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Xinlu Sun and Zhifu Mi

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Factors driving China's carbon emissions after the COVID-19 outbreak

Xinlu Sun [1], Zhifu Mi[1,*]

The Bartlett School of Sustainable Construction, University College London, London WC1E 7HB, UK

Abstract

The outbreak of the coronavirus (COVID-19) may exert profound impacts on China's economic development and carbon emissions via structural changes. Due to a lack of data, previous studies have focused on quantifying the changes in carbon emissions but have failed to identify structural changes in the determinants of carbon emissions. Here, we use the latest input–output table of China's economy and apply structural decomposition analysis to understand the dynamic changes in the determinants of carbon emissions from 2002 to 2020, specifically the impact of COVID-19 on carbon emissions. We find that the contribution of production structure to carbon emission growth was enlarged due to the pandemic, after a continuous decline since 2007. Lower production efficiency and reliance on carbon-intensive inputs indicated the deterioration in production structure. The contribution of per capita consumption to emission growth was decreased because of the economic contraction in the first half of 2020. For policy implications, efforts should be undertaken to increase investment in low-carbon industries and increase the proportion of consumption in GDP to shift the investment-led growth to consumption-led growth for an inclusive and green recovery from the pandemic.

Keywords: CO_2 emissions, input–output analysis, structural decomposition analysis, pandemic impacts, green recovery.

Introduction

The COVID-19 pandemic swept the globe and exerted a profound impact on the global economy by halting economic activities in most countries. In response to the pandemic, China imposed drastic measures, including locking down most of its cities for more than two months in the first quarter (Q1) of 2020. This led to a shrinkage of the economy by 6.8% in 2020 Q1, which was the first contraction since 1992 [1]. By the summer of 2020, the halted economy was gradually reopened because widespread community transmission was eliminated in China, and travel restrictions were largely eased. Consequently, China rebounded from the contraction in the first half of the year and its economy expanded by 2.3%, becoming the only major economy to grow in the pandemic-ravaged year.

The changes in economic activities also caused a steep drop and then a strong rebound in carbon emissions. Many studies have found that COVID-19 greatly curtailed carbon emissions in the first half of 2020 in China. These studies focused on quantifying the emission changes at the sectoral or national level. Han et al. [2] found that lower coal consumption in secondary industry and cement production led to declines in carbon emissions in 2020 Q1. Norouzi et al. (2020) found effects on electricity and petroleum demand, which may be magnified through the global supply chain[4]. However, the short-term impact of the pandemic and declining carbon emissions was offset once the economic recovery began. Zheng et al. revealed that China's CO2 emissions fell by 11.5% between January and April 2020 compared to the same period in 2019 and then rebounded to pre-pandemic levels due to the fast recovery of economic activities [5]. Curtailed carbon emissions via halted economic activities and the collapse in demand were therefore temporary, and a rebound has been witnessed with the easing of lockdown

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[*] Corresponding author: z.mi@ucl.ac.uk (Z Mi)

policies. However, the possible structural changes of carbon emissions that may exert profound impacts and drive long-term transitions urgently need to be identified [6,7].

Changes in consumption patterns, energy preferences, production structure, and investment policies may have already altered the patterns of the driving factors of the carbon emissions. Some positive effects have been witnessed, including changes in consumption behaviour towards less carbon-intensive sectors [8]. For example, lockdown policies have reshaped consumption patterns and boosted the development of the internet and online shopping industries, while energy consumption in traditional manufacturing and transport sectors has greatly decreased[9]. In addition, the demand for renewable energy has accelerated, but fossil fuel has become less preferred [2,10]. The power mix shifted towards renewable energy. The lockdown measurements lead to a large reduction of coal-fired power generation and renewables maintained a high share even with the release of the confinement [11]. On the other hand, the negative impact could offset previous carbon abatement efforts. Conceivably, the willingness of governments and companies to reduce carbon emissions could be largely diminished by the pandemic in light of the urgency to achieve robust economic recovery [12]. Therefore, investment may be targeted in carbon-intensive infrastructure. Falling energy demand retards the growth of renewable energy installation. This could be compounded by the collapse in oil prices, which increases the allure of fossil fuel in economic recovery. The impacts of the changes in production structure remain to be quantified. On the one hand, production structures were altered because of the increased demand in pharmacy industries but drop in the economic activities of services, construction and some manufacturing sectors in early 2020 [13]. But on the other hand, the rebound in China’s carbon emissions in 2020 was initially driven by coal power, cement and other heavy industries[14]. These factors acting in utterly different directions could have structural impacts and change the determinants of carbon emissions.

It is of interest to systematically investigate the structural changes in carbon emissions in China for timely and targeted policy interventions. The structural changes due to COVID-19 have larger impact on environment than on macroeconomics[13]. The urgent detection of such changes could assist in identifying and modifying policies that are less effective in achieving green recovery and derive policy implications to avoid carbon-intensive development trajectories [7]. Currently, companies are suffering a multitude of challenges, such as a deterioration in demand, interruptions in the supply chain, revocation of export orders, shortage of raw material, and distortion in transportation networks [15]. Wang et al. [16] warned of the risk of deterioration in energy efficiency when recovering from the hardship. Detecting the structural changes in carbon emissions is essential to identify inappropriate recovery patterns and adjust policies to get the economy back on track.

However, previous studies have failed to systematically investigate the structural changes in carbon emissions due to the lack of data. Some studies have alternatively reviewed the structural impact of the 2008 financial crisis, but there is growing consensus that the socioeconomic impact of the COVID-19 pandemic is far more severe than that of the financial crisis [10,12,17]. The financial crisis made profound changes to China's economic transition process and carbon emissions, by decreasing the contribution of exports to the GDP[18] and increasing carbon emissions because of the carbon-intensive economic stimulus strategy[16,19,20]. Compared with the financial crisis, the economic crisis associated with the pandemic is more deeply connected with individual behaviour. The impact of the COVID-19 is also different, with unprecedent speed and severity[21]. Subsequently, with the slowed economic development, carbon emissions plateaued from 2013 to 2016. Therefore, the structural impact of COVID-19 should be identified as early as possible for targeted adjustment and interventions to prevent structural deterioration.

In this study, we used the latest-released input–output table of China in 2020 and applied structural decomposition analysis to understand the dynamic evolution of the driving forces of China's carbon emissions from 2002 to 2020. In particular, we analysed the structural changes in carbon emissions from 2018 to 2020 to investigate the impact of the COVID-19 pandemic. With the latest input–output table of China's economy, we are able to reveal the structural impact of COVID-19 and to identify the changes in the determinants of China's carbon emissions. The results could reveal the possible negative impacts of COVID-19 from the perspective of structural changes and therefore assist in timely policy adjustments to prevent structural deterioration. In this study, the dynamic changes in five socioeconomic factors that drive changes in the increase of carbon emissions, including population, energy efficiency, production structure, consumption patterns, and per capita consumption volume, are analysed in the period under consideration.

Methods

Environmental input–output analysis and structural decomposition analysis

Input–output analysis was originally developed by Wassily Leontief in the 1930s to delineate the economic linkage among industries by quantifying the input and output flow [22]. The framework was expanded to a broader field by simply adding a column to describe the resource or emission intensity of each sector, including carbon emissions, energy consumption, and other environmental topics. This is known as the environmental input output analysis (EIOA). The fundamental theory of the EIOA is shown in Eq. (1):

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \boldsymbol{F} \tag{1}$$

where $X = (x_i)$ is the vector of the total output and x_i is the total output of sector i; I is the identical matrix and $(I-A)^{-1}$ is the Leontief inverse matrix. The matrix $A = (a_{ij})$ is the technical coefficient matrix, and $a_{ij} = z_{ij}/x_j$, in which z_{ij} is the monetary input of sector j from sector i. In the final demand matrix, $F = (f_i)$, f_i is the final demand for the products of sector i.

$$\boldsymbol{C} = \boldsymbol{E}\ (\boldsymbol{I} - \boldsymbol{A})^{-1} \boldsymbol{F} \tag{2}$$

where C is the matrix of total carbon emissions embedded in goods and services used for final consumption and E is a vector of carbon emission intensity of all sectors, which is measured by carbon emissions per unit of economic output. Emissions induced by fossil fuel combustion and cement production are included in this study. Eq. (2) shows the calculation of carbon emissions induced by final demand, including rural and urban households, government, capital and changes in inventory stock, as well as exports.

Structural decomposition analysis (SDA) combines input-output analysis and decomposition analysis. SDA can quantitatively measure the contribution of each socioeconomic factor in driving the changes in both direct and indirect carbon emissions. The input and output linkages between different sectors can be accounted for when identifying the direct and indirect impact of each driving factor. Therefore, SDA has been widely used to interpret the dynamic effects of socioeconomic drivers in the process of carbon emission abatement in different regions. Previous studies have explored the impact of socioeconomic drivers on China's production-based carbon emissions as well as consumption-based emissions[23–25].

The changes in national carbon emissions can be decomposed by SDA as follows [19]:

$$\Delta \boldsymbol{C} = \Delta \boldsymbol{E} \boldsymbol{L} \boldsymbol{Y_S} \boldsymbol{Y_C} \boldsymbol{P} + \boldsymbol{E} \Delta \boldsymbol{L} \boldsymbol{Y_S} \boldsymbol{Y_C} \boldsymbol{P} + \boldsymbol{E} \boldsymbol{L} \Delta \boldsymbol{Y_S} \boldsymbol{Y_C} \boldsymbol{P} + \boldsymbol{E} \boldsymbol{L} \boldsymbol{Y_S} \Delta \boldsymbol{Y_C} \boldsymbol{P} + \boldsymbol{E} \boldsymbol{L} \boldsymbol{Y_S} \boldsymbol{Y_C} \Delta \boldsymbol{P} \tag{3}$$

where $\boldsymbol{\Delta}$ denotes the change in a factor, $\boldsymbol{L}$ is the Leontief inverse matrix, $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$, $\boldsymbol{P}$ is the population, $\boldsymbol{Y_s}$ is a column vector of consumption patterns, and $\boldsymbol{Y_c}$ is the per capita consumption volume. SDA can quantify the contribution of the changing factor to emission changes while all the other factors are held constant. As there are five factors, 5! = 120 equivalent decomposition forms can be obtained. Various methods have been proposed to execute the decomposition, including polar decomposition and midpoint weight decomposition [26]. Given the pros and cons of different methods to address this issue, we take the average of all possible first-order decompositions and calculate the weights accordingly. A detailed discussion of this issue can be found in previous studies [27,28].

Carbon emission inventories

We apply the administrative territorial scopes defined by the Intergovernmental Panel on Climate Change (IPCC) to develop China's carbon emission inventories. Carbon emissions from both fossil fuel consumption and cement production are calculated in this study. Emissions induced by fossil fuel combustion, C_e, are calculated as

$$C_e = D_e \times N \times H \times O \tag{4}$$

where D_e denotes unit fossil fuel consumption, with missing or double accounting avoided. $N \times H \times O$ are the emission factors for fuel combustion, calculated by three product terms, the net calorific value measuring heat released from unit fossil fuel represented by N, the carbon content representing CO2 emitted from unit released heat represented by H, and the oxygenation calculating oxidization rate of fossil fuel combustion represented by O.

Carbon emissions released during the industrial process in cement production, C_p, are calculated as

$$C_p = D_p \times T \tag{5}$$

where D_p denotes 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 [29].

Linking imports to the global multiregional input–output model

In this study, carbon emissions embodied in China's imports are calculated by linking to the global multiregional input–output (MRIO) model. One possible approach is to adopt the carbon intensity of China's production sector. However, this accepts the assumption that the technologies used to produce China's imported goods and services are at the same level as China's domestic production. This causes large errors because carbon intensity in China is usually higher than the global average. Therefore, we link China's imports to the global multiregional input–output model. The widely used EXIOBASE database is used here, and China's imports in each sector and by each final demand agency are divided into all other regions according to the EXIOBASE MRIO tables in the corresponding year. We coordinate the sectors in China's IO tables and the global MRIO tables. Finally, the linked MRIO model includes the economic flows of 20 sectors in China and 48 other regions in the world. The carbon emissions embodied in imports are calculated as follows:

$$\boldsymbol{C_{im}} = \boldsymbol{\bar{E}} \ (\boldsymbol{I} - \boldsymbol{\bar{A}})^{-1} \boldsymbol{F_{im}} \tag{2}$$

where C_{im} represents the embodied carbon emissions in imports; $\bar{E}$ is a row vector of carbon intensities for all sectors in all regions; $\bar{A}$ is the direct requirement matrix among all sectors in all regions; and F_{im} is a column vector of China’s imports from all sectors in all regions, including consumption of both intermediate inputs and final demands.

Data sources

The datasets used in this paper are all publicly accessible and easily downloadable through database websites. China's input–output tables and population data are published by the National Bureau of Statistics of China, and energy consumption data are derived from the National Statistics Yearbook [30]. The global MRIO tables are obtained from the EXIOBASE database[31]. All IO tables are deflated to 2020 constant prices. The exchange rates of Euro and RMB are from the World Bank database[32]. Carbon emission inventories are not published officially. We therefore use the national energy balance sheet, energy consumption data of each industry, and cement production data derived from the website of China Emission Accounts and Datasets (CEADs) (www.ceads.net)[33,34], National Energy Statistics

Yearbook and National Statistics Yearbook to establish China's emission inventories. The emission factors, and the concordance of the sectors in the MRIO tables, energy consumption datasets and 20 sectors in the IO tables used in the analysis are derived from previous studies (Appendix Table A1 and Table A2) [19,20].

Limitations

In this study, we focus on the early-stage impact of the COVID-19 as the data used in this research are in 2020. Scholars elucidated that there is a trend of burst-like dynamics of the economic crisis impacts in recent year [35], compared with the persistent impact of earlier crisis in 1960-1990s. For example, the 2008 financial crisis caused a sharp but short-lived decrease in GDP, and carbon emissions quickly rebounded in 2010 due to instant responses by government investment and in energy prices, indicating that the period of the impact of the economic crisis shortens. As China was the first major economy to recovery rapidly from the pandemic lockdown in 2020, timely detection of changes in the contribution of the emission driving factors are necessary to reveal the potential structural changes in the future. In addition, it would be more appropriate to use data in 2019-2020 to reveal the impact of the COVID-19 but the input-output table in 2019 is inaccessible. Studies in the future using data in the later years could reveal more information about the impact of the pandemic

Results

Slowdown of China's carbon emission increases

From 2002 to 2020, China's carbon emissions increased by 187% from 3.6 Gt to 10.2 Gt (Fig. 1A). The growth rate of China's carbon emissions did not follow a constant trend. Overall, the path of the increase can be divided into four phases during this period. Before the global financial crisis, China's carbon emissions experienced a high-speed rise because of growing economic development and carbon-intensive exports. The average increase rate of production-based carbon emissions was 17.8% annually from 2002 to 2007. This made China the largest carbon emitter in the world in 2006 [36,37]. The shock of the global financial crisis in 2008 greatly reduced global demand and slowed the increase in carbon emissions in China (3.4%). Entering the postcrisis era, the Chinese government released a series of stimulus packages to boost a robust economic recovery. A four trillion-yuan stimulus plan targeting some carbon-intensive sectors, including infrastructure and construction, was announced to bolster economic expansion. The economic stimulus strategy not only helped the country escape the quagmire of the economic crisis but also led to an intense rebound of carbon emissions growth. From 2008 to 2011, the average growth rate of China's carbon emissions was 9.7% annually. A tipping point of economic development appeared after a rapid recovery from the financial crisis as China entered the "new normal" in 2012-2013, which meant lower economic growth rate but higher quality. With a retarded GDP growth rate, production-based carbon emissions peaked in 2013 at 9.8 Gt and then continued to decline in 2014 and 2015. Carbon emissions were reduced by 3% in this period. The reduction in carbon emissions in this period attracted much attention from academia as it confirmed the feasibility of achieving a low-carbon transition while maintaining relatively high GDP growth in China. However, the carbon peak in 2013 was a temporary accomplishment, and carbon emissions rebounded after 2017. By 2020, carbon emissions had rebounded from the bottom volume of 9.5 Gt to 10.2 Gt. Although the recent annual carbon emissions surpassed the peak value in 2013, it is apparent that the rate of increase slowed to an average of 1.9% per year.

Overall, the rapid growth of carbon emissions has ended since the beginning of the new normal. Before 2012, carbon emissions increased by 17% per year, while after 2012, the annual increase rate was drastically reduced to 1.5%. The stabilized carbon emissions were attributed to the decoupling of economic development from carbon-intensive production more than to slowed GDP growth and therefore reflected the characteristics of the new normal phase, with lower speed but higher quality of economic growth. Changes in carbon intensity, which is carbon emissions per unit of GDP, indicate that the carbon reduction from 2013 to 2016 was mainly due to the dramatic decline in carbon intensity.

In terms of the sources of carbon emissions, curtailed coal usage was the effective pathway for decarbonization in this period (Fig. 1B). Consequently, the carbon intensity was substantially reduced by 21% during 2013-2016. In contrast, carbon intensity remained nearly constant in the post-financial-crisis era. From 2008 to 2011, carbon intensity was curtailed by only 3%. The difficulty in decarbonization in this period was because of the urgency of achieving economic recovery and extensive investment in energy-intensive sectors. In recent years, China has encountered a bottleneck period in carbon abatement as marginal abatement increases. From 2017, when carbon emissions started to rebound, the carbon intensity was reduced by 8% until 2020, which was much slower than the earlier stage of the new normal phase.

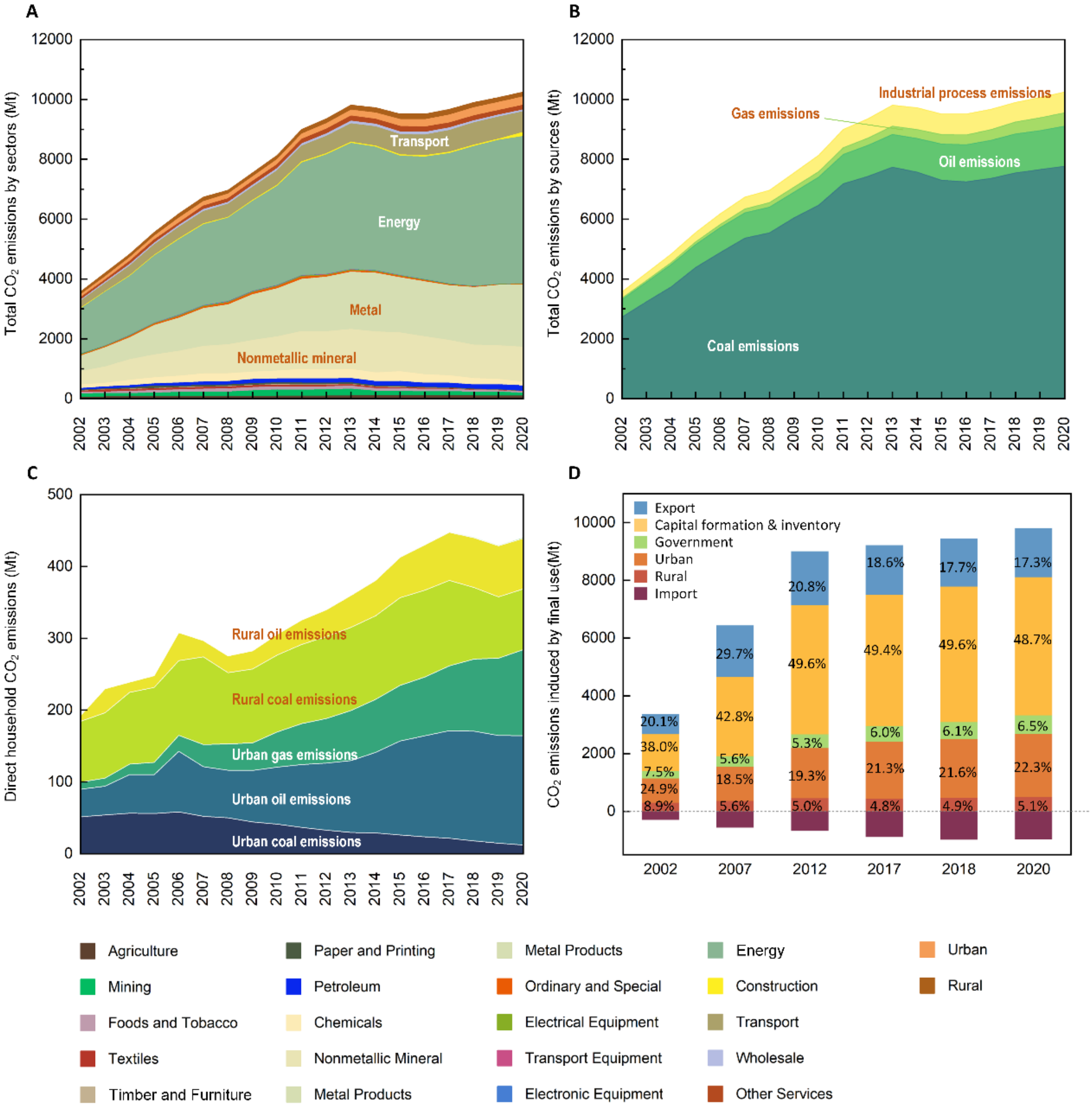

Fig. 1. Trends of China's carbon emissions from 2002-2020. A. Trends of carbon emissions by sectors. B. Trends of carbon emissions by fuel. C. Direct household CO2 emissions in China. CO2 emissions induced by different final uses (rural consumption, urban consumption, government consumption, capital formation, inventory changes and exports).

Direct carbon emissions from household energy consumption have also plateaued in recent years. Household carbon emissions increased from 192 Mt to 448 Mt from 2002 to 2017 because of the increasing energy demand (Fig. 1C). The rising energy consumption of urban households was the main reason for increased carbon emissions. The purchasing power and carbon-intensive lifestyle of urban households as well as rapid urbanization resulted in the contribution of urban households to direct carbon emissions. A clear transition of the energy mix is revealed, and carbon emissions induced by the coal consumption of both urban and rural households have been critically reduced. Urban households have successfully switched from coal usage to gas for their essential life demands. In 2002, carbon emissions from urban coal and gas usage were 51 Mt and 10 Mt, respectively. The roles of coal and gas have been reversed since 2010, and carbon emissions from urban coal and gas usage were 12 Mt and 120 Mt in 2020, respectively. Access to gas in rural areas in China has been a problem that obscures rural energy transitions because of rural households' scattered inhabitation and distance from the gas grid. However, rural coal-induced carbon emissions peaked in 2015 at 122 Mt and continued to decrease to 85 Mt in 2020. The reduction in coal usage was mainly due to the electrification of rural household energy consumption. From 2002 to 2020, rural electricity consumption increased from 67 billion kWh to 524 billion kWh. Nonetheless, coal usage is still the main resource for rural carbon emissions, and therefore, the accessibility of clean and high-quality energy is still a challenge in rural China. Oil-induced carbon emissions have been increasing in both urban and rural areas, which is mainly attributed to gasoline and liquefied petroleum gas (LPG) usage. Urban and rural residents use LPG for cooking when natural gas is difficult to access. The increase in LPG usage has been stabilized because of progress in gas pipeline construction. Gasoline continued to increase drastically with the rapid expansion of private car ownership. Reducing the carbon emissions induced by household oil consumption requires policies that target the transition of oil fuel vehicles towards new energy vehicles as well as encouraging more responsible consumption behaviours with regard to low-carbon transport.

Determinants of the carbon emissions change before COVID-19

We apply SDA to understand the changes in the driving forces of China's carbon emissions from 2002 to 2020. The five socioeconomic factors include population, consumption volume, consumption pattern, production structure and energy efficiency. We divide the 15 years into five stages according to the characteristics of carbon emission changes. The first stage is the rapid increase stage after accession to the WTO (2002-2007). The second stage is the post-financial-crisis era, when carbon emissions rebounded (2007-2012). The next stage is the beginning of the new normal phase, when carbon emissions plateaued (2012-2017). The fourth stage is the rebound stage, when carbon emissions started to increase again, but at a low speed (2017-2018). The last stage is set to investigate the impact of the COVID-19 pandemic on the determinants of carbon emission changes in China (2018-2020).

In the long run, the improvement of energy efficiency has been the sole factor that drives the decarbonization of China's economy (Fig. 2A and 2B). From 2002 to 2020, the contribution of energy efficiency to emission reduction was 188%, which means that carbon emissions per unit of total output have been significantly decreased. The continuously declining carbon intensity is mainly achieved by progress in low-carbon technology energy and the elimination of backward production capacity. From 2002 to 2012, efficiency gains in the manufacturing sector and some light industries, including equipment production sectors, food, textiles, and paper, contributed to 99% of the carbon reduction in China (Fig. 3A-D). After the financial crisis, the advantage of energy efficiency was slightly weakened. One of the main reasons was the deterioration in carbon reduction of the energy sector, including electricity, gas and water production and supply. From 2007 to 2012, the carbon intensity of the energy sector rose by 3%. Due to the supply-side adjustment and the elimination of backward production capacity, energy efficiency has been enhanced in the new normal (from 33% during 2007-2012 to 49% during 2012-2017). In this period, the carbon intensity of most sectors decreased immensely. For instance, the carbon intensity of the "Petroleum, Coking, Nuclear Fuel" sector declined by 49% in the new normal, while this figure was only 17% in 2007-2012, indicating that the energy efficiency improvement almost tripled. In 2017-2018, energy efficiency improvements accelerated, with efficiency gains in some sectors, including the construction sector, transport sector, chemical sector, and energy sector.

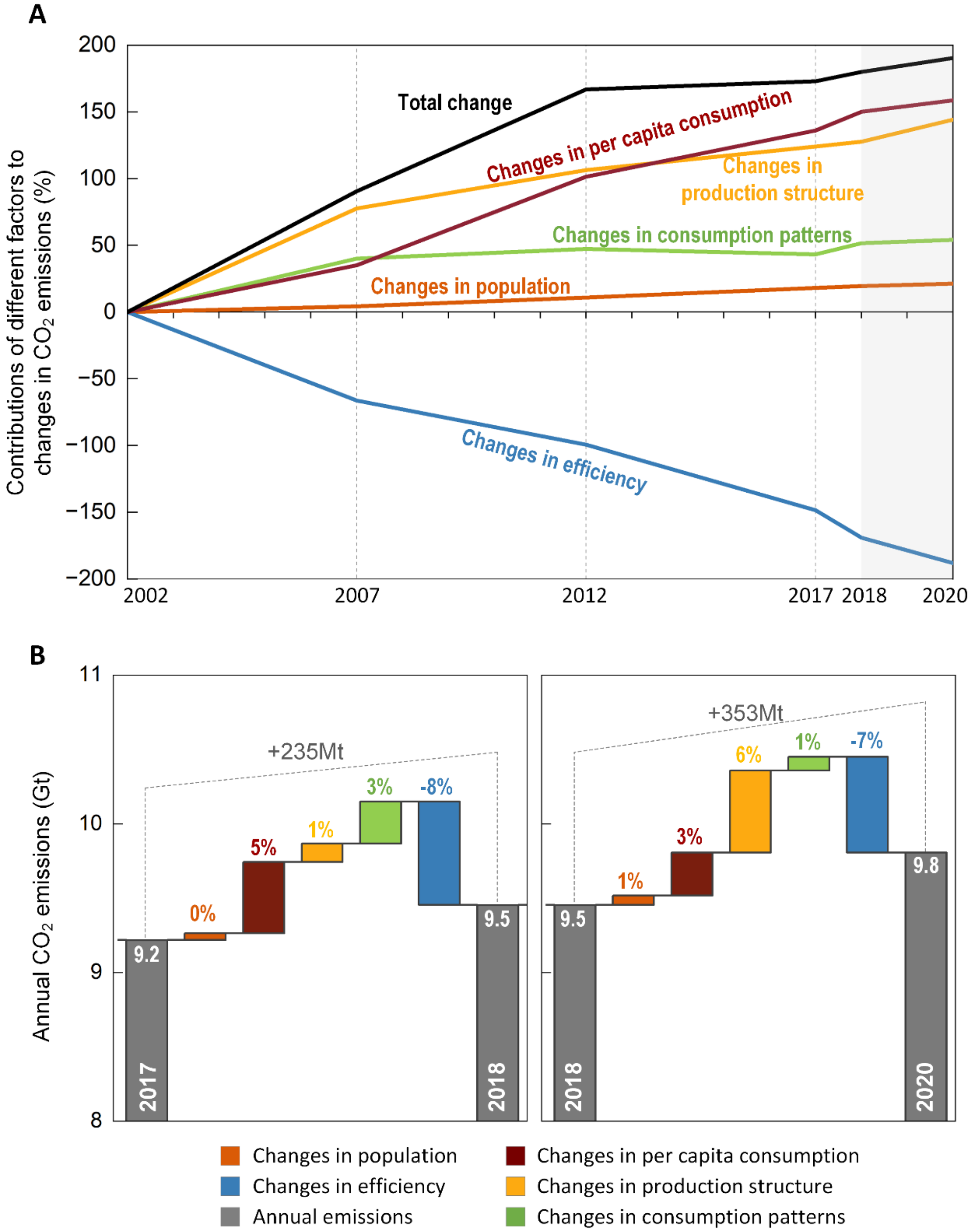

Fig. 2. Trends of the drivers of carbon emissions from 2002 to 2012. A. Contributions of different factors to changes in Chinese CO2 emissions between 2002 and 2020, taking 2002 as the base year. B. Absolute contributions of different factors to changes in Chinese CO2 emissions for 2002–2007, 2007-2012, 2012–2017, 2017–2018 and 2018–2020.

After driving up the increase in carbon emissions for ten years from 2002-2012, consumption patterns started to become a decarbonization force during 2012-2017 and then recently reversed again. The contribution of consumption patterns is in accordance with the consumption structure caused by different final users, namely, rural and urban households, government, capital and inventory, and exports. In general, a clear shift of the driving forces of carbon emissions from capital formation to household consumption is revealed (Fig. 1D). Before the new normal, the accelerated economic growth as well as the tremendous investment for the recovery from the financial crisis drove the growth of capital formation and induced carbon emission increases. From 2002 to 2012, carbon emissions caused by the final demand of capital and inventory changes increased by 4358 Mt, accounting for 77% of the total carbon increase. The reliance on international trade and expanded export demand, especially before the financial crisis, led to an increase of 1075 Mt carbon emissions from 2002 to 2007. With the search for an inclusive and sustainable industry structure, China strengthened its efforts to prevent the disorderly expansion of capital and promoted supply-side transformation to optimize the industry structure in the new normal. Consequently, carbon emissions induced by capital formation largely declined. Carbon emissions induced by exports also decreased in the new normal stage because of rising labour costs and restricted sustainability requirements. The contribution of private and government consumption has been enhanced since then. However, the decarbonization effect by consumption patterns was reversed again since 2017 with the consumption caused by the rebounded contribution of capital formation. The incremental carbon emissions induced by capital and changes in inventory increased from 42% in 2012-2017 to 59% in 2017-2018. This trend continued in 2020 as consumer confidence had not completely recovered.

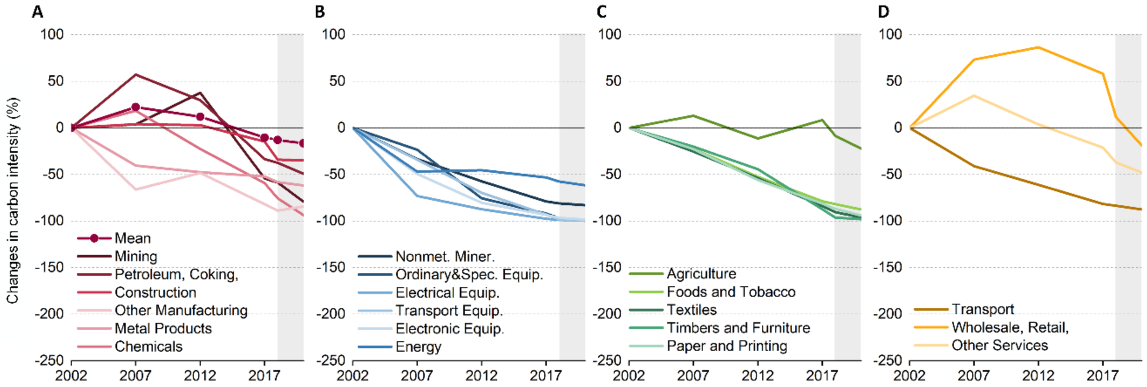

Fig. 3 Changes in carbon intensity for all sectors from 2002–2020 in China. A. Trends in carbon intensity for the nation and for the construction and the heavy-industry-related sectors. B. Trends in carbon intensity for the energy and manufacturing and processing sectors. C. Trends in carbon intensity for the agriculture and light-industry-related sectors. D. Trends in carbon intensity for the tertiary industry sectors.

Per capita consumption volume, production structure, and population have driven the growth of carbon emissions in the whole period under consideration. Consumption volume, indicating the changes in GDP growth, is the predominant factor that accounts for the rise in carbon emissions. With the entrance of the new normal, the pursuit of lower speed but higher-quality economic development also slowed emission expansion. The production structure contributed to the increase in China's carbon emissions, but the contribution was constricted in the new normal. From 2002 to 2007, the production structure explained a 78% increase in carbon emissions, and the contribution of the production structure to carbon emissions was condensed to 29% during 2007-2012. The increase in carbon emissions of the construction sector by capital formation was the main cause of the increase in China's carbon emissions (Fig. 4). Being policy-sensitive and capital-driven, the expansion of the construction sector before 2012 was mainly due to the rapid development of the real estate market as well as the economic stimulus package targeting high-speed rail network and infrastructure construction after the financial crisis. This also led to the expansion of related sectors, for example, the transport equipment sector that produces high-speed trains. The accession to the WTO boosted the manufacturing sectors in China because of the large demand for exports. Consequently, carbon emissions induced by exports of ordinary and special equipment, transport equipment and chemicals increased considerably in this period. The extensive carbon emissions of the construction sector and several manufacturing sectors, driven by capital formation and exports, explained most of the total increase in this period. In the new normal phase, the contribution of the production structure to the carbon emission increase was less and therefore was offset by rapid energy efficiency improvement. The growing trend of the population is rather stable and contributes to a growth rate of emissions of 1.2% annually.

Rebound in carbon-intensive production after the COVID-19 outbreak

The COVID-19 pandemic exerts a direct impact on China's carbon emissions by weakening final demand, i.e., GDP growth. The annual contribution of per capita consumption volume to the carbon emission increments was sharply reduced to 2% from 2018 to 2020, much less than the average level in the new normal (5%). The pandemic in the first quarter of 2020 halted economic activities in China, and lockdown policies in the country greatly depressed household consumption. Therefore, private-induced carbon emissions in many sectors were reduced, such as the food and tobacco, chemical, wholesale and retail sectors. In general, the contribution of rural and urban household consumption to carbon emission increases was from energy consumption. Self-isolation in response to the pandemic created a novel working pattern that included remote work and meetings. This trend curtailed the transport demand of residents but enlarged the proportion of household energy demand to total consumption. In contrast, government consumption in the transport sector was expanded. From 2018 to 2020, the decreased carbon emissions of the transport sector due to the reduced transport demand by households and capital were offset by government consumption, which contributed to an increase of 20 Mt. The increase in government-induced transport carbon emissions was more than ten times the levels from 2012 to 2017 (1.5 Mt). The abnormally expanded transport demand of the government was because of the tremendous demand for transporting anti-pandemic and living materials during the lockdown. Furthermore, the increase in carbon emissions in other nonenergy sectors was nearly zero, indicating that consumer confidence has not completely recovered from COVID-19. A significant contraction in demand in discretionary purchases, such as clothes and retail, drives the downwards trend of carbon reduction by household consumption. Stimulating private consumption is still the priority to achieve green and resilient recovery from the COVID-19.

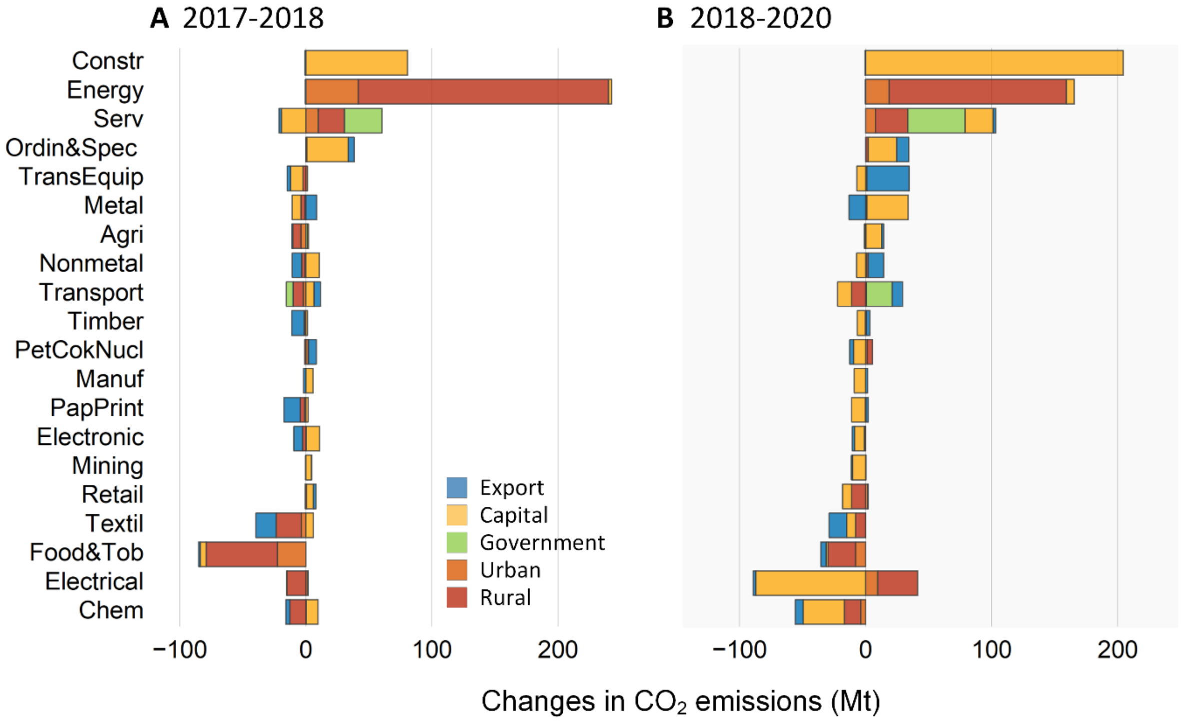

Fig. 4. Contributions of different sectors and final uses to Chinese CO2 emissions growth. A and B show the results for 2017-2018, and 2018-2020, respectively.

The growth of carbon emissions induced by the production structure towards carbon-intensive production slowed in the new normal, but COVID-19 disrupted this benign trend. In the new normal, the effect of supply-side adjustment assisted in the optimization of the production structure, reflected in sectoral emission changes. The elimination of backward production capacity can be seen in the decline of investment-induced emissions in carbon-intensive sectors, such as the electrical equipment, metal products and ordinary and special equipment sectors. In addition, production was adjusted according to consumption, shifting from capital- and export-driven to household consumption-driven. The greatly reduced carbon increases were caused by household consumption in less carbon-intensive sectors, such as food production, wholesale, retail and catering, while production in the carbon-intensive manufacturing sectors continued to decline, such as the transport equipment, ordinary and special equipment, and electrical equipment sectors (Fig. A2). However, the adjusting trend of the production structure towards low-carbon production was disrupted by the pandemic in 2018-2020. In these two years, the production structure contributed to an annual growth rate of 3% in the increase of carbon emissions, higher than the average rate (1%) in the new normal phase (2012-2018). The deterioration in production structure resulted from increased intermediate input intensity and reliance on carbon-intensive input. In 2018 to 2020, intermediate input intensity (the share of intermediate inputs in the total inputs) of several sectors, especially carbon-intensive sectors, was increased, including the petroleum and coking, non-metallic mineral products, metal products, electricity, construction and transport sectors. For example, in 2017 and 2018, the intermediate inputs accounted for about 52% of total inputs, while the proportion was enlarged to 61% in 2020. Consequently, the overall intermediate input intensity of all sectors grew from 56.8% to 57.9% during 2018 to 2020, which was reduced from 2017 to 2018 in contrast. This indicates less value-added created by the same output, therefore a reduced production efficiency and usually a lower productivity[38]. Apart from intermediate input intensity, changes in production structure in 2020 were attributed to the reliance on carbon-intensive inputs, i.e. the increase in the share of carbon-intensive inputs in the total inputs. For example, the intermediate inputs of the petroleum and coking sector and chemicals sector accounted for 2.2% and 8.2% of the total inputs in all sectors in 2018, and the proportions were expanded to 2.4% and 8.5% in 2020. To be specific, the transport sector consumed more products from the petroleum and coking sector, increased from 6.3% to 8.0% during 2018 to 2020, indicating the preference in fossil fuel.

The interaction between demand structure and production structure led to a deteriorated production structure toward energy-intensive and export-oriented production (Fig. 2). One of the reasons is that the spread of the pandemic worldwide and the well-controlled cases in China led to a robust recovery of China's economic activities in the second half of 2020. Because of the weak demand for household consumption, the economic recovery in 2020 was mainly supported by investment and exports. The halted industrial production in the first quarter gradually rebounded after the second quarter as lockdowns eased. The earlier easing of lockdown measures compared with the rest of the world increased the demand for Chinese exports; therefore, export-induced carbon emissions rebounded markedly. The dominant contribution was from the export of transport equipment (33 Mt). Exports of nonmetal products and ordinary and special equipment also led to increases in carbon emissions. Another reason was the stimulus package for economic recovery from the pandemic. In 2020, the Chinese government released a series of fiscal and monetary policies to stimulate the contracted economy, targeting tax breaks, consumer subsidies, and infrastructure investment. The new infrastructure construction plan has become a strategy to achieve the goals of both stimulating job creation and reviving a flagging economy. Investment in key segments has been accelerated, including industrial internet, 5G network, smart city, intelligent transportation, and artificial intelligence. These stimulus measures helped China escape the economic slowdown but also led to a rebound of carbon emissions in the construction sector . Therefore, the carbon emissions of the construction sector (204 Mt) again became the major source of the emission increase in 2018-2020 (Fig. A2).

The accelerated enhancement in energy efficiency during 2017-2018 was terminated by the pandemic. Although it has been the major driving force of decarbonization in China for decades, the potential for energy efficiency improvements has been constricted with the transformation of the energy mix and technology updates. The annual contribution of efficiency gains to carbon reduction was as high as 13.2% in 2002-2007 but drastically declined to 3.5% in the following stage from 2007 to 2012. The loss of efficiency advantage gradually recovered in the new normal phase to an annual contribution rate of 3.7% due to the decisive supply-side reform. In 2017-2018, the improvement of energy efficiency was further promoted, with a contribution rate to carbon reduction of 8%. In this period, a hastened decline in the carbon intensity of many key sectors can be observed. For example, the carbon intensity of the energy sector decreased by 9% in 2018 compared with the 2017 level. Efficiency gains were even greater in some manufacturing sectors. Carbon intensity declined by more than half in the transport equipment production sector (76%), the timber and furniture sector (70%), the ordinary and special machinery sector (59%), and the electrical equipment production sector (54%). However, the energy efficiency improvement was decelerated by COVID-19, and the annual contribution rate of efficiency gains to carbon reduction dropped to 3.4% in 2018-2020. Decarbonization in most sectors slowed again. The carbon intensity of the “other manufacturing” sector even increased by 19%. Therefore, policy intervention is necessary to adjust the rebounded preference for energy-consumption supported production and deteriorated energy efficiency.

In summary, the COVID-19 exerted impacts on carbon emissions via the increased contribution of production structure to carbon emissions growth. Production structure is one of the main drivers of China’s carbon emissions for decades but the contribution was largely constrained after the global finance crisis because of decreasing share of exports to economic growth and supply-side reform. However, after the outbreak of COVID-19, the contribution of production structure to driving up the carbon emissions rebounded due to lower production efficiency and preference in carbon-intensive inputs. In addition, energy consumption and investment- and export-supported economic growth were boosted. Consequently, the growth rate of carbon emissions in the pandemic era was not mitigated as much as expected. Carbon emissions grew at an annual rate of 1.0% from 2012 to 2018, while from 2018 to 2020, the annual growth rate increased to 1.8%, and emissions grew even faster in 2020 (1.8%) than in 2019 (1.7%).

Discussion

China's carbon emissions plateaued since the beginning of the new normal but started to rebound in 2016. Although the shock of the COVID-19 pandemic halted economic activities in early 2020, the return of economic growth in the latter half of 2020 caused a robust rebound in carbon emissions. We analysed the changes in the driving forces of carbon emissions in the period 2002-2020 via input–output analysis and SDA. The changes in the contribution of five socioeconomic factors to the total carbon emission changes were analysed, including population, energy efficiency, production structure, consumption pattern and per capita consumption volume.

Increased contribution of production structure to carbon emission growth

In the long run, structural upgrades of industries have slowed the contribution of the production structure as a driver of carbon increments since the new normal, while a deterioration in production can be seen in the economic recovery from the COVID-19. Efficiency improvement is the dominant force that contributes to carbon reduction and consumption patterns contributed slightly to decarbonization in the new normal. The significance of energy efficiency, consumption patterns and industrial updates to China’s carbon emission reductions is also revealed in the literature [20,39,40]. The slowing economic growth has also contributed to lower increases of carbon emissions since the new normal. Halted economic activities during the COVID-19 lockdown further diminished carbon emission increases due to economic growth. The steady and slow rising population caused an increase rate of 1.2% every year from 2002 to 2020.

The deterioration in production structure was much mitigated after the new normal while the rebounded demand caused by export and investment again witnessed rapid increase in carbon-intensive production. Before the new normal, production structure was the dominant force that drove carbon emission growth because of the reliance on energy-intensive and export-oriented production The long-term low-end market that China's supply chain targets in international trade led to enormous resource utilization while creating little value added. This not only increased the vulnerability of the production structure but also overburdened the environment and climate. In the new normal phase, the country started to chase inclusive and sustainable growth driven by innovation and technology. The previous exclusive pursuit of high-speed growth was abandoned, while stock adjustment and high-quality increases became the goal. In the process of structural upgrades, the elimination of the backward production capacity and supply-side reform has been accelerated. However, the seek for recovering from the pandemic-associated economic crisis witnessed a rebound in the contribution of production structure to carbon emission growth. This is both resulted from higher intermediate input intensity and reliance on carbon-intensive inputs. During 2018 to 2020, more intermediate inputs and more carbon-intensive products, e.g., fossil fuel, are required to produce the same number of outputs, indicating lower production efficiency as well as preference in high-carbon products. The interaction between production and consumption structures further led to investment- and export-supported emission growth. The fiscal stimulus packages targeting new infrastructure led to increased carbon emissions in the construction sector and expanded export share boosted some carbon-intensive production, for example, non-metallic products. In the post pandemic era, investments in low-carbon technologies and industries are important to avoid future carbon emission trajectories locked in the high-carbon industries.

Efficiency gains have been the predominant force that reduces carbon emissions, accounting for 188% of carbon reduction, while the contribution was undermined due to the pandemic. The contribution of efficiency improvements to carbon reductions in China is consistent with the results of other analysis periods in the literature. The improvements to energy efficiency are mainly due to technological progress as well as energy transformation. The investment in and development of green energy innovation helps to cut the cost of cleaner energy. For example, the cost of solar power in China was lowest in 2021, at \$0.034/kWh [41]. Advances in technological evolution facilitate energy efficiency during production as well as transitions in the energy mix. The proportion of thermal power generated by coal and other fossil fuels as the most carbon-intensive power has continuously decreased, while renewable energy accounts more for energy consumption. Other factors, such as the market revolution shifting from a monopoly market to competition and energy network transmission, also contribute to the improvement of energy efficiency. Nonetheless, the benign trend in decoupling of China’s economic growth from fossil fuel consumption was impeded by the COVID-19 in 2020 because of the drop in energy prices and reluctance in decarbonization action of the companies in light of the urge for economic recovery. The preference in fossil fuel led to undermined contribution of energy efficiency to carbon reduction in 2020. Policies should be implemented to motivate energy transitions into renewable energy usage and to develop a well-functioning carbon trading mechanism.

Consumption patterns contributed slightly to the carbon reduction in 2012-2017 but have deteriorated since 2017. The optimization of consumption patterns is related to the shift from investment- and export-supported increases towards domestic consumption-supported growth. Since the new normal, carbon emissions induced by capital formation and exports have continued to decline, while household and government consumption have become the main agencies that cause increases in emissions. This trend is accompanied by a shift from heavy industry investment to consumption in services and therefore contributes to the optimization of consumption patterns. In 2020, the lock-down measurement and travel restrictions reduced household consumption, especially in the food, textile, transport, and retail sectors. This helps to cut the contribution of consumption patterns to carbon emissions in 2018 to 2020. But the pandemic also diminished consumer confidence and therefore, stimulating private consumption is important for a continuous transition in the consumption patterns.

Green and resilient recovery from the pandemic

While the determinants of emissions have not been changed, impacts of the COVID-19 can be seen in evidence of rapid growth of carbon-intensive production, rising contribution of investment and exports to the emission increase, and slowed-down efficiency gains. Policies need to focus on stimulating the weak consumption of urban and rural households and optimizing the promotion of the low-carbon industry to prevent the deterioration of the production structure.

First, stimulus measures targeting a robust rebound of consumption are urgently needed for the economic recovery from the COVID-19. China is eager to prop up economic growth by expanding consumption and domestic demand in the new normal. COVID-19 obstructed progress in increasing private consumption because of lowered income and weakened consumer expectations. The contribution of private and public consumption to the increase in carbon emissions from 2018 to 2020 (56%) was downsized compared with the period from 2012 to 2018 (95%). In addition, the carbon emissions from household consumption were primarily induced by energy usage, while transport- and retail-related emissions decreased in 2020, indicating that private consumption in travelling and retail commodities has not recovered from the pandemic. Since the success in containing the first wave of COVID-19 in early 2020, China has not completely reopened or returned to the pre-pandemic normality. The economic growth in the second half of 2020 was mainly led by recovery in investment and export while consumption-led expansion was still at a low level. Therefore, efforts should be taken to increase the consumption-to-GDP ratio, and improving consumer expectations and boosting domestic consumption towards low-carbon patterns is essential for a resilient recovery from the pandemic.

Second, there is a good opportunity to increase investment in decarbonization technologies and accelerate the development of low-carbon industries to achieve a green and inclusive recovery. To prompt development in key segments, such as artificial intelligence and digital information technology, China has invested in new infrastructure construction. The increased infrastructure investment leads to an increase in carbon emissions caused by capital formation. For emerging economies, increasing infrastructure investment is an appropriate fiscal measure to spur economic recovery. From the perspective of achieving climate targets (carbon peak before 2030 and carbon neutrality before 2060), China should seize the opportunity and increase its investment in green technologies and industries to gain competitiveness in decarbonization in the future, for example, supporting the low-carbon transition and promoting the green and sustainable finance of private companies. This would also produce jobs in low-carbon industries and help to prepare for the demand for skilled labour in related industries.

Third, encouraging innovation and improving the proportion of high value-added products in exports are crucial to enhancing the position of China's manufacturing in the global supply chain. With the rising production cost in China due to the shortage of cheap labour and restrictions on carbon reduction, the risk of industrial relocation has been mounting. The development of sophisticated manufacturing is the key to expanding China's presence in the global market in the future. In 2020, the carbon emissions of exports were heightened compared with the 2018 level for the first time since the new normal. With the booming demand as the rest of the world was still suffering from the pandemic in the second half of 2020, the prosperity of exports in 2020 provided a good chance to enhance the comparative competitiveness of China's manufacturing. Policies should target high value-added and low-carbon industries and improve competitiveness in the global market to prevent the rebounding of carbon-intensive and unsustainable production.

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Author contributions

Z.M. designed the study. X.S. performed the analysis and prepared the manuscript. X.S. and Z.M. interpreted the data and participated in writing the manuscript together.

Declaration of interest

The authors declare no competing interests.

Appendix

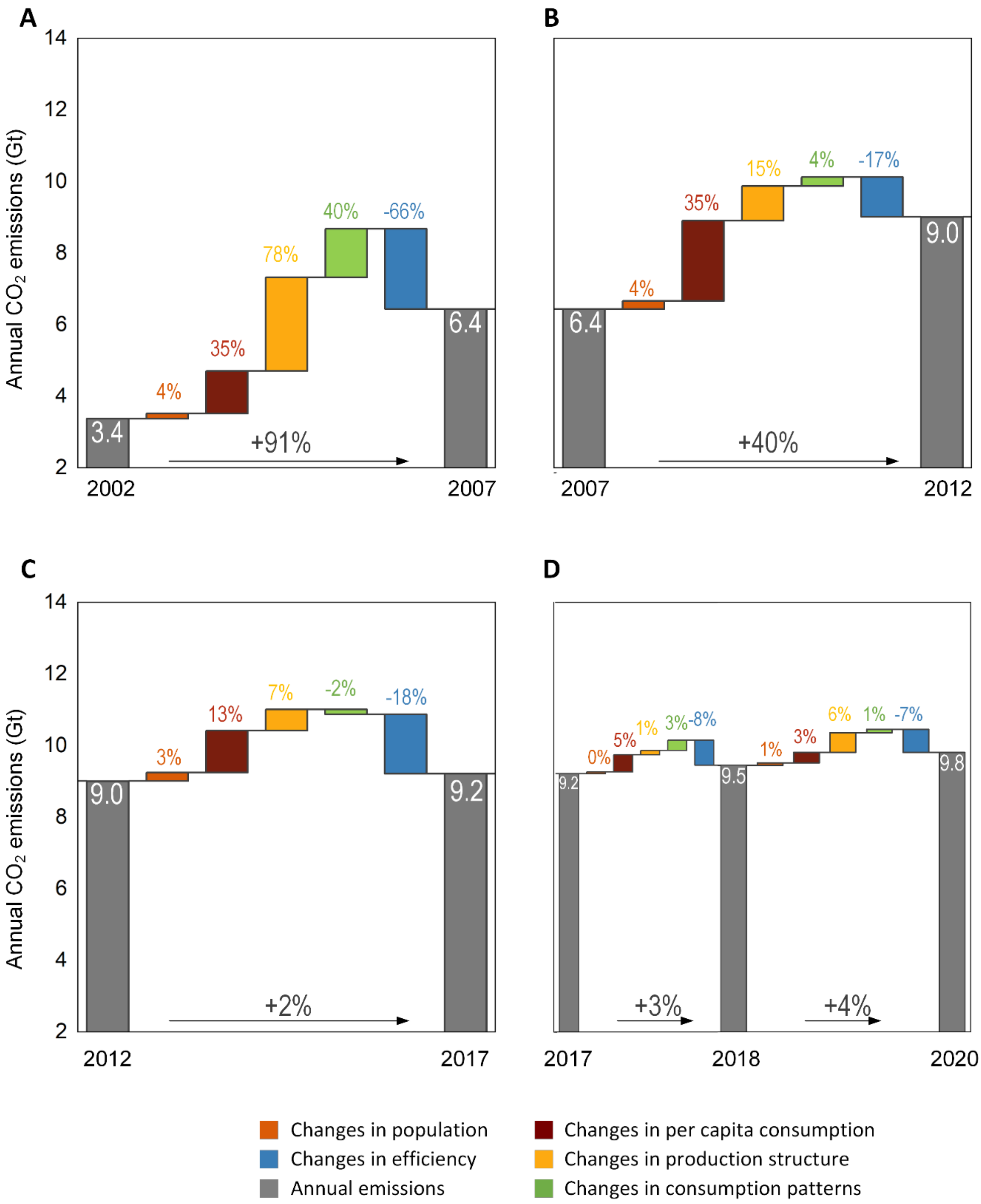

Fig. A1. Absolute contributions of different factors to changes in Chinese CO2 emissions for all stages. A. 2002-2007. B. 2007-2012 C. 2012-2017. D. 2017-2018 and 2018-2020.

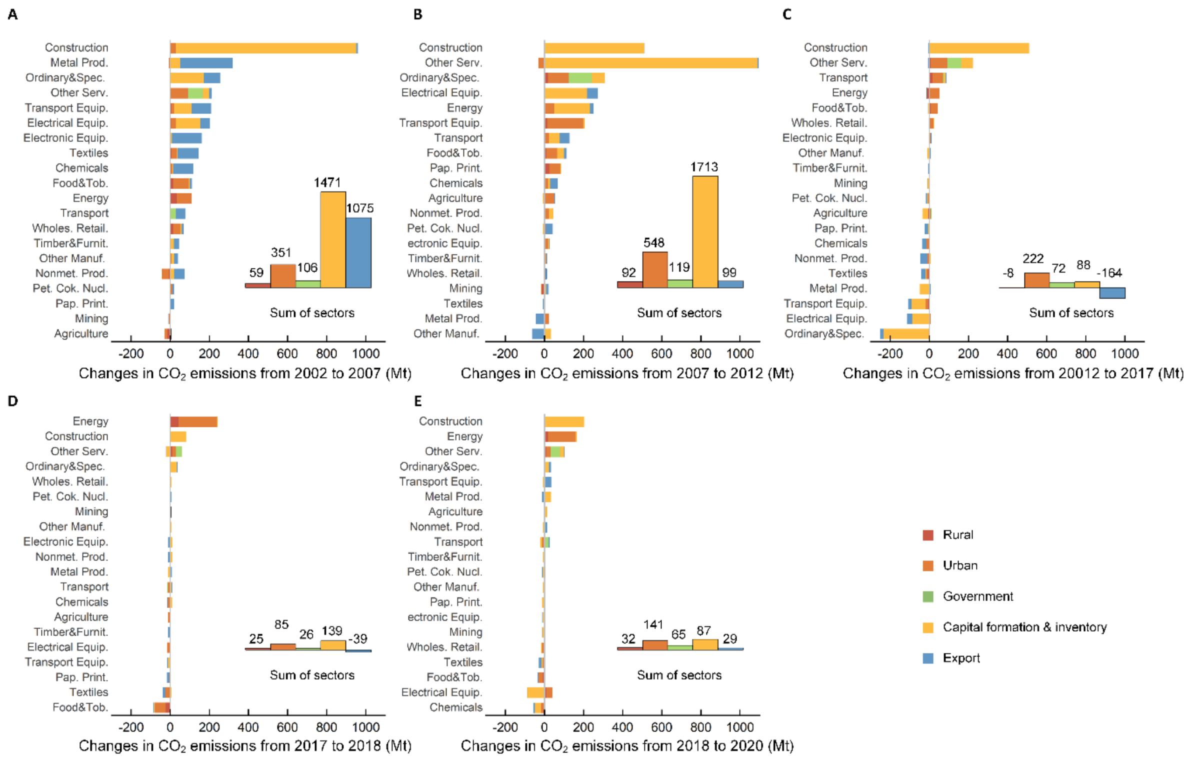

Fig. A2. Contributions of different sectors and final uses to Chinese CO2 emissions growth from 2002 to 2020. A, B, C, D and E show the results for 2002–2007, 2007–2012, 2012–2017, 2017-2018, and 2018-2020, respectively.

Table A1 CO_2 emission factors for energy consumption

No.	Energy types	Emission factors (Mt CO_2 / 10^4 t, 10^8 m^3)
1	Raw coal	0.0162
2	Cleaned coal	0.0204
3	Other washed coal	0.0119
4	Briquettes	0.0138
5	Coke	0.0288
6	Coke oven gas	0.1153
7	Other gas	0.0596
8	Other coking products	0.0252
9	Crude oil	0.03
10	Gasoline	0.0293
11	Kerosene	0.0304
12	Diesel oil	0.0309
13	Fuel oil	0.0317
14	Liquefied petroleum gas (LPG)	0.0313
15	Refinery gas	0.0334
16	Other petroleum products	0.0303
17	Nature gas	0.2161
18	Non-fossil Heat	0
19	Non-fossil Electricity	0
20	Other energy	0

Table A2 Concordance of sectors for Chinese IO tables, carbon emission inventories and Exiobase

MRIO tables.	Carbon emission inventories	Exiobase MRIO tables
Agriculture	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy	Cultivation of paddy rice, wheat, cereal grains n.e.c, vegetables, fruit, nuts, oil seeds, sugar cane, sugar beet, plant-based fibers, crops n.e.c; Cattle, pigs, poultry farming, meat animals n.e.c, animal products n.e.c, raw milk; Wool, silk-worm cocoons; Manure treatment (conventional), storage and land application; Manure treatment (biogas), storage and land application; Forestry, logging and related service activities; Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing
Mining	Coal Mining and Dressing; Petroleum and Natural Gas Extraction; Ferrous Metals Mining and Dressing; Nonferrous Metals Mining and Dressing; Nonmetal Minerals Mining and Dressing; Other Minerals Mining and Dressing	Mining of coal and lignite; extraction of peat; Extraction of crude petroleum, natural gas, and services related; Extraction, liquefaction, and regasification of other petroleum and gaseous materials Mining of uranium and thorium ores, iron ores, copper ores, nickel ores, aluminium ores, precious metal ores, lead, zinc and tin ores, other non-ferrous metal ores, and concentrates; Quarrying of stone, sand and clay; Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c
Foods and Tobacco	Food Processing Food Production Beverage Production Tobacco Processing	Processing of meat cattle, meat pigs, meat poultry, meat products n.e.c, vegetable oils and fats, dairy products, food products n.e.c; Processed rice; Sugar refining; Manufacture of beverages, fish products, tobacco products
Textiles	Textile Industry; Garments and Other Fiber Products; Leather, Furs, Down and Related Products	Manufacture of textiles, wearing apparel; Dressing and dyeing of fur; Tanning and dressing of leather; Manufacture of luggage, handbags, saddlery, harness and footwear
Timbers and Furniture	Logging and Transport of Wood and Bamboo; Timber Processing, Bamboo, Cane, Palm Fiber & Straw Products; Furniture Manufacturing	Manufacture of wood and of products of wood and cork, except furniture; Manufacture of articles of straw and plaiting materials; Re-processing of secondary wood material into new wood material
Paper and Printing	Papermaking and Paper Products; Printing and Record Medium Reproduction; Cultural, Educational and Sports Articles	Pulp; Re-processing of secondary paper into new pulp; Paper; Publishing, printing and reproduction of recorded media
Petroleum, Coking, Nuclear Fuel	Petroleum Processing and Coking	Manufacture of coke oven products; Petroleum Refinery; Processing of nuclear fuel

Chemicals	Raw Chemical Materials and Chemical Products; Medical and Pharmaceutical Products; Chemical Fiber; Rubber Products; Plastic Products	Plastics, basic; Re-processing of secondary plastic into new plastic; N-fertiliser; P- and other fertilizer; Chemicals n.e.c; Manufacture of rubber and plastic products
Nonmetallic Mineral Products	Nonmetal Mineral Products	Manufacture of glass and glass products; Re-processing of secondary glass into new glass; Manufacture of ceramic goods, bricks, tiles and construction products, in baked clay, cement, lime and plaster; Re-processing of ash into clinker; Manufacture of other non-metallic mineral products n.e.c.
Metal Products	Smelting and Pressing of Ferrous Metals Smelting and Pressing of Nonferrous Metals Metal Products	Manufacture of basic iron and steel, ferro-alloys, precious metals, aluminum, lead, zinc and tin, copper, and other non-ferrous metal; Re-processing of secondary metal into new; Casting of metals; Manufacture of fabricated metal products, except machinery and equipment.
Ordinary and Special Machinery	Ordinary Machinery Equipment for Special Purposes	Manufacture of machinery and equipment n.e.c.
Transport Equipment	Transportation Equipment	Manufacture of motor vehicles, trailers and semi-trailers, and other transport equipment
Electrical Equipment	Electric Equipment and Machinery	Manufacture of electrical machinery and apparatus n.e.c.
Electronic Equipment	Electronic and Telecommunications Equipment	Manufacture of office machinery and computers Manufacture of radio, television and communication equipment and apparatus
Other Manufacturing Industry	Instruments, Meters, Cultural and Office; Machinery; Other Manufacturing Industry; Scrap and waste	Manufacture of medical, precision and optical instruments, watches and clocks; Manufacture of furniture; manufacturing n.e.c; Recycling of waste and scrap, and bottles by direct reuse.
Electricity, Gas, Water	Production and Supply of Electric Power, Steam and Hot Water; Production and Supply of Gas and Tap Water	Production of electricity by coal, gas, nuclear, hydro, wind, petroleum and other oil derivatives, biomass and waste, solar photovoltaic, solar thermal, tide, wave, ocean, Geothermal, n.e.c; Transmission, distribution and trade of electricity; Manufacture and distribution of gas; Steam and hot water supply; Collection, purification and distribution of water
Construction	Construction	Construction; Re-processing of secondary construction material into aggregates
Transport	Transportation, Storage, Post and Telecommunication Services	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts and accessoiries; Retail sale of automotive fuel; Transport via railways; Other land transport; Transport via pipelines; Sea and coastal water transport; Inland water transport; Air transport; Supporting and auxiliary transport activities; activities of travel agencies; Post and telecommunications

Wholesale, Retail, Catering	Wholesale, Retail Trade and Catering Services	Wholesale trade and commission trade, except of motor vehicles and motorcycles; Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods; Hotels and restaurants
Other Services	Others	Financial intermediation, insurance and pension funding, activities auxiliary to financial intermediation; Real estate activities; Renting; Computer and related activities; Research and development; Other business activities; Public administration and defence; compulsory social security; Education; Health and social work; Incineration of waste; Biogasification of waste; Composting of food waste, paper and wood, incl. land application; Waste water treatment; Landfill of waste; Activities of membership organisation n.e.c; Recreational, cultural and sporting activities; Other service activities; Private households with employed persons; Extra-territorial organizations and bodies

References

(1) National Bureau of Statistics. *Gross domestic product (GDP) in the first quarter of 2020.* http://www.stats.gov.cn/tjsj/zxfb/202004/t20200417_1739602.html.

(2) Han, P.; Cai, Q.; Oda, T.; Zeng, N.; Shan, Y.; Lin, X.; Liu, D. Assessing the Recent Impact of COVID-19 on Carbon Emissions from China Using Domestic Economic Data. *Sci Total Environ* **2021**, *750*, 141688. https://doi.org/10.1016/j.scitotenv.2020.141688.

(3) Norouzi, N.; Zarazua de Rubens, G.; Choupanpiesheh, S.; Enevoldsen, P. When Pandemics Impact Economies and Climate Change: Exploring the Impacts of COVID-19 on Oil and Electricity Demand in China. *Energy Res Soc Sci* **2020**, *68*, 101654. https://doi.org/10.1016/j.erss.2020.101654.

(4) Guan, D.; Wang, D.; Hallegatte, S.; Davis, S. J.; Huo, J.; Li, S.; Bai, Y.; Lei, T.; Xue, Q.; Coffman, D.; Cheng, D.; Chen, P.; Liang, X.; Xu, B.; Lu, X.; Wang, S.; Hubacek, K.; Gong, P. Global Supply-Chain Effects of COVID-19 Control Measures. *Nat Hum Behav* **2020**, *4* (6), 577–587. https://doi.org/10.1038/s41562-020-0896-8.

(5) Zheng, B.; Geng, G.; Ciais, P.; Davis, S. J.; Martin, R. V.; Meng, J.; Wu, N.; Chevallier, F.; Broquet, G.; Boersma, F.; van der A, R.; Lin, J.; Guan, D.; Lei, Y.; He, K.; Zhang, Q. Satellite-Based Estimates of Decline and Rebound in China's CO_2 Emissions during COVID-19 Pandemic. *Sci Adv* **2020**, *6* (49), eabd4998. https://doi.org/10.1126/sciadv.abd4998.

(6) Cazcarro, I.; García-Gusano, D.; Iribarren, D.; Linares, P.; Romero, J. C.; Arocena, P.; Arto, I.; Banacloche, S.; Lechón, Y.; Miguel, L. J.; Zafrilla, J.; López, L.-A.; Langarita, R.; Cadarso, M.-Á. Energy-Socio-Economic-Environmental Modelling for the EU Energy and Post-COVID-19 Transitions. *Sci Total Environ* **2022**, *805*, 150329. https://doi.org/10.1016/j.scitotenv.2021.150329.

(7) Liu, Z.; Ciais, P.; Deng, Z.; Lei, R.; Davis, S. J.; Feng, S.; Zheng, B.; Cui, D.; Dou, X.; Zhu, B.; Guo, R.; Ke, P.; Sun, T.; Lu, C.; He, P.; Wang, Y.; Yue, X.; Wang, Y.; Lei, Y.; Zhou, H.; Cai, Z.; Wu, Y.; Guo, R.; Han, T.; Xue, J.; Boucher, O.; Boucher, E.; Chevallier, F.; Tanaka, K.; Wei, Y.; Zhong, H.; Kang, C.; Zhang, N.; Chen, B.; Xi, F.; Liu, M.; Bréon, F.-M.; Lu, Y.; Zhang, Q.; Guan, D.; Gong, P.; Kammen, D. M.; He, K.; Schellnhuber, H. J. Near-Real-Time Monitoring of Global CO2 Emissions Reveals the Effects of the COVID-19 Pandemic. *Nat Commun* **2020**, *11* (1), 5172. https://doi.org/10.1038/s41467-020-18922-7.

(8) Ibn-Mohammed, T.; Mustapha, K. B.; Godsell, J.; Adamu, Z.; Babatunde, K. A.; Akintade, D. D.; Acquaye, A.; Fujii, H.; Ndiaye, M. M.; Yamoah, F. A.; Koh, S. C. L. A Critical Analysis of the Impacts of COVID-19 on the Global Economy and Ecosystems and Opportunities for Circular Economy Strategies. *Resour Conserv Recycl* **2021**, *164*, 105169. https://doi.org/10.1016/j.resconrec.2020.105169.

(9) Ai, H.; Tenglong, Z.; Zhengqing, Z. The Real Economic Costs of COVID-19: Insights from Electricity Consumption Data in Hunan Province, China. *Energy Econ* **2022**, 12.

(10) Mofijur, M.; Fattah, I. M. R.; Alam, M. A.; Islam, A. B. M. S.; Ong, H. C.; Rahman, S. M. A.; Najafi, G.; Ahmed, S. F.; Uddin, Md. A.; Mahlia, T. M. I. Impact of COVID-19 on the Social, Economic, Environmental and Energy Domains: Lessons Learnt from a Global Pandemic. *Sustain Prod Consum* **2021**, *26*, 343–359. https://doi.org/10.1016/j.spc.2020.10.016.

(11) IEA. *Covid-19 Impact on Electricity*; 2021.

(12) Hepburn, C.; O'Callaghan, B.; Stern, N.; Stiglitz, J.; Zenghelis, D. Will COVID-19 Fiscal Recovery Packages Accelerate or Retard Progress on Climate Change? *Oxf Rev Econ Policy* **2020**, *36* (Supplement_1), S359–S381. https://doi.org/10.1093/oxrep/graa015.

(13) OECD. *OECD Policy Responses to Coronavirus (COVID-19): The Long-Term Environmental Implications of COVID-19*; OECD Publishing: Paris, 2021.

(14) Lauri Myllyvirta. *China's CO2 Emissions Surged Past Pre-Coronavirus Levels in May*; Carbon Brief, 2020.

(15) Yu, Z.; Razzaq, A.; Rehman, A.; Shah, A.; Jameel, K.; Mor, R. S. Disruption in Global Supply Chain and Socio-Economic Shocks: A Lesson from COVID-19 for Sustainable Production and Consumption. *Oper Manag Res* **2021**. https://doi.org/10.1007/s12063-021-00179-y.

(16) Wang, Q.; Wang, S.; Jiang, X. Preventing a Rebound in Carbon Intensity Post-COVID-19 – Lessons Learned from the Change in Carbon Intensity before and after the 2008 Financial Crisis. *Sustain Prod Consum* **2021**, *27*, 1841–1856. https://doi.org/10.1016/j.spc.2021.04.024.

(17) International Monetary Fund. *World Economic Outlook, April 2020: The Great Lockdown*; 2020. https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020.

(18) World Bank. *Exports of goods and services (% of GDP) - China*. https://data.worldbank.org/indicator/NE.EXP.GNFS.ZS?locations=CN.

(19) Mi, Z.; Meng, J.; Guan, D.; Shan, Y.; Liu, Z.; Wang, Y.; Feng, K.; Wei, Y.-M. Pattern Changes in Determinants of Chinese Emissions. *Environ Res Lett* **2017**, *12* (7), 074003. https://doi.org/10.1088/1748-9326/aa69cf.

(20) Zheng, J.; Mi, Z.; Coffman, D.; Shan, Y.; Guan, D.; Wang, S. The Slowdown in China's Carbon Emissions Growth in the New Phase of Economic Development. *One Earth* **2019**, *1* (2), 240–253. https://doi.org/10.1016/j.oneear.2019.10.007.

(21) John Bluedorn; Gita Gopinath; Damiano Sandri. *An Early View of the Economic Impact of the Pandemic in 5 Charts*; IMF Blog, 2020.

(22) Leontief, W. *Environmental Repercussions and the Economic Structure: An Input-Output Approach*; Routledge, 2018.

(23) Mi, Z.; Meng, J.; Guan, D.; Shan, Y.; Liu, Z.; Wang, Y.; Feng, K.; Wei, Y.-M. Pattern Changes in Determinants of Chinese Emissions. *Environ Res Lett* **2017**, *12* (7), 074003. https://doi.org/10.1088/1748-9326/aa69cf.

(24) Zheng, J.; Mi, Z.; Coffman, D.; Shan, Y.; Guan, D.; Wang, S. The Slowdown in China's Carbon Emissions Growth in the New Phase of Economic Development. *One Earth* **2019**, *1* (2), 240–253. https://doi.org/10.1016/j.oneear.2019.10.007.

(25) Zheng, H.; Zhang, Z.; Wei, W.; Song, M.; Dietzenbacher, E.; Wang, X.; Meng, J.; Shan, Y.; Ou, J.; Guan, D. Regional Determinants of China's Consumption-Based Emissions in the Economic Transition. *Environ Res Lett* **2020**, *15* (7), 074001. https://doi.org/10.1088/1748-9326/ab794f.

(26) Su, B.; Ang, B. W. Structural Decomposition Analysis Applied to Energy and Emissions: Some Methodological Developments. *Energy Econ* **2012**, *34* (1), 177–188. https://doi.org/10.1016/j.eneco.2011.10.009.

(27) Dietzenbacher, E.; Los, B. Structural Decomposition Techniques: Sense and Sensitivity. *Econ Syst Res* **1998**, *10* (4), 307–324.

(28) Hoekstra, R.; Van Den Bergh, J. C. Structural Decomposition Analysis of Physical Flows in the Economy. *Environ Resource Econ* **2002**, *23* (3), 357–378.

(29) Liu, Z.; Guan, D.; Wei, W.; Davis, S. J.; Ciais, P.; Bai, J.; Peng, S.; Zhang, Q.; Hubacek, K.; Marland, G. Reduced Carbon Emission Estimates from Fossil Fuel Combustion and Cement Production in China. *Nature* **2015**, *524* (7565), 335–338.

(30) National Bureau of Statistics. *National Data*. https://data.stats.gov.cn/english/.

(31) Stadler, K.; Wood, R.; Bulavskaya, T.; Södersten, C.-J.; Simas, M.; Schmidt, S.; Usubiaga, A.; Acosta-Fernández, J.; Kuenen, J.; Bruckner, M. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *J Ind Ecol* **2018**, *22* (3), 502–515.

(32) World Bank. *Exchange rates and prices - World Development Indicators*. http://wdi.worldbank.org/table/4.16.

(33) Shan, Y.; Huang, Q.; Guan, D.; Hubacek, K. China CO2 Emission Accounts 2016–2017. *Sci Data* **2020**, *7* (1), 1–9.

(34) Shan, Y.; Guan, D.; Zheng, H.; Ou, J.; Li, Y.; Meng, J.; Mi, Z.; Liu, Z.; Zhang, Q. China CO2 Emission Accounts 1997–2015. *Sci Data* **2018**, *5* (1), 1–14.

(35) Peters, G. P.; Marland, G.; Le Quéré, C.; Boden, T.; Canadell, J. G.; Raupach, M. R. Rapid Growth in CO2 Emissions after the 2008–2009 Global Financial Crisis. *Nature climate change* **2012**, *2* (1), 2–4.

(36) Davis, S. J.; Cao, L.; Caldeira, K.; Hoffert, M. I. Rethinking Wedges. *Environ Res Lett* **2013**, *8* (1), 011001.

(37) Zhang, Y.-J.; Peng, Y.-L.; Ma, C.-Q.; Shen, B. Can Environmental Innovation Facilitate Carbon Emissions Reduction? Evidence from China. *Energy Policy* **2017**, *100*, 18–28.

(38) Baptist, S.; Hepburn, C. Intermediate Inputs and Economic Productivity. *Phil. Trans. R. Soc. A.* **2013**, *371* (1986), 20110565. https://doi.org/10.1098/rsta.2011.0565.

(39) Guan, D.; Meng, J.; Reiner, D. M.; Zhang, N.; Shan, Y.; Mi, Z.; Shao, S.; Liu, Z.; Zhang, Q.; Davis, S. J. Structural Decline in China's CO2 Emissions through Transitions in Industry and Energy Systems. *Nat Geosci* **2018**, *11* (8), 551–555.

(40) Mi, Z.; Sun, X. Provinces with Transitions in Industrial Structure and Energy Mix Performed Best in Climate Change Mitigation in China. *Commun Earth Environ* **2021**, *2* (1), 1–12.

(41) Max Hall. *Solar power costs continued to fall in 2021, despite rising panel prices*. PVMagazine - Photovoltaics Markets and Technology. https://www.pv-magazine.com/2022/07/14/solar-power-costs-continued-to-fall-in-2021-despite-rising-panel-prices/.