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# China carbon emission accounts 2020-2021

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## HIGHLIGHTS

- Accounting of IPCC administrative territorial emissions from fossil fuels and cement production for China and its provinces in 2020–2021
- Accounting of consumption-based emissions for China from 2002 to 2020
- Revealing the dynamic impact of COVID-19 on China's carbon emissions

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## ABSTRACT

In the past a few years, the outbreak of the COVID-19 epidemic has significantly changed global emission patterns and increased the challenges in emission reduction. However, a comprehensive analysis of the most recent trends of China's carbon emissions has not been conducted due to a lack of up-to-date emission accounts by regions and sectors. This study compiles the latest $CO_2$ emission inventories for China and its 30 provinces during the epidemic (2020−2021), following the administrative-territorial approach from the International Panel on Climate Change (IPCC). Our inventories cover energy-related emissions from 17 types of fossil fuel combustion and cement production across 47 economic sectors. To provide a holistic view of emission patterns, we esitamted consumption-based emissions in China. We find that the COVID-19 epidemic led to a 50% reduction in the growth rate of territorial emissions in 2020 compared to 2019. This trend then reversed in 2021 as lockdown measures gradually relaxed. Our study reveals the impact of the rapid expansion of exports, driven by epidemic prevention materials and "stay-at-home economy" products on widening the differences between territorial- and consumption-based emissions. Our study offers a timely blueprint for designing strategies towards carbon peak and neutrality, especially in the context of sustainable recoveries and carbon mitigation post-pandemic.

## 1. Introduction

As the impact of global warming has intensified around the world, it is essential for collective efforts of nations worldwide to reduce carbon emissions. Reliable emission estimations ensure mitigation strategies and policymaking are both feasible and impactful, which provide a comprehensive grasp of the global carbon cycle [23]. As China has became the world's top $CO_2$ producer [13], the country takes more responsibility for emission reductions. China is actively pursuing various strategies to mitigate $CO_2$ emissions, aligning itself with ambitious targets such as peaking emissions before 2030 and achieving carbon neutrality before 2060 (i.e., Dual-Carbon goals). Given China's role in global emissions and its influence on global emission trajectories, these targets are not just significant for China but have global implications. Their achievement could potentially advance the realization of the temperature control goals outlined in the Paris Agreement.

China has made great progress in reducing carbon emissions in recent years. In 2020, the emission intensity (carbon emission per unit of gross domestic product) dropped by 48.4% compared to 2005, which surpassed the 40.0%–45.0% reduction target promised by the

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government [9]. However, there are still great challenges for China to achieve the Dual-Carbon goals. First, China has been heavily reliant on fossil fuel consumption (up to 84.1% in 2020), which has contributed to a high-carbon energy mix and huge carbon emissions [41]. Secondly, the expansion of sectors with high energy consumption increases the share of manufacturing, leading to large emissions [30]. Finally, the rapid economic growth in China inevitably leads to high energy consumption [32].

In 2020, the onset of COVID-19 and the subsequent lockdowns around the world affected carbon emissions. In China, during the first four months, reduced industrial activities and social engagements led to a decrease in energy consumption, resulting in lowered emissions. Specifically, from January to April, emissions from manufacturing saw a decrease of 70.50Mt, which is a 5.9% decline compared to the same period in 2019 [26]. Nevertheless, instead of wide-scale lockdowns, the country adopted localized, brief lockdown measures from April onwards. Hence, its impact was less pronounced and a noticeable increase in emissions could be observed. This rise was highlighted by the 3.4% increase in manufacturing emissions in April, compared to April 2019 [26]. Given that the drop in carbon emissions in many sectors in 2020 was not due to structural changes but rather to mandatory behavioural changes, a rapid rise in emissions is to be expected after the relaxation of restrictions [23]. The unpredictable epidemic has introduced a significant degree of uncertainty to the global emission trajectory, making it more difficult to formulate emission reduction policies. Accurate accounting of carbon emissions is crucial for assessing the pandemic's impact and for shaping future strategies aimed at achieving carbon neutrality. By observing how major economies, like China, react to abrupt disruptions, we can gain valuable insights that can guide nations in building resilience against unforeseen events and in their pursuit of sustainable development.

There are still some difficulties and gaps in estimating emission inventory. First, China lacks an official continuous emission inventory, with data available only for select years (1994, 2005, 2010, 2012, 2014, 2017, 2018) [17,35,36]. An inconsistent emission inventory does not reach the standard of a high-quality dataset (Paris Agreement) and fails to provide necessary information and details on emissions reduction. Second, widely used $CO_2$ emission databases are constructed with different statistics criteria, shown in Table S1 in Supplementary material 1. Different statistics criteria make these datasets incomparable to any meaningful extent. Thirdly, while there are studies that provide provincial-level emission data [8,58], gaps remain regarding the emissions by detailed sectors and energy types. For example, Guevara et al. [18] set the emission scenario for the $CO_2$ fossil fuel and $CO_2$ biofuel. Doumbia et al. [7] construct the COVID-19 emission scenario with a total of four sectors: power, industry, residential and transportation. Although these sectors and energy types account for a high proportion of emissions, they do not reflect a comprehensive picture of industry-wide emissions. Given that China's Dual-Carbon goals necessitate the collective action of all provinces, the completeness of such data essential. Finally, of all the above works, only Guevara et al. [18] made their final emissions dataset public. The remaining studies do not provide the raw data or clarify the data source, resulting in non-transparent and unreliable estimated data.

In addition to territorial emissions, consumption-based emissions have been seen as a complement to national emission accounting. Consumption-based approach trackes emissions embodied in supply chains, thereby quantifying the carbon emissions embodied in the consumption patterns of a given region. This approach enables a comprehensive assessment of carbon accountability, shifting the focus from producers to consumers. Such a shift promotes strategies aimed at mitigating climate change from a consumption perspective. However, most studies that compute consumption-based emissions have limitations in their temporal and spatial scope. For example, Feng et al. [12] estimated the outsourcing of inter-provincial $CO_2$ emissions in China in 2007. The results indicate that products and services that are consumed outside of the province in which they are produced account for 57.0% of China's emissions. Sun and Mi [50] estimated the consumption-based emissions from 2012 to 2020 and analysed the factors driving the changes of emissions. They found that exports and investments in construction sector are the primary drivers of emission growth. Therefore, the consumption-based emissions of China need more in-depth analysis.

Aiming at the above research gaps, this paper represents an extensive update of existing China's emission estimates [17,46,47] by including (i) a description of the trends of territorial $CO_2$ emissions from both energy combustion and cement production over the historical period 1997–2022, with a strong focus on the period of the COVID-19 pandemic, (ii) the most comprehensive long time series energy/emission inventories, covering 47 economic sectors and 17 energy types, (iii) consideration of the change in emissions for 30 provinces encompassing the period before and after COVID-19, and (iv) providing a more holistic perspective from consumption-based emissions, look closer into the disparities between territorial-based emissions and consumption-based emissions over the long-term history. The dataset developed in this study is to support the quantification of China's $CO_2$ emission changes, and to reveal the heterogeneous impact of COVID-19 on emissions across China's 30 provinces and 47 economic sectors. The consistent and comparable emission inventory will provide valuable information, guilding government responses to the future unforeseen crisesand aiding in the development of future abatement initiatives. Furthermore, this could serve as a blueprint for other nations, offering lessons on navigating large-scale disruptions and developing responsive policy frameworks. The energy-related and process-related emission inventories have been published in our open-source dataset $CO_2$ China Emission Accounts and Datasets (CEADs, www.ceads.net).

## 2. Methods

### 2.1. Accounting approaches

There are several accounting approaches for estimating carbon emissions [48]. Production-based accounting estimates the emissions released from production activities in a region. Territorial-based accounting covers all emissions generated within the country. Unlike production-based accounting, territorial-based accounting does not consider emissions resulting from international aviation or shipping. A more thorough carbon footprint could be provided by consumption-based accounting. It identifies the emissions associated with products and services that take place in one region but are produced elsewhere [56]. Territorial-based accounting is the mandatory accounting method in the United Nations Framework Convention on Climate Change (UNFCCC), as these statistics enable comparisons between countries' progress in reducing emissions and are quite accurate [57].

### 2.2. Territorial-based accounting

In this study, territorial-based emissions are compiled in line with guidance from the International Panel on Climate Change administrative-territorial approach [22] and cover the carbon emissions for China and its 30 provinces from 1997 to the latest available year of reporting (2021). We consider territorial-based accounting from two main sources: energy-related emissions and process-related emissions. The scope, format, and data source between national and provincial estimates in this paper are consistent.

#### 2.2.1. Energy-related sectoral emissions

Energy-related emissions indicate carbon emissions from fossil fuel combustion. The energy-related emissions, broken down by sectors and energy types, can be calculated based on the following equation.

$$CE_{ij} = AD_{ij} \times NCV_i \times CC_i \times O_{ij} \quad (1)$$

Where $i$ and $j$ are defined as the fuel type and sector. $CE_{ij}$ indicates the amount of $CO_2$ released from the combustion of fuel $i$ in sector $j$. $AD_{ij}$ is activity data, representing the amount of fossil fuels consumed by fossil fuel $i$ and sector $j$. We consider the energy combustion for the activity data only and exclude the part of non-energy use and energy loss. Emission factor can be separated into $NCV_i$, $CC_i$ and $O_{ij}$. $NCV_i$ is net caloric value, representing the heat released by fuel $i$ when it cools to its initial state (ambient temperature after complete combustion). $CC_i$ is carbon content, indicating the mass percentage of carbon in all elements measured in the fuel $i$. $O_{ij}$ is the oxidization rate, indicating the fraction of fuel oxidized during combustion. This study adopts survey-based emission factors from our earlier research [[28],46].

Our emission inventory covers 17 fossil fuels (shown in Table S2 in Supplementary material 1) and 47 sectors (shown in Table S3 in Supplementary material 1). In terms of the classification of sectors, our inventory follows China's national economic accounting standard and approach [37]. The same statistical approach facilitates the comparison for future studies.

#### 2.2.2. Energy-related reference emissions

Energy-related reference emissions are estimated using energy supply data. It is a top-down method, which can be regarded as a complement to the sectoral approach [22]. We estimated the reference emissions of raw coal, crude oil, and natural gas, since they are primary energy. The reference emissions are calculated as:

$$CE_{ref\_i} = AD_{ref\_i} \times EF_i \tag{2}$$

Where, $CE_{ref\_i}$ indicates the emissions estimated using reference method. The activity data ($AD_{ref\_i}$) can be estimated based on the mass balance of energy:

$$\begin{aligned} AD_{ref\_i} = {} & Production + Imports - exports \\ & + (Moving\ in\ from\ Other\ Provinces \\ & - Sending\ Out\ to\ Other\ Provinces) \pm Changes\ in\ Stocks \\ & - Non\ Energy\ Use\ of\ Fuels - Loss \end{aligned} \tag{3}$$

Noticeably, items in brackets are only considered when estimating the provincial emissions.

#### 2.2.3. Process-related emissions

In this paper, we estimate process-related emissions from cement production, as cement production is the third-largest source of carbon emissions globally [2] and contributes around 75.0% of process-related $CO_2$ emissions in China [46]. The chemical reaction in cement manufacture occurs when carbonates (largely $CaCO_3$) contained in limestone are converted into oxides (primarily lime, CaO) and $CO_2$ by the addition of heat. The process-related emissions can be estimated as:

$$CE_{cement} = AD_{cement} \times EF_{cement} \tag{4}$$

Where, $CE_{cement}$ indicates the emissions from cement production. $AD_{cement}$ is the mass of total cement production. The value of $EF_{cement}$ is collected from Liu et al. [28].

### 2.3. Consumption-based accounting

We adopt the input-output model to estimate consumption-based emissions of China in this study. An environmentally extended input-output model has been widely used to calculate the indirect emissions and embodied emissions of an economic sector in one country [20,59]. More detailed explanations can be found in previous studies [34,55].

The total output of sectors within an economy **x** can be expressed as

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{y} \tag{5}$$

Where $\boldsymbol{x}$ is the total output of sectors. $\boldsymbol{A} = (z_{ij}/\boldsymbol{x}_j)$ is the technological coefficient matrix, representing the intersectoral economic linkages. $z_{ij}$ is the intermediate inputs from sector i to sector j. $\boldsymbol{x}_j$ is the total output of sector j. $\boldsymbol{A}\boldsymbol{x}$ is the sum of intermediate consumption from sectors; $\boldsymbol{y}$ is the final demand of sectors. When solved for the total output, Eq. (5) can yield

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{y} \tag{6}$$

Where $\boldsymbol{I}$ is the identity matrix, $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse matrix.

Further, we introduce Eq. (7) to estimate the consumption-based emissions.

$$\boldsymbol{C} = \boldsymbol{\varepsilon}(\boldsymbol{I} - \boldsymbol{A})^{-1}\widehat{\boldsymbol{y}} \tag{7}$$

Where, $\boldsymbol{C}$ is the matrix of emissions caused by final demands for sectors (i.e., sectoral consumption-based emissions); $\boldsymbol{\varepsilon}$ is the vector of emission intensity, which is the territorial-based emissions per unit of output of a sector.

Since territorial-based emissions consider household emissions (rural and urban), our consumption-based accounting includes the emissions by household's direct energy use, for consistency and comparability. In our study, the boundary of consumption-based emissions refers to emissions driven by final demands (i.e., government consumption, import, capital formation, rural and urban households consumption) in China.

### 2.4. Uncertainty assessment

Two primary sources of uncertainty in energy-related sectoral emissions stem from activity data and emission factors. In order to examine this uncertainty, we applied the Monte Carlo method, which is recommended by IPCC emission accounting guidelines. The approach involves inputting probability distributions for each model (activity data and emission factors). Based on their respective probability density functions, random values for emission factors and activity data are selected, which are then used to compute the corresponding emission values. Using MATLAB, this process is iteratively executed 20,000 times, with the results from each iteration contributing to the construction of the overall emission's probability density function.

### 2.5. Data sources

Based on the territorial-based accounting method mentioned above, the activity data of each fossil fuel in each sector, and emission factors are collected. Energy consumption data for both national level and 30 provinces are obtained from the China Energy Statistics Yearbook 2021 and 2022 [41]. The activity data of cement at both national and provincial levels are collected from the China Statistical Yearbook 2021 and 2022, along with the corresponding provincial statistical yearbook for the same years. The emission factors are drawn from our earlier research [28,46], which provides China-specific measured values based on extensive investigation.

To preliminary estimate the national-level emissions data for 2022, we apply the growth rates of energy consumption (by coal, oil, and natural gas) [42] to the energy inventory in 2021 and get the energy consumption data for 2022. We then use this predicted energy data to estimate emissions for 2022.

In terms of the consumption-based accounting method, input-output tables (IOTs) for the year 2002, 2005, 2007, 2010, 2012, 2015, 2017, 2018 and 2020 are collected from the Bureau of Statistics in China [40].

## 3. Results

### 3.1. Trends of territorial-based emissions in China

Fig. 1 shows territorial-based $CO_2$ emissions by fuel categories in China from 1997 to 2022. China's emissions grew considerably from 1997 (2923.86 Mt) to 2013 (9534.24 Mt), then fell slightly to 9253.50

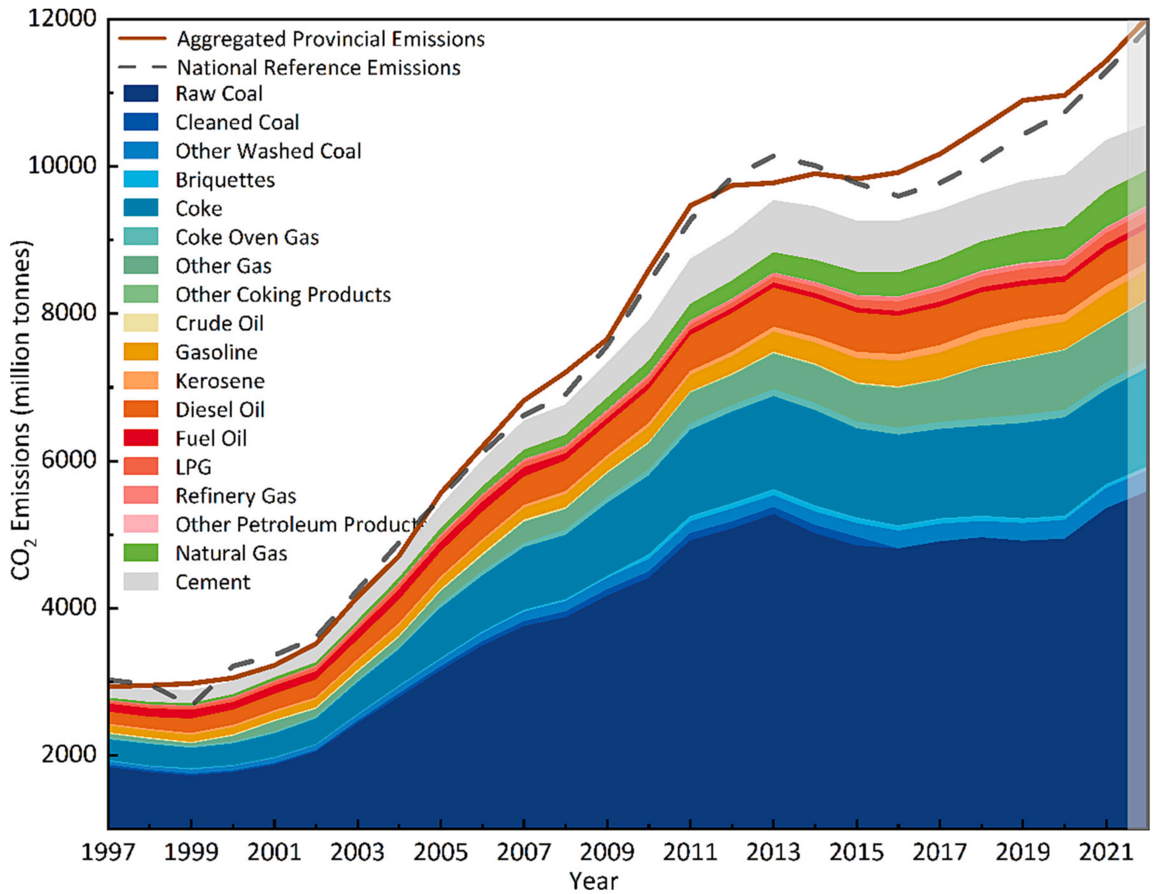


**Fig. 1. $CO_2$ emissions in China by category, in millions of tones, over 1997 to 2022.** All emissions data in 2022 are predictive, and distinguished with a grey overlay to differentiate them from historical data.

Mt. in 2015 and increased by 14.2% in 2022 (10,571.34 Mt). During the COVID-19 pandemic (2020–2021), emissions exhibited an upward trend compared to 2019. However, the annual growth rate from 2019 to 2020 stood at 0.9%, lower than that from 2018 to 2019 (1.8%). As the epidemic became more controllable, there was a marked retaliatory rebound in growth, evidenced by the annual growth rate from 2020 to 2021 surging to 4.8%. In the broader picture, carbon emissions are still increasing and have not reached a plateau phase. China's per capita $CO_2$ emissions have tripled between 2000 and 2021, and have surpassed the figures of the UK and the EU from 2013 onwards [52]. By the end of 2020, emission intensity decreased by 19.3% compared to that in 2015, beating the official target of an 18.0% reduction set for the 13th Five-Year Plan.

In examining energy types, it is evident that the adjustments to the energy mix over the past decade have yielded significant results. On the one hand, emissions growth for each energy type has decelerated. During 2015–2020, the average annual growth rate of emissions from coal, oil and natural gas was 0.4%, −8.1% and 7.1% respectively, which was considerably slower than that during 2010–2015 (1.9%, 0.3% and 11.6% respectively). This achievement could be attributed to the slowdown of the growth rate of energy consumption (3.8% and 2.8% in 2010–2015 and 2015–2020 respectively), which is lower than that of GDP (7.9% and 5.6% in 2010–2015 and 2015–2020 respectively). Such a trend underscores China's shift towards a high-quality and stable development phase where the economy thrives with a relatively lower rate of energy consumption growth [4]. On the other hand, there's a marked change in the proportion of emissions from different energy sources. The proportion of emissions from raw coal and crude oil decreased (from 62.8% and 0.5% in 1997 to 51.7% and 0.1% in 2021 respectively), while that from natural gas increased significantly (from 1.1% in 1997 to 4.7% in 2021). This transition aligns with the evolving energy production structure: production proportions for raw coal and crude oil declined (from 74.2% and 17.2% in 1997 to 67.0% and 6.6% in 2021 respectively), while natural gas production steadily climbed (from 2.1% in 1997 to 6.1% in 2021) [41].

In terms of process-related emissions, China's emissions from cement production rose from 142.74 metric tons in 1997 to 615.49 metric tons in 2022. Nevertheless, cement emissions are expected to stabilize and gradually decrease in the future, largely owing to the constraints on cement production brought about by escalating labor and raw material costs.

Analyzing emissions by economic sectors, the Production and Supply of Electric Power, Steam and Hot Water remains the most substantial emitter in 2021 (Fig. 2). This significant contribution to emissions is due to China's reliance on traditional fossil fuels for electricity and heat generation. For example, in 2021, China's thermal power generation, predominantly fueled by coal, accounts for 71.1% of the national power generation [39].

When looking at the industry structure over a long period (from 1997 to 2021), we have witnessed a considerable transformation. Amid accelerated industrialization in China, emissions from manufacturing surged, growing from 2393.30Mt in 1997 (81.9% of the total emissions) to 8837.44Mt in 2021, which makes up 85.3%. The emissions contribution from the Production and Supply of Electric Power, Steam, and Hot Water sector jumped from 37.0% (1085.30Mt) in 1997 to 50.7% (5253.15Mt) in 2021. Additionally, the share of the ferrous metal mining and processing sector increased from 12.0% in 1997 to 17.9% in 2021. However, due to the prevailing steel surplus and the drop in crude steel production, it is anticipated that emissions from the steel industry will experience a decline [45]. This would consequently lead to a

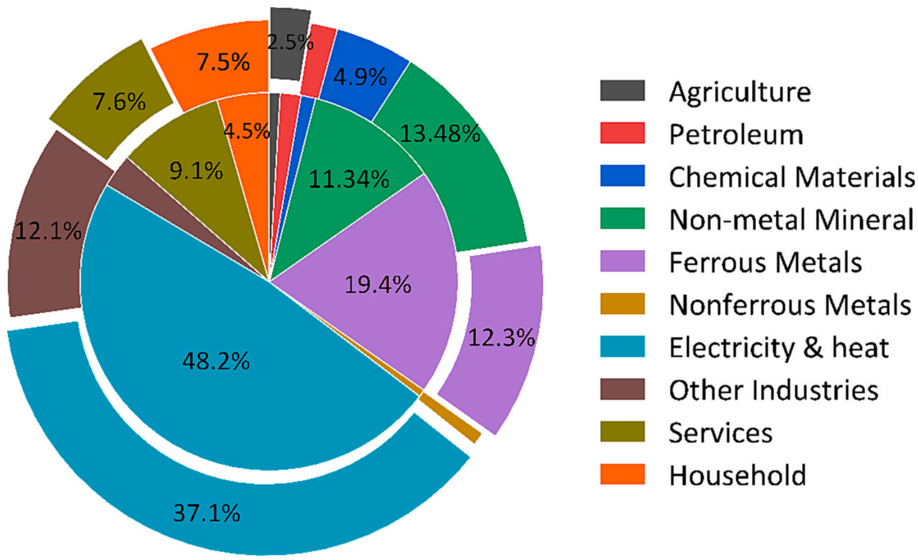


**Fig. 2. Sector contributions from production perspectives for $CO_2$ in China in 1997, 2021.** The inner circle shows the proportion of sectoral emissions in 2021, and the outer circle represents the data of 1997.

reduction in emissions from the mining and processing of ferrous metals. Even as manufacturing continues its rapid pace of development, its carbon emission intensity is on a decline, recording a drop of 15.2% during the 13th Five-Year Plan period. This positive trend underscores the effective strides made towards the low-carbon development of China's manufacturing sector. In contrast, emissions from the tertiary sector have nearly tripled, accounting for 13.1% of the total emission growth from 1997 to 2021. Within this sector, the Transportation, Storage, Post and Telecommunication Services sector stands out, being responsible for a substantial 61.5% of the increase. Meanwhile, the agricultural sector remains a minor contributor, with its share diminishing from 2.5% in 1997 to a mere 0.9% in 2021.

### 3.2. Difference between consumption-based and territorial-based emissions of China

As a vital component of emission accounts, consumption-based emissions offer a more comprehensive perspective for analyzing China's emission patterns. Consumption-based emissions is shaped by various final demand categories: rural and urban households

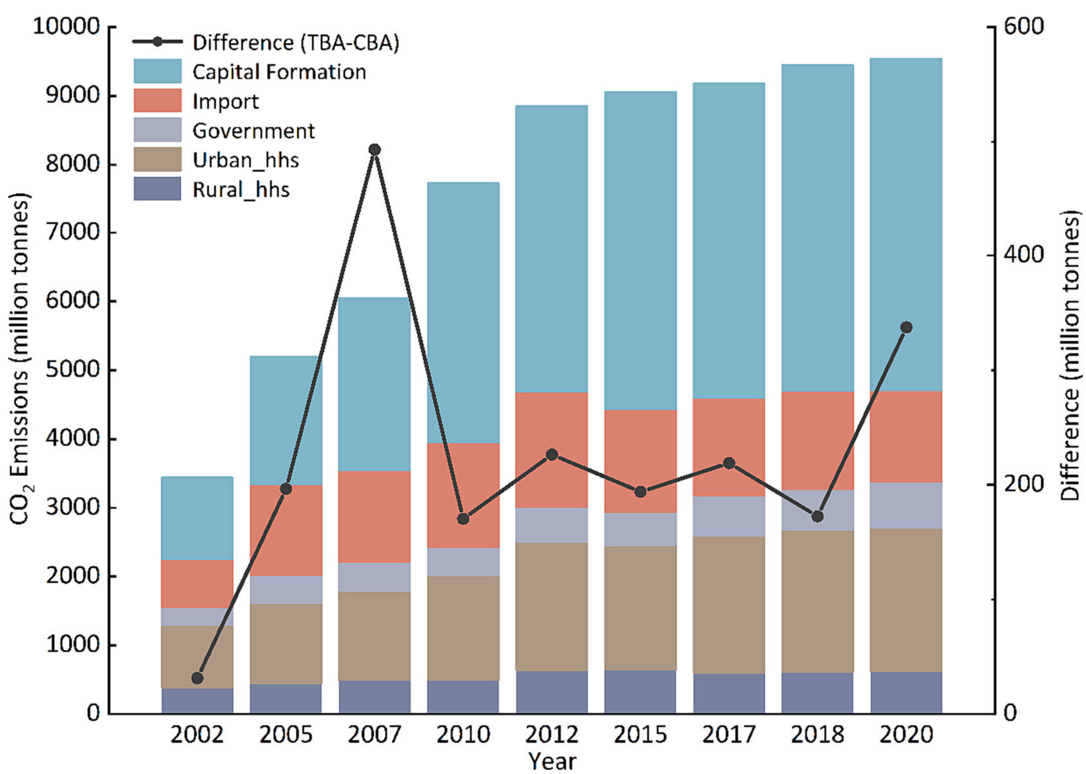


**Fig. 3. The consumption-based emissions from 2002 to 2020.** hhs is the abbreviation of households. Rural_hhs includes the emissions from rural households consumption and Urban_hhs includes the emissions from urban households consumption. Difference equals territorial-based emissions minus consumption-based emissions.

consumption, government consumption, capital formation and imports (Fig. 3). Over the years, capital formation consistently stands out, contributing to 46.0% of emissions on average. This aligns with China's high savings rate, with investment playing a dominant role rather than consumption in driving demand [33]. Emissions from rural household consumption decreased from 11.2% (in 2002) to 6.5% (in 2020), mainly attributable to the urbanization process in China [44]. The proportion of the rural population declined from 60.9% to 36.1%. Emissions arising from urban households and government consumption have been relatively steady, around 21.0% and 7.0% respectively. Emissions tied to imports have decreased from 20.2% to 13.9% over the same period, despite a steady 10.3% annual growth in import value. This suggests the nature of imports is shifting towards products with lower emission and eco-friendlier footprints.

When considering the difference between territorial-based emissions and consumption-based emissions (that equates to the emissions resulting from exports), this disparity can reveal how trade patterns influence carbon emissions. In Fig. 3, we observe the positive value of 'Difference', it is evident that exports surpass imports. This surge in exports has significantly influenced China's increasing carbon emissions in recent years, providing China with a strategic advantage in international climate discussions [11]. The difference gradually widened from 2002, peaking in 2007, and then entering a period of decline. Following its entry into the World Trade Organization in 2001, China saw a remarkable 28.3% annual growth in its export volume between 2002 and 2007. The high emissions associated with the export of carbon-intensive commodities, such as metal goods and electronics, were notable [38]. However, after 2008, due to stricter export regulations coupled with the financial downturn, the average annual growth in exports slowed to 3.5% between 2010 and 2015. Further, improvements in China's industrial and energy mix may also have contributed to the slowdown in China's implied $CO_2$ exports, as the growth rate of implied $CO_2$ exports has declined much faster than trade exports [51].

In 2020, China witnessed a resurgence in this 'Difference', with the ratio of increase reaching a significant 95.5%, primarily driven by an increase in exports. Despite the global pandemic, there was a significant uptick in China's export volumes (mainly medical supplies and electronic devices) in 2020, increasing by 3.62%, much higher than 0.51% in 2019. This growth can result in the effectiveness of China's epidemic prevention and control measures, which ensured the stable production of goods in high demand globally, such as medical supplies (including face masks) and electronic devices (including laptops, tablets, and

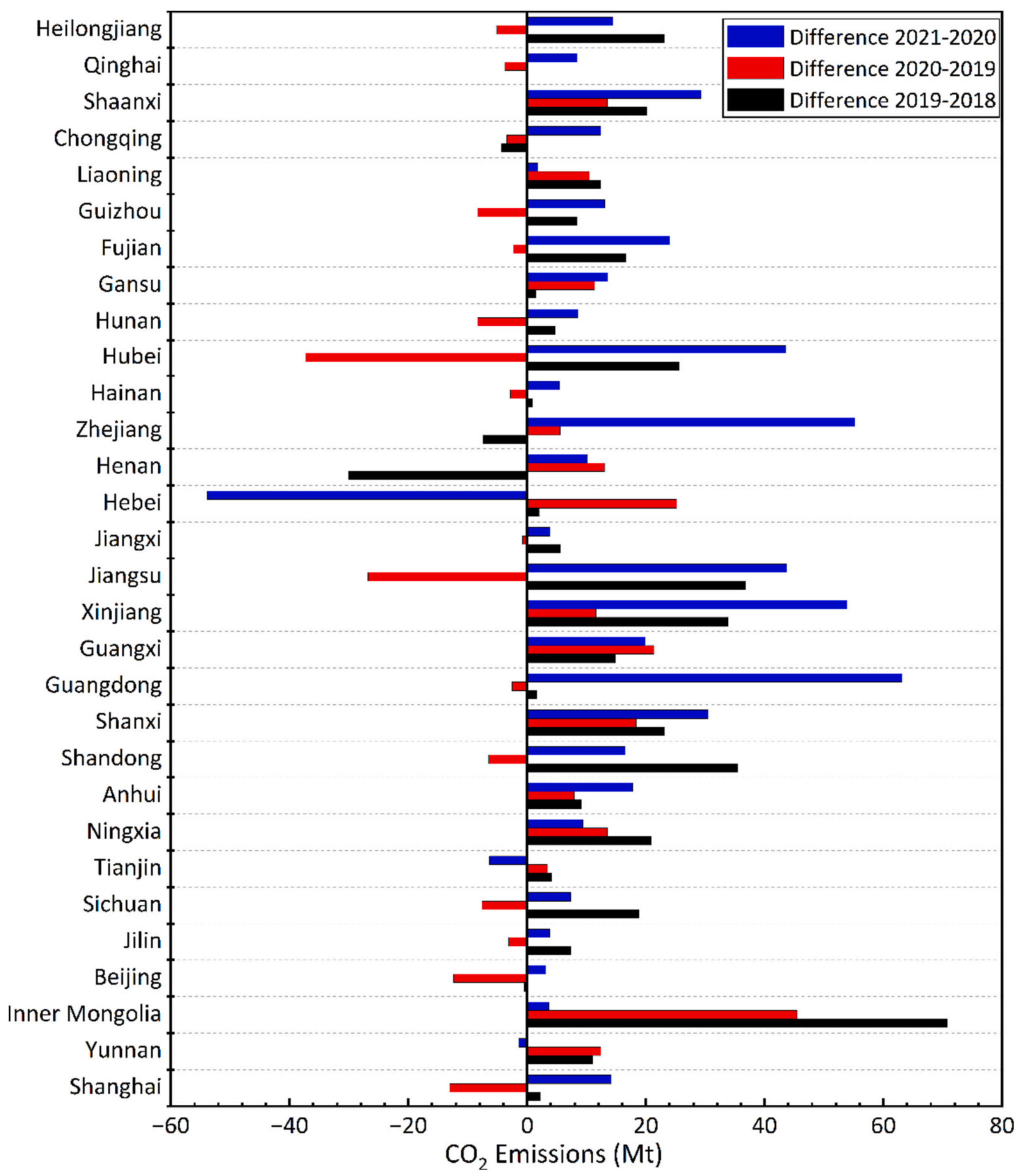


**Fig. 4.** The changes in China's provincial territorial emissions from 2018 to 2021.

household appliances). Exports in these categories grew by 31.0% and 22.1% respectively, contributing 1.9% and 1.3% to the overall export growth, respectively [38]. Meanwhile, imports have witnessed a decline for the second consecutive year, in 2019 and 2020, intensifying the 'Difference'.

### 3.3. The changes in provincial-territorial emissions during the COVID-19

Compared with 2019, nearly two-thirds of China's provinces reduced their $CO_2$ emissions in 2020 (Fig. 4). However, this trend shifted in 2021, with most provinces exhibiting a surge in emissions.

Since manufacturing is the major driver of the $CO_2$ emission decline [60], provinces with robust manufacturing bases observed substantial $CO_2$ emission reduction in 2020. For example, Jiangsu and Shandong reduced their $CO_2$ emissions by 3.4% and 0.7% respectively in 2020, while their emissions all increased by 4.8% and 3.9% respectively in 2019. The transportation sector is also an important driver [1]. Provinces like Fujian and Shanghai, with extensive transportation networks, experienced a clear decrease in 2020, (−0.8%, −6.8% respectively). This contrasted with their growth rates of 6.4% and 1.2% respectively in 2019. Additionally, remarkable $CO_2$ reductions were evident in Hubei province (whose capital is Wuhan) and Beijing, reflecting their extended lockdown phases that spanned over three months. Due to the swift resumption of social-economic activities after April, the pandemic had a minimal impact in western China. Provinces like Yunnan, Shaanxi, and Ningxia displayed consistent emission patterns in both 2019 and 2020. This stability may be attributed to the west's sparse populated, which likely curtailed the virus's transmission potential. In contrast, 14 provinces reported increased emissions in 2020. Provinces like Inner Mongolia and Xinjiang, abundant in coal, increased their emissions by 5.7% and 2.6% respectively. Meanwhile, Zhejiang, hit hard during the lockdown, witnessed a drop in emissions by 31.30 Mt in the early months [26]. However, yearly emissions increased, partially due to the initiation of Zhejiang Petrochemical Co., Ltd. in 2019 [6]. Drought in 2020 in Guangxi resulted in a boost in thermal power generation [60], leading to emissions 21.38 Mt. higher than 2019.

Many provinces had increasing emissions after the pandemic in 2021. This increase in emissions was particularly noticeable in provinces like Shanxi and Xinjiang, where heavily relied on energy-intensive industries. Similarly, significant rises were observed in Jiangsu and Guangdong, renowned for their robust manufacturing bases and prosperous service sectors. These notable inclinations in emissions reflect the resurgence of socio-economic activities post-epidemic. Although emissions in those provinces show a resurgent growth trend, they have not entirely returned to pre-pandemic levels. In areas severely affected by the pandemic, such as Hubei and Beijing, recovering to the pre-pandemic emission levels may require a longer period. Conversely, a small number of provinces, such as Hebei and Tianjin, saw a decline in emissions in 2021. This trend was largely due to the progress made in steel industry reforms within these provinces. Specifically, Hebei Province had the highest reduction volume in crude steel production, accounting for 77.6% of the national reduction [19,43]. Meanwhile, compared to 2020, Tianjin had the most significant reduction ratio in crude steel production nationwide, at 16.0% [53]. These significant reductions in energy-intensive industrial outputs resulted in a decline in carbon emissions in these two provinces.

Considering each province's development phase, resource availability, strategic objectives, and environmental considerations, China established varied $CO_2$ emission intensity reduction goals for the 13th Five-Year span (2015–2020) (details in Table S4 in Supplementary material 1). By the end of this period in 2020, 17 provinces achieved their set targets, whereas the other 13 fell short.

The provinces that didn't reach their set targets are predominantly those with heavy industrial focus, such as Guangdong and Shandong, or those rich in resources, like Shanxi and Hebei. Of these, only Inner Mongolia, Ningxia, and Xinjiang saw their carbon emissions intensity increase, rising 13.1%, 23.4% and 0.2% respectively during the 13th Five-Year Plan period. These provinces, while rich in energy resources, are still economically lagging. Their economic backbone largely comprises of manufacturing, especially energy-intensive sectors like coal and steel. This makes the journey to carbon neutrality for these regions particularly arduous. Conversely, provinces meeting their targets often enhanced their industrial structures and shifted towards more service-oriented economies. Take Chongqing as an example: its sectoral breakdown transitioned from 7.3%, 45.0%, and 47.7% in 2015 (agriculture, manufacturing, and services respectively) to 7.2%, 40.0%, and 52.8% in 2020. Notably, developed regions like Shanghai, Beijing, and Guangdong, where finance and services are the main pillars, alongside provinces known for their potent natural carbon absorption capabilities like Zhejiang and Fujian, exhibit comparatively lower carbon emissions intensity.

Per capita carbon emission serves as a crucial measure of regional carbon emission levels [25]. Manufacturing and energy-centric provinces, such as Shanxi, Hebei, and Tianjin, rank high in per capita emissions, with Inner Mongolia, Ningxia, and Xinjiang topping the list (shown in Fig. 5). Contrastingly, Hainan, with its economy anchored in the service sector, and densely populated developed provinces like Beijing and Guangdong, report low per capita emissions. Even though Sichuan has a strong presence in energy and manufacturing and ranks sixth in emissions intensity, its per capita emissions stood only above Beijing in 2020. This can be credited to its clean energy-focused production. In 2020, hydropower represented a staggering 84.9% of the province's electricity generation [49].

### 3.4. Comparisons with existing estimates and uncertainty assessment

Fig. 6 contrasts our emission findings with estimates from other organizations, including EIA, BP, IEA, EDGAR, GCB, and MEIC. Over the 24-year period, EDGAR (Emissions Database for Global Atmospheric Research) consistently presents the highest figures. When we focus on the period from 2018 to 2020, the national sectoral emissions values are the lowest, aligning closely with the BP data reported. Our provincial aggregate emissions are in line with GCB, and also follow the close values for EIA. While national estimates from GCB and IEA include emissions from fossil fuel combustion and cement production, they use the default emission factors provided by IPCC. This might account for their higher emission values compared to our estimations (National reference emissions and National sectoral emissions). Nevertheless, the discrepancy between GCB and IEA points to inherent uncertainty. Although EDGAR, EIA, and BP only include emissions from fossil fuel, EDGAR's and EIA's figures are higher than BP's, highlighting the variances in different databases.

Two primary sources of uncertainty in the data (activity data and emission factors) can be assessed using the Monte Carlo method. The uncertainty surrounding China's energy-related emissions for 2020 and 2021 is estimated to be (−3.43%, 3.45%) and (−3.54%, 3.51%), with a 97.5% confidence interval. This level of precision is acceptable, as our uncertainty range falls within the ±5% benchmark set for global countries [14,15].

Additionally, discrepancies in data can arise from varied accounting methods. The reference emissions and territorial-based emissions display similar trajectories, the former consistently exceeds the latter by approximately 4.1% annually. Three factors account for this deviation. First, the territorial-based emissions approach does not factor in energy loss during its transformation, while the reference emissions approach does. Secondly, reference emissions exclude transportation loss and non-energy use from the primary energy, leaving out secondary energy. Thirdly, the energy balance table in China shows about a 1.2% disparity between energy production and consumption data [16]. Given that secondary energy emissions aren't captured in reference emissions and significant inter-provincial secondary energy trades exist, reference emissions serve as a supplementary measure to territorial-based

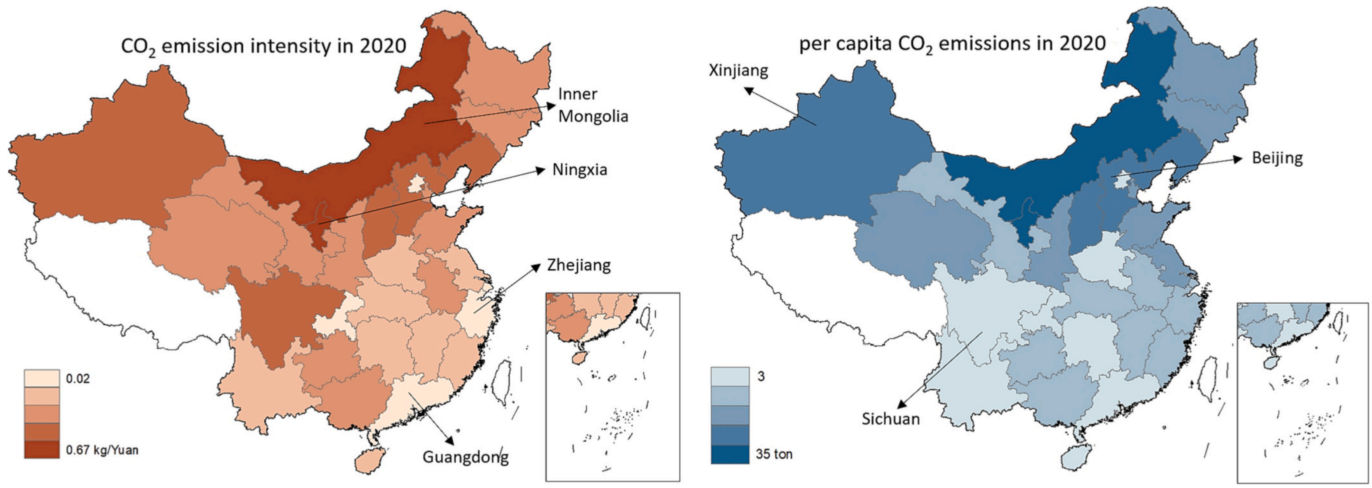


**Fig. 5. $CO_2$ emission intensity and per capita emissions of China's provinces in 2020.**

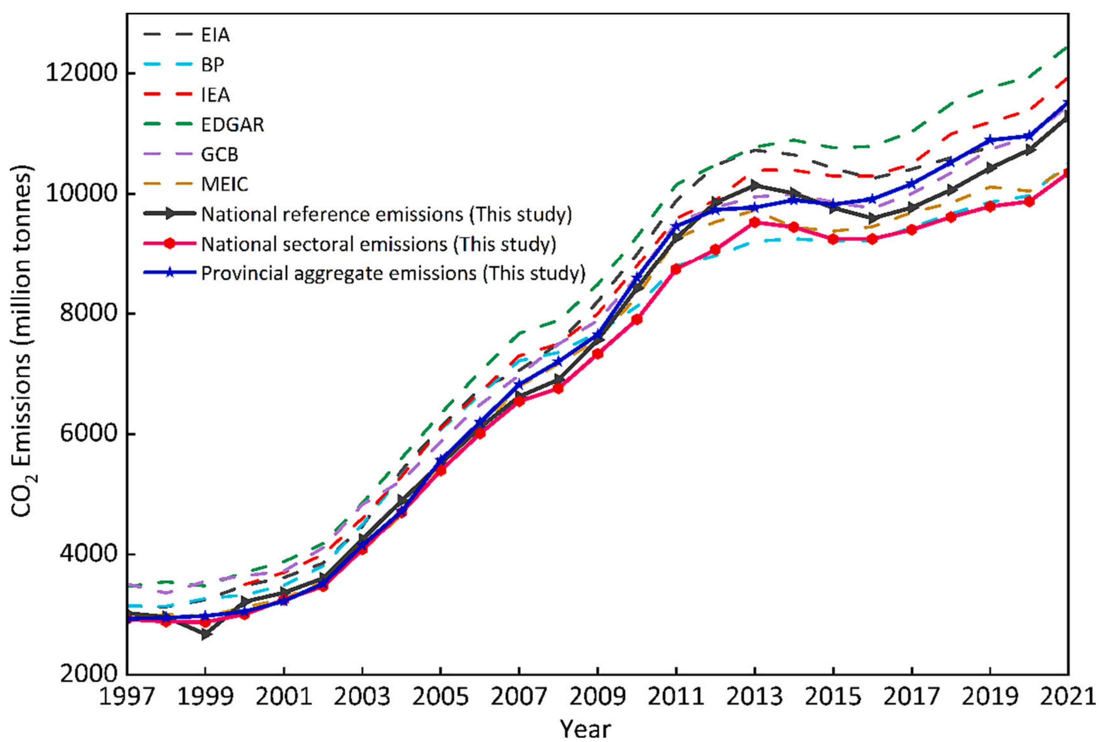


**Fig. 6. Comparisons with other estimates for 1997–2021.** Data source: EIA (Energy Information Administration)[10]; BP (British Petroleum) [3]; IEA (International Energy Agency) [21]; EDGAR (Emissions Database for Global Atmospheric Research) [5]; GCB (Global Carbon Budget) [14]; MEIC (Multi-resolution emission inventory for China) [31]. Note: IEA, GCB, MEIC and our data provide emissions data covering fossil fuel combustion and cement production. EDGAR, EIA, and BP only include emissions from fossil fuels.

emissions in international conventions. The latter provides a more accurate and comprehensive picture of $CO_2$ emissions.

Finally, emissions data of China in 2022 are forecasted roughly, which leads to large uncertainty. Based on the 2021 emissions data, we apply the growth rate of energy consumption of coal, oil, and natural gas to estimate the emissions in 2022.

## 4. Discussion

Our study reveals that the influences of COVID-19 pandemic and associated lockdown measures on carbon emissions were only temporary, regardless their profound impacts on both daily life and the economy. The stagnation in economic and social activities directly led to a notable decrease in emissions in the first quarter of 2020 [26]. However, starting from April, central and local governments, along with citizens gradually recovered their social-economic activities [26], which led to an increase in emissions that offset the reductions in the first quarter. Therefore, China's territorial-based $CO_2$ emissions in 2020 rose by 0.9% compared to 2019. In 2021, an urgent need for economic recovery resulted in a continuous resurgence on the majority of social activities. This led to emissions rising in most provinces. The 2021 rebound indicates the interconnected dynamics of economic recovery and emissions pattern changes at both national and provincial levels. Although the COVID-19 pandemic had resulted in our behavioural changes, leading to a fluctuation in emissions trends, it was not significant enough to drive a long-lasting reduction in emissions.

When examining emissions alongside consumption, we found a notable surge in the differences between territorial and consumption-based emissions in 2020. As socio-economic activities gradually resumed after April 2020, China rapidly expanded production and exported a wide range of products. These included not only medical supplies like face masks, which mitigated the global shortage of essential healthcare items, but also various electronic devices, such as laptops, tablets, and household appliances, supporting remote work, education, and daily living needs during the pandemic. However, the production of these export goods led to a stable rise (2.69%) in territorial emissions in 2020. The growth rate of consumption-based emissions (with 0.99%) was lower than that of territorial-based emissions due to the severe effect on the global supply chain. Thus, the difference between territorial- and consumption-based emissions nearly doubled compared to 2018.

Previous studies have discussed the contradiction between economic recovery and reducing carbon emissions post-pandemic [24,27]. Unlike the rebound after the 2008–2009 global financial crisis, the emission pattern changes from 2020 to 2021 indicate that we have not entirely replicated the sharp increases seen in the past. This is a positive sign of temporary transiting towards a greener energy system and economic structure. However, given the increasingly tightening global carbon budget, we still need to take action to mitigate potential rebounds and strengthen global efforts to reduce emissions in the long term, and finally achieve emission reduction targets of the Paris Agreement. In this context, energy and economic structural changes are considered to be critical for achieving emission reduction targets. Our study reveals that China's energy structure has improved in the past two decades, but it still heavily relies on fossil fuels. Transitioning towards cleaner and more sustainable energy systems is essential, as underscored at the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) [54]. However, this transition presents tremendous challenges for China, given its high dependence on fossil fuels. Substantially increasing the utilization rate of renewable energy is a crucial aspect of this transition. Investing in solar, wind, hydro, and other renewable energy sources not only helps reduce carbon emissions but also enhances energy security, which is a key pathway for achieving global sustainable development.

## 5. Conclusions

Our research offers a comprehensive analysis of China's carbon emissions patterns, shedding light on the emission changes during the COVID-19 pandemic. Our work enriches the existing emissions data for China and its provinces by providing comprehensive data acrossvarious sectors and fossil fuel types from 1997 to 2021. This is pivotal for policymakers and researchers to develop and refine strategies aimed at achieving China's ambitious Dual-Carbon targets.

This study lays a data foundation for ongoing monitoring and strategy development towards the nation's carbon peak and neutrality. The insights gained here hold significant value for the international community. These insights not only tackle the contradiction between economic growth and environmental sustainability intensified by the COVID-19, but also enhance our abilities to tackle the challenge of energy transition, as recently highlighted during the COP28. Future works will expand to include more countries, offering a comprehensive global view that supports emission reductions and sustainable development.

## CRediT authorship contribution statement

**Jinghang Xu:** Writing – original draft, Software, Formal analysis. **Yuru Guan:** Writing – review & editing, Software, Methodology. **Jonathan Oldfield:** Writing – review & editing. **Dabo Guan:** Writing – review & editing. **Yuli Shan:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.

## Declaration of competing interest

None.

## Data availability

The energy statistic data for China and its 30 provinces can be obtained from the China Energy Statistics Yearbook 2021 [41]. The emission factors in emission accounts are summarized in Liu et al. [28]. All the data and results developed in this study can be downloaded freely from Carbon Emission Accounts and Datasets for emerging countries (CEADs) at www.ceads.net/data/.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.122837.

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