of the emissions are induced by capital formation and inventory. However, the increase in emissions from investment in the construction sector has greatly reduced, resulting in overall investment-induced emission reductions in the new normal. Fourth, export-induced emissions have shifted from the largest phased increment due to policy dividends after China's accession to the WTO to a decline negatively affected by rapidly reduced global demand during the crisis. In contrast to the market forces that ruled during the crisis, exports have mainly been affected by policies after entering the new normal. Shifts toward improving final demand have weakened

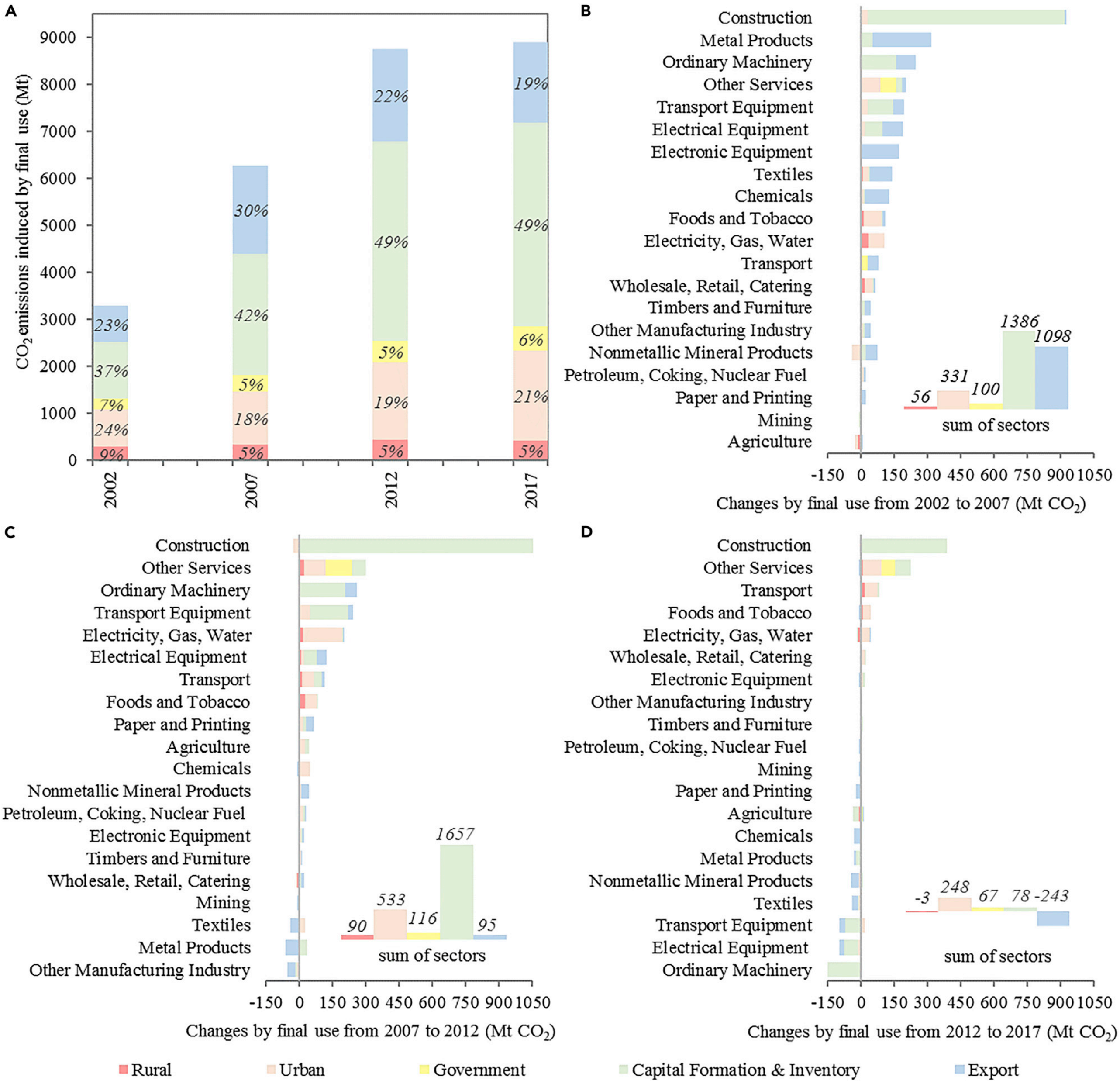

Figure 4. CO$_2$ Emissions Induced by Consumption Demand from 2002–2017 in China

(A) CO$_2$ emissions embodied in final use categories (rural, urban, government, capital formation and inventory, and export) from 2002–2017.

(B) Changes in China's CO$_2$ emissions by final use of all sectors and their sum for 2002–2007.

(C) Changes in China's CO$_2$ emissions by final use of all sectors and their sum for 2007–2012.

(D) Changes in China's CO2 emissions by final use of all sectors and their sum for 2012–2017.

export dependence, stimulated domestic demand, and upgraded the consumption structure. Thus, the total emissions caused by exports have been greatly reduced. With a strong contribution to export-embodied emissions, the "metal products" sector led to emission increments that ranked second in the emissions-increased sectors before the crisis, but its ranking quickly fell during and after the crisis. In the new normal, export-caused emissions have largely declined in the "light" and "manufacturing" sectors, which are mostly distributed in coastal areas and heavily affected by foreign trade; these sectors include "nonmetallic mineral products" (−35 Mt), "ordinary machinery" (−34 Mt) and "chemicals" (−29 Mt).

DISCUSSION

This study analyzes changes in the drivers of China's CO$_2$ emissions and finds that these changes, particularly efficiency gains and consumption improvements in the new normal, have contributed to the slowing of emissions growth in China. Emissions in China are showing a plateaued trend in the new normal from 2012–2017 compared with the significant increases seen from 2002–2012. Based on SDA, the causes of changes in CO_2 emissions are decomposed into five socioeconomic drivers: population, production structure, energy efficiency, per capita consumption volume, and consumption patterns. CO_2 emissions increments in China have predominantly been caused by the strong production structure, and their slowing increase rate is mainly attributed to the deceleration of economic growth as measured by per capita consumption volume. The relatively steady, slow-rising trend in population has caused a slight increase in CO_2 emissions. Most importantly, by eliminating backward production to increase capacity utilization and restructuring the industrial structure at the sector level, advanced technology applications and energy structure adjustments have greatly improved energy efficiency. Simultaneously, while China de-emphasizes the export-dependent open market and investment-oriented responses to the financial crisis and encourages new consumption-led patterns, China has been actively seeking economic transformation, focusing on an important shift toward consumption upgrades. Hence, energy efficiency gains and consumption improvements have offset CO_2 emissions in China, contributing greatly to emission reductions through intensive and sustainable development patterns in the new normal stage. The cause of the plateaued trend for changes in CO_2 emissions in the new normal is the positive shift in the trend for changes in two specific drivers, represented by efficiency gains and consumption improvements.

Efficiency Gains

Changes in energy efficiency as measured by carbon intensity, especially efficiency gains in the new normal, are the most important determinants offsetting the increase in China's CO_2 emissions. By shifting from extensive growth to intensive development in the new normal, China has promoted energy transformation to establish a clean, efficient, economic, safe, and sustainable modern energy system.

First, the energy structure is shifting from high to low carbon. The proportion of green, low-carbon energy in the energy supply, as an irreversible trend, is constantly increasing. To accelerate the adjustment of the energy structure, China is promoting a transformation from fossil energy sources to a sustainable energy system based on clean energy. Specifically, China is promoting the clean and efficient use of fossil energy by strictly controlling new thermal power projects to improve the level of clean use of coal.

Second, energy technology shifts from imitation to innovation. Environmental protection pressures for emission reductions require a significant reduction in energy costs while accelerating the development of clean energy. By promoting the technological energy revolution, improved efficiency and reduced energy costs and consumption can be realized through both gradual technological innovation and breakthroughs. For example, China is focusing on major scientific and technological projects in energy fields such as shale gas, deep-sea oil and gas, natural gas hydrate, and new-generation nuclear power to break through key core technologies.

Third, the energy market is shifting from one characterized by monopoly structure to one characterized by competition. With the transformation of the economy in the new normal, China's slowing energy demand indicates that the mismatch between supply and demand has lessened, providing a rare opportunity to promote market-oriented reforms.

Fourth, energy transmission is shifting from one-way to a network. Under the new normal, advanced technologies—including the Internet, big data, and the cloud—have reshaped the way energy is produced, transmitted, sold, and utilized. Through the application of new technologies, the entire process of interconnection and interaction between people, materials, and energy can be captured, with an aim of unifying management of fluid factors such as scattered and isolated energy sources and information.

Consumption Improvements

The volume and structural changes in consumption, especially the pattern improvements in the new normal, are significant factors driving the slowing growth of China's CO_2 emissions. By shifting from economic growth to social development as the primary aim within the new normal, expanded consumption demand and improved consumption structure as the final link in production cycle can be achieved through strategic patterns of value-added efficiency.

First, with the acceleration of urbanization, green urban and rural development is bringing new consumption demand, including a need for urban infrastructure and new rural construction. More specifically, new rural construction can create new demand, promote consumption volume and structural upgrading, change rural consumption patterns, and exploit rural consumption potential. Thus, the rural market has broad prospects if the consumption capacity of rural residents is enhanced through increased income levels.

Second, the sustained expansion of demand is realized by improving the consumption environment and developing the consumption culture. The demand volume can benefit from an improved consumption culture, forming rational, healthy, scientific, civilized, and sustainable consumption values.

Third, at the sector level, a benign interaction between consumption and industrial structure can be achieved by upgrading both consumption and industrial structure. Additionally, the formation of reasonable industrial chains through product development and production layout can promote consumption demand through new product innovation while also providing support for the development of service-related industries by vigorously cultivating the growth of service consumption.

Theoretical and Practical Implications

By using the most recently released classic and extended datasets, this paper applies the additive SDA method to study changes in China's CO_2 emissions to reduce the potential impacts from temporal aggregation. Because an increasing number of recent studies with methodological development focus on the multiplicative SDA, theoretical contributions can be made in this area.[36] For example, to investigate changes in the carbon intensity target, China's carbon intensity from 2002 to 2012 is analyzed by using multi-SDA with both Leontief and Ghosh IO models.[37]

Based on the results of this study, China's carbon emissions have plateaued in the new normal mainly due to changes in efficiency gains and consumption patterns, thereby providing practical policy recommendations to continue the current, promising trend of emission reductions. The appropriate path for implementing emissions can be formulated according to the aforementioned changes and intrinsic mechanisms. In particular, CO_2 emissions varied due to different drivers; thus, corresponding countermeasures should be taken when aiming for different changes.

The dynamic changes in energy efficiency, with a continuous benign trend, imply the maintenance of ongoing policies. By studying changes in energy efficiency from a dynamic perspective, the effectiveness of previous efficiency-related policies can be clearly understood, which can then further provide potentials for future emission reductions. First, new and clean energy, including hydropower, nuclear power, wind energy, biomass energy, and solar energy, should be further developed. Simultaneously, China will focus on the development of geothermal and ocean energy industries to improve industrial development. Second, by formulating an energy equipment development strategy, China is breaking the management constraints that restrict the development of energy innovation to accelerate construction of an energy science and technology innovation system. Simultaneously, implementing market-based mechanisms represented by contract-energy management and demand-side management is an efficient way to promote an energy development model and to encourage business model innovation. Third, by gradually opening the competitive field and connections, a modern energy market system with unified rules, complementary functions, and multi-level designs can be established. Fourth, China is accelerating the development of distributed energy and integrated energy service markets. The Internet of energy may enable the integration of energy and information, which in turn will lead to technological and industrial changes with profound implications. In general, findings from this paper and previous studies show that efficiency gains, as the most conducive to emission reductions, make it possible for China to achieve the goal in line with the Paris Agreement with its current efforts and steps.

However, the dynamic changes in consumption patterns, which experienced a profound transition under the new normal, indicate the need for shifting strategies to the appropriate orientations. By studying changes in consumption patterns from a dynamic perspective, the advantages or disadvantages of patterns in the current development stage can be mirrored, which can promptly adjust the next improvements by shifting towards green-consuming ideas and habits. First, to enhance the consumption capacity of urban residents, it is possible to facilitate an increased income by changing the previous pattern of land urbanization, accelerating the process of population urbanization, increasing the development of urban basic industries, and providing financial support for private enterprises. Therefore, it is possible to achieve demand expansion and development transformation in the process of accelerating sustainable urbanization. Second, by learning from the new normal, vigorous development of low-carbon, green, environmentally friendly products will be conducive to the formation of optimized industries, and changes in consumption patterns through financial, credit, industrial, and other policies will accordingly increase enthusiasm for household consumption. Third, adjustment of the industrial structure toward high-tech industries can promote improvements in human capital and in the efficiency of labor use, thereby driving increases in income. Simultaneously, preferential policies to support low-carbon consumption can be introduced by supporting energy conservation, environmental protection, and green consumption with tax incentives and sales subsidies to encourage consumers to engage in evidence-based, rational consumption, including purchasing electric bicycles, new-energy vehicles, solar water heaters, and sewage purification equipment. At the regional level, different regions can improve consumption patterns according to their advantages. For example, western provinces can promote the consumption of clean-energy products, and the east can accelerate the shift to high-tech industries.

EXPERIMENTAL PROCEDURES

Structural Decomposition Analysis (SDA)

In terms of analyzing drivers, the existing research mostly employs econometrics and decomposition analysis (DA). The disadvantage of econometrics is that it is impossible to accurately calculate each driver's specific contribution and the proportion of that contribution to changes in emissions.[16,38] Index decomposition analysis (IDA) and structural decomposition analysis (SDA) are two common DA methods.[39,40] By considering the latest methodological development, the comprehensive comparisons between IDA and SDA techniques have been clearly analyzed.[36,41] Although IDA can solve the problem mentioned above, it can only measure factors affecting direct carbon emissions and cannot calculate the indirect carbon emissions induced by the energy consumption from production among sectors.[32,42] SDA, with a combination of input-output (IO) theory and structural decomposition techniques, can solve this problem by evaluating both direct and indirect effects and separately quantifying the contribution of each factor to carbon emissions.[43] SDA, based on the IO model, decomposes the variation of a dependent variable in the economic system into the sum of the corresponding drivers to measure the contribution of each driver.[44–46] The main advantage of SDA is that it comprehensively analyzes both the direct and indirect effects of various driving factors that industrial structures provided by IO tables;[47] therefore, SDA is widely applied to assess the driving forces behind changes in global CO_2 emissions[48–50] or specific countries worldwide, such as the processes driving the reduction of CO_2 emissions in the US.[43] At present, SDA is also extensively used in research on the drivers of China's carbon emissions.

Based on the framework developed by Wassily Leontief in the late 1930s to quantify the relation of input and output flows among industries in the national economic system,[51] IO theory has been widely expanded to various areas of interest, including carbon emissions,[52–54] energy use,[6,55,56] resource footprints,[57–59] and other environmental issues.[60–62] This work uses the fundamental equation known as the Leontief equation:

$$X = LF = (I - A)^{-1}F \qquad \text{(Equation 1)}$$

where X is a column vector of the total output formed by the output of each sector; F is the vector of final use comprising rural consumption, urban consumption, government, capital formation and inventory, and export; L denotes the Leontief inverse matrix calculated by $(I-A)^{-1}$, with the identity matrix expressed as I and the technical coefficient matrix representing intersectoral flows expressed as A.

As an approach to environmental accounting, by using emissions or energy as exogenous transactions among the network of national sectors, the environmental IO method is applied in this study to analyze the direct and indirect CO_2 emissions from households and industries,[63–65] which is estimated as follows:

$$C = ELF = E(I - A)^{-1}F \qquad \text{(Equation 2)}$$

where C denotes the vector of total CO_2 emissions; and E is the row vector of the carbon intensity defined as carbon emissions per unit of output.[66,67] By considering the differences between competitive and non-competitive imports assumptions used for energy or environment IO analysis,[68] imports here are assumed to be the competitive imports type.

In this study, SDA is used to decompose changes in national CO_2 emissions (ΔC) in year t compared with year $t-1$ considering five driving factors—population, production structure, energy efficiency, per capita consumption volume, and consumption patterns—as follows:

$$\Delta C = \Delta PLEF_vF_p + P\Delta LEF_vF_p + PL\Delta EF_vF_p + PLE\Delta F_vF_p + PLEF_v\Delta F_p \quad \text{(Equation 3)}$$

where ΔC is the change in China's CO_2 emissions; P is the national population; L is the Leontief inverse matrix; E is the energy efficiency measured by carbon intensity; F_v is the per capita consumption volume measured by final use per unit of population (i.e., GDP per capita, as the final use in IO table is calculated by expenditure-method GDP); and F_p is the consumption patterns structured by five components in final use.

Each of the five items in Equation 3 represents the contribution of the changing factor to emissions in the absence of changes in other drivers. In SDA, weight selection criteria for the base and reporting periods vary. Thus, there are several methods in SDA for executing the decomposition, including polar decomposition and midpoint weight decomposition. Based on the advantages and disadvantages summarized in previous studies,[28] the average of all possible first-order decompositions is applied in this study. Because there are five drivers, weights are calculated by 5! = 120.[69,70]

Carbon Emission Inventories

In this study, administrative territorial scopes as defined by the Intergovernmental Panel on Climate Change (IPCC) are applied to calculate China's CO_2 emissions.[9,71,72] Emissions include both emissions from fossil fuel combustion and from cement industry processes. The former energy-related emissions are calculated as:[73,74]

$$C_e = D_e \times N \times H \times O \quad \text{(Equation 4)}$$

where C_e represents CO_2 emissions from fossil fuel combustion; and D_e is unit fossil fuel consumption, with missing or double accounting avoided.[75] The remaining three terms on the right side of the equation are the emission factors for fuel combustion, including the net calorific value measuring heat released from unit fossil fuel defined as N, the carbon content representing CO_2 emitted from unit released heat defined as H, and the oxygenation calculating oxidization rate of fossil fuel combustion defined as O.

The latter process-related emissions are calculated as:[73]

$$C_p = D_p \times T \quad \text{(Equation 5)}$$

where C_p are CO_2 emissions from cement production; D_p is the amount of cement production; and T is the emission factor for the cement process, measured by CO_2 emitted in unit cement production as 0.2906 ton CO_2 per ton of cement.[76]

Data Sources

This study uses three sets of data: the national population, input-output tables, and corresponding CO_2 emissions. Published by the National Bureau of Statistics of China (NBSC), China's IO tables with the price index, energy consumption data, and population data can be derived from the National Statistics Yearbook.[77] Given data availability, IO tables for China for 2002, 2007, 2012, and 2017 are used in this study, and all IO tables are deflated to 2017 constant prices. Data on carbon emissions are not officially released in China.[78] Hence, a method to construct China's CO_2 emission inventories is developed in this study. To compile CO_2 emission inventories, three sets of data are mainly used: fossil fuel consumption, cement production, and emission factors. Inventories can be sourced from the China Emission Accounts and Datasets (CEADs), which is an open-access energy and emission data sharing platform.[79] The concordance of 45 sectors (excluding division into urban and rural) in emission inventory data and 20 sectors in the IO table is shown in Table S1 in the Supplementa1 Information.

Some abnormal data, such as missing data, are adjusted by inserting values with the assumption of the same annual emission growth rate: (1) emissions caused by natural gas in the "other minerals mining and dressing" sector in 2003, (2) emissions caused by raw coal in the "equipment for special purposes" sector in 2004, and (3) emissions caused by natural gas in the "cultural, educational, and sports articles" sector in 2005.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2019.10.007.

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AUTHOR CONTRIBUTIONS

Z.M. designed the study. J.Z. performed the analysis and prepared the manuscript. Y.S. provided carbon emissions data. J.Z., Z.M., D.C., and D.G. interpreted the data. Z.M. and S.W. coordinated and supervised the project. All authors participated in writing the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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