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Earth's Future



RESEARCH ARTICLE

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Assessment to China's Recent Emission Pattern Shifts

Yuru Guan¹ , Yuli Shan¹ , Qi Huang², Huilin Chen^{3,4} , Dan Wang¹, and Klaus Hubacek¹ 

Key Points:

- The most up-to-date emission inventories for China and its provinces
- A combined accounting approach of scope 1 and 2 emissions
- China's 2020 carbon intensity mitigation target was achieved ahead of schedule

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Energy and emission data are crucial to climate change research and mitigation efforts. The accuracy of energy statistics is essential for mitigation strategies and evaluating the performance of low carbon energy transition efforts. This study provides the most up-to-date emission inventories for China and its provinces for 2018 and 2019. We also update the carbon dioxide (CO₂) emission inventories of China and 30 provinces since 2012 based on the newly revised energy statistics. The inventories are compiled in a combined accounting approach of scope 1 (Intergovernmental Panel on Climate Change territorial emissions from 17 types of fossil fuel combustion and cement production by 47 socioeconomic sectors) and scope 2 (emissions from purchased electricity and heat consumption). The most recent energy revision led to an increase in reported national CO₂ emissions by an average of 0.3% from 2014 to 2017. The results show that data revisions raised China's carbon intensity mitigation baseline (in 2005) by 5.1%–10.8% and thus made it more challenging to fulfill the mitigation pledges. However, the 2020 carbon intensity mitigation target was achieved ahead of schedule in 2018. A preliminary estimate of China's national emissions for 2020 shows that the COVID-19 pandemic and lockdown was not able to offset China's annual increase in CO₂ emissions. These emissions inventories provide an improved evidence base for China's policies toward net-zero emissions.

1. Introduction

China's efforts to combat climate change have attracted widespread attention since it became the world's largest emitter of carbon dioxide (CO₂) in 2006. To achieve the 2°C (or even 1.5°C) Global Temperature Target (Wang et al., 2019), China submitted the Intended Nationally Determined Contributions (INDC) to the Paris Agreement in 2015 and announced the updated targets in 2020. The government has committed to reducing carbon intensity (i.e., CO₂ emissions per unit of gross domestic product (GDP)) by more than 65% compared with the 2005 level, peaking the CO₂ emissions by 2030 (Fu et al., 2015), and increasing the share of non-fossil energy in energy consumption to approximately 25% (Xinhua News Agency, 2020). The peak in China's CO₂ emissions is not only a key target in China's climate change mitigation efforts, but also a necessary condition for a global emissions peak. In 2020, China announced an even more ambitious goal of achieving carbon neutrality before 2060. As China's economy has entered a “new normal” of slower economic growth (Zheng et al., 2019), creating less carbon-intensive development pathways, therefore, has become an important strategy.

Reliable, transparent, and accurate energy statistics are fundamental to estimating CO₂ emissions, formulating emission reduction policies, promoting energy transition, and mitigating climate change (Guan et al., 2012, 2018; Shan, Guan, Hubacek, et al., 2018). Previously, the National Bureau of Statistics of China (NBS) has officially revised the national energy statistics three times in the 2005, 2009, and 2014 yearbooks, respectively (Guan et al., 2012; Zheng et al., 2018). In the China Energy Statistics Yearbook 2019 (NBS, 2020), the government revised its energy consumption data from 2014 to 2017 according to the results of the Fourth National Economic Census and released the energy statistics for 2018 for the first time. Nevertheless, there are still considerable inconsistencies between the national and provincial aggregated data, leading to an obstacle in CO₂ emissions estimation. Meanwhile, the Chinese government did not officially release its annual CO₂ emissions inventory and even the latest inventory is only for 2014 (NDRC, 2018a, 2018b). Many research institutes and scholars have been committed to filling this lack of timely emissions inventories (Guan et al., 2012; Li et al., 2018; Zhu, 2013). Unfortunately, due to the differences in activity data, emission factors, accounting boundaries, and selected

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approaches, differences in China's CO₂ emissions accounts still exist. For example, its national emissions ranged from 9.2 to 10.4 Gt in 2016 among nine current published data sets (Han, Zeng, et al., 2020) and provinces' emissions in 2012 ranged from –225 to 403 Mt in 2012 between Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC) data set and Peking University-CO₂ (PKU) data set (Han, Lin, et al., 2020).

As for accounting boundaries, following the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), emissions are broken down into three scopes by the Greenhouse Gas Protocol (WBCSD & WRI, 2001). All direct emissions within a geographical boundary are referred to as scope 1 or IPCC territorial emissions, including emissions generated by fossil fuel combustion on site and industrial production. If indirect emissions were generated as a consequence of electricity and heat purchased and used within the geographical boundary, these emissions would be accounted for as scope 2. All other indirect emissions that occur outside the geographical boundary as a result of local production or economic activities are defined as scope 3. Existing carbon emission inventories for China have mainly focused on scope 1 direct emissions, in which emissions caused by the electricity and heat generation sector were all attributed to local production activities (Basu et al., 2020; Jackson et al., 2017; Lin & Raza, 2019).

It is worth mentioning that, unlike other products, electricity and heat are unique in that they are not only products generated within the territory, but also as secondary energy which could be transmitted and used by other downstream consumers. Therefore, such indirect emissions are allocated to energy consumers in scope 2 accounts (Wang et al., 2019). Most of the current studies on scope 2 adopted a location-based method (Brander et al., 2018; WRI, 2015), (i.e., multiplying activity data (electricity or heat consumption) by average emission factors per regional grid (Shan et al., 2021; Wei et al., 2020)). The most important factor leading to differences in regional grid emission factors is the fuel type consumed by the respective power plants. For example, regions with a higher share of thermal power plants have higher electricity emission factors. The widely varying resource endowments of China's provinces lead to different energy supply and different electricity and heat generation emission factors. In this context, using emission factors would lead to inaccuracies. Our study directly focuses on the process of converting primary energy into electricity and heat, so that such errors are avoided in theory. Moreover, previous scope 2 emissions for China only provided a total amount instead of sectoral emissions.

Production- and consumption-based accounting is proposed, the content of which overlaps with the accounting of scope 1, 2, and 3 (Wiedmann et al., 2020). Production-based emissions (PBE) overlap with scope 1 emission boundary except for the emissions from international aviation and shipping. In contrast, consumption-based emissions (CBE) allocate all emissions along the supply chain to the final consumption item (Sudmant et al., 2018). There are also numerous studies on consumption-based carbon emissions accounting based on input-output analysis or life cycle analysis (Guan et al., 2019; Li et al., 2021; Mi et al., 2019). As such consumption-based and production-based approaches provide complementary information rather than one being superior to the other.

We provide an updated account of scope 1 direct emissions of China and its 30 provinces based on the most recent revised energy data, including the national emission inventory (2014–2019) and provincial emission inventories (2018–2019). This underlying revision adjusted the total national energy use providing more accurate accounting for almost all fuel types whereas previous revisions only focused on the consumption data of coal, and did not provide any updates to other fuels such as oil and fossil gas. We also estimate the national emissions for 2020 based upon the latest China Statistical Bulletin 2021. These scope 1 emission inventories that cover both emissions from 17 types of fossil fuel combustion and cement production by 47 socioeconomic sectors, and follow a uniform accounting framework proposed by Shan, Huang, et al. (2020) and thus have the consistent and comparable format, scope, methods, and data sources across the country and its provinces (Shan, Guan, Zheng, et al., 2018). Due to the revision of the national industrial classification since 2012 (see Table S1 in Supporting Information S1), this study also provides updated national inventories of the same fossil fuels in 48 sectors from 2012 to 2020. We further calculate sectoral scope 2 indirect emissions induced by purchased electricity and heat consumption from 2000 to 2019 at both national and provincial levels, and then combine such scope 2 emissions with scope 1 emissions to calculate sectoral emission accounts. Based on these updated inventories, we investigate the variances in China's CO₂ emissions provided by different sources and quantify the uncertainties of China's emissions. Based on our updated inventories, we discuss and analyze the achievement of China's climate mitigation targets and evaluate the implications of revisions in the energy statistics on these targets. The results are expected to provide an improved evidence base for China's carbon emission reduction policies.

2. Data and Methods

2.1. Scope 1 Emission Accounts

Based on the IPCC (2006) sectoral approach, we calculate scope 1 direct emissions of China and its 30 provinces. Scope 1 emissions $CE_{\text{direct},j}$ of sector j include the emissions from fossil fuel combustion (i.e., energy-related emissions, $CE_{\text{energy-related},j}$) and industrial production (i.e., process-related emissions, $CE_{\text{process-related},j}$) within the administration boundary:

$$CE_{\text{direct},j} = CE_{\text{energy-related},j} + CE_{\text{process-related},j} \quad (1)$$

The energy-related emissions can be calculated by Equation 2:

$$CE_{\text{energy-related},j} = \sum_i AD_{ij} \times NCV_i \times CC_i \times O_{ij} \quad (2)$$

where AD_{ij} refers to fossil fuel consumption by sector j . $NCV_i \times CC_i \times O_{ij}$ represents the emission factor for fuel combusted in sector j , which can be further separated into three parts: net heating value NCV_i , carbon content CC_i for fuel and oxidation rate O_{ij} for fuel used in the sector j .

For the industrial production process, this study only considers cement production, which accounts for almost 70% of China's total process-related emissions (NDRC, 2018a; Shan et al., 2019). Cement-related emissions are calculated using the cement production $AD_{t,j}$ multiplied by the emission factor $EF_{t,j}$:

$$CE_{\text{process-related},j} = AD_{t,j} \times EF_{t,j} \quad (3)$$

The recently released National Economic and Social Development Statistical Bulletins provide preliminary data on total energy consumption and the changes in coal, crude oil, and natural gas consumption in 2020 (NBS, 2021). We use the existing energy inventory for 2019 as a benchmark, and calculate the energy consumption of various fuels according to the official annual change rate of coal, oil, and natural gas consumption (see Table S2 in Supporting Information S1), and estimate the national CO_2 emissions in 2020. Our estimation of 2020 could be cross-verified by existing literature. For example, the discrepancies of our national aggregated emissions of 2020 and Liu et al. (2020)'s estimations of the total emissions are -5.6% .

2.2. Scope 2 Emission Accounts

To combine scope 2 emissions with sectoral scope 1 emission inventory, we further calculate scope 2 emissions of sector j induced by purchased electricity $CE_{\text{ele-related},j}$ and heat $CE_{\text{heat-related},j}$ from 2000 to 2019 at both national and provincial levels, as Equation 4:

$$CE_{\text{indirect},j} = CE_{\text{ele-related},j} + CE_{\text{heat-related},j} \quad (4)$$

In this study, the total scope 2 electricity emissions ($CE_{\text{ele-related}}$) can be calculated in four steps: (a) calculating the total emissions caused by local thermal power production (CE_{ele}), which are estimated by using the thermal power production data from the processing and transforming of energy balance table as the final energy consumption; (b) separating the emissions caused by electricity exports (E_{export}) and electricity transferred out of the province ($E_{\text{trans-out}}$, only in provincial accounts) from the total local electricity generation ($E_{\text{generation}}$); (c) adding the emissions caused by electricity imports ($CE_{\text{ele-import}}$); (d) adding the emissions caused by the electricity transferred from outside the province ($CE_{\text{ele-trans-in}}$, only in provincial accounts).

$$CE_{\text{ele-related}} = CE_{\text{ele}} \times \left(1 - \frac{(E_{\text{export}} + E_{\text{trans-out}})}{E_{\text{generation}}} \right) + \sum_k CE_{\text{ele-import},k} + CE_{\text{ele-trans-in}} \quad (5)$$

where k in Equation 5 is an index for import countries or regions. According to UN Comtrade Database (2021), China mainland imported electricity from five countries/regions (i.e., from Myanmar to Yunnan

Province, from Hong Kong Special Administrative Region to Guangdong Province, from North Korea to Liaoning Province, from Russian to Heilongjiang Province, and from Kyrgyzstan to Xinjiang Province). We adopt the country-specific electricity generation emission factor (i.e., emissions per kWh of electricity generated) (Brander et al., 2021) multiplied by respective imported electricity to estimate $CE_{\text{ele-import},k}$. $CE_{\text{ele-trans-in}}$ can be calculated by the same method, based on China's specific electricity generation emission factor (Brander et al., 2021) and the electricity transferred from outside the province. And then, sectoral scope 2 electricity scope 2 emissions ($CE_{\text{ele-related},j}$) can be estimated according to the corresponding share of final electricity consumption ($r_{\text{ele},j}$) by Equation 6:

$$CE_{\text{ele-related},j} = CE_{\text{ele-related}} \times r_{\text{ele},j} \quad (6)$$

Sectoral scope 2 heat emissions ($CE_{\text{heat-related},j}$) can be calculated in a similar approach:

$$CE_{\text{heat-related}} = CE_{\text{heat}} \times \left(1 - \frac{H_{\text{trans-out}}}{H_{\text{generation}}} \right) + CE_{\text{heat-trans-in}} \quad (7)$$

$$CE_{\text{heat-related},j} = CE_{\text{heat-related}} \times r_{\text{heat},j} \quad (8)$$

where $CE_{\text{heat-related}}$ is the total scope 2 heat emissions; CE_{heat} refers to the total emissions caused by local heat production, which is estimated by using the heating supply data from the processing and transforming of energy balance table as the final energy consumption; $H_{\text{trans-out}}$ and $H_{\text{generation}}$ are the heat transferred out of the province and the total local heat generation respectively; $CE_{\text{heat-trans-in}}$ represents the emissions induced by the heat transferred from outside the province, which is calculated based on China's specific heat emission factor (Yitanjia, 2014) and the heat transferred from outside the province; $r_{\text{heat},j}$ indicates the share of final heat consumption in sector j .

2.3. Uncertainty Assessment

Significant uncertainty exists in China's CO_2 emission accounts. We followed the IPCC (2006) and employed a Monte Carlo approach to quantify the uncertainty of energy-related emissions by varying activity data and emission factors. The first step is to assume the probability density functions (normal distributions) for the activity data and emission factors with the coefficient of variation (CV, the standard deviation divided by the mean) (Liu et al., 2015). In terms of various fossil fuels, the CVs of emission factors for coal, oil, and natural gas are 3%, 1%, and 2% respectively. In terms of activity data, we employ specific CVs for different sectors estimated by Liu et al. (2015), that is, 5% for electricity and heat generation, 20% for household, 16% for transportation, 30% for agriculture, and 10% for other sectors. Finally, we adopt the 97.5% confidence intervals for the estimations and perform 20,000 stochastic simulations in MATLAB R2021a. In our uncertainty assessment, we ignore process-related emissions from cement production because of its relative small contribution.

2.4. Data Sources

Sectoral energy data and emission factors are used to estimate the emissions. The national energy data for the years 2012–2019 were obtained from the China Energy Statistics yearbook 2013, 2014, 2019, and 2020 published by the NBS (2020). For the provincial emission account 2018–2019, each province's energy balance table was collected from the China Energy Statistics Yearbook 2019, 2020 and their sectoral energy consumption data were obtained from the provincial corresponding statistical yearbooks. The imported electricity data used in scope 2 emission accounts 2000–2019 were collected from the UN Comtrade Database (United Nations Statistics Division, 2021) and China Electricity Statistics Yearbook 2020 (China Electricity Council, 2020). The emission factors in energy-related emission accounts are based on a set of China-specific measured values summarized in Liu et al. (2015). The country-specific electricity generation emission factors in scope 2 emission accounts were collected from the Definitive Emission Factor Database (Brander et al., 2021). The China-specific heat generation emission factor is 0.11 t CO_2 /GJ, recommended by China Carbon Trading Market (Yitanjia, 2014). The auxiliary socioeconomic data used in this study, such as GDP and population, were collected from national statistical yearbooks, provincial statistical yearbooks, and relevant reports.

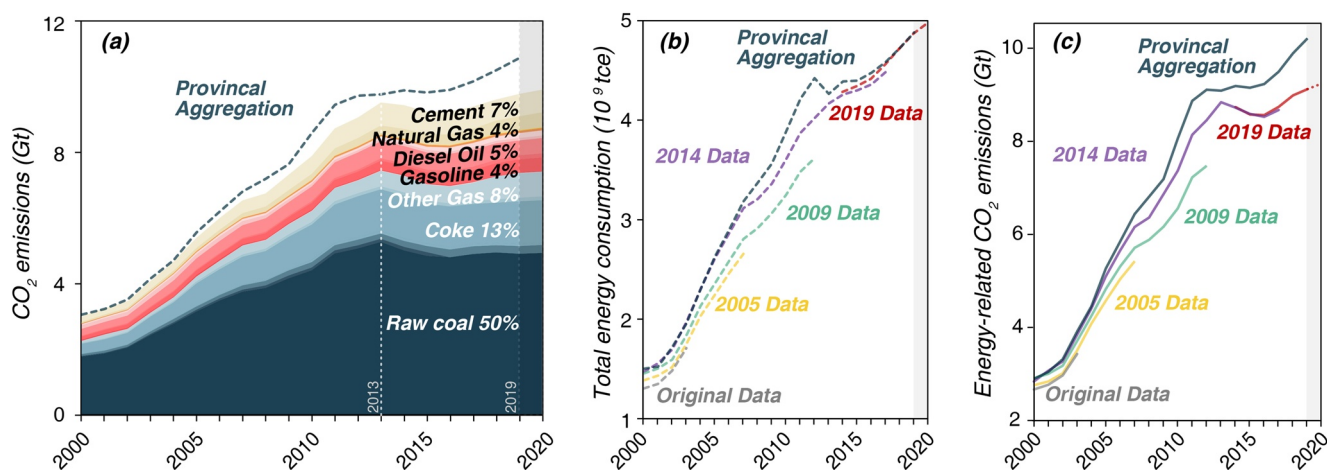


Figure 1. (a) The source of China's carbon dioxide (CO_2) emissions by fuel type and cement production for 2000–2020; (b) Total energy consumption by various data versions. (c) Energy-related CO_2 emissions by different data versions; Note: The percentages in subfigure (a) present the emission structure in 2019, and only those with a share greater than or equal to 4% are marked.

3. Results and Discussion

3.1. Updated Scope 1 Emissions in China and Its Provinces

We compile the most up-to-date CO_2 emission accounts of China and its 30 provinces based on the newly revised energy statistics, including the national emission inventory (2014–2020) and provincial emission inventories (2018–2019).

As shown in Figure 1a, China's scope 1 emissions increased at an average rate of 9.3% per year, from 3.00 Gt in 2000 to 9.53 Gt in 2013, and then declined after the 2013 peak. As discussed in many studies, the downward trend was a temporary dip (Feng et al., 2015; Guan et al., 2018). From 2014 to 2020, China's scope 1 emissions showed an overall upward trend and reached 9.80 Gt in 2019. The COVID-19 pandemic and lockdown was not able to offset China's annual increase in CO_2 emissions (Han et al., 2021; Le Quéré et al., 2020; Shan, Ou, et al., 2020). China's scope 1 emissions in 2020 still increased by 1.4% compared to 2019 and reached 9.93 Gt, but it is worth mentioning that the growth rate is lower than before. In contrast, the aggregated emissions of 30 provinces did not show a significant peak between 2012 and 2016, but rather a short plateau, which is then followed by an average increasing 3.1% per year from 2016 (9.92 Gt) to 2019 (10.88 Gt).

Coal has been dominating China's emissions. In the latest 2019 inventory, coal-generated 75.4%, oil 13.3% and natural gas combustion 4.4%, and cement production 7.0% of total CO_2 emissions. China's energy use is highly relying on coal resources because of its abundant reserves and relatively low extraction costs. Since China's coal consumption peak in 2013, the Chinese government has developed a series of policies for the eastern provinces to limit coal consumption while developing new energy technologies to accelerate the phasing out of oil and gas (Qi et al., 2016). In 2019, non-fossil energy contributed 15.3% of China's total energy consumption. China's installed capacity of non-fossil energy power generation in 2030 could reach the level of thermal power capacity in 2014 (Fu et al., 2015). It is expected that by the second half of this century, a sustainable industrial system based on new and renewable energy will gradually take shape, when net-zero emissions will also be achieved (He, 2013).

From the perspective of spatial distribution, provincial CO_2 emissions, emission intensity, and per capita emissions show considerable regional heterogeneity (shown in Figure 2). In 2019, the top 10 provinces in terms of GDP contributed 61.8% of the national GDP and 42.5% of CO_2 emissions, while the bottom 10 provinces only contributed 10.9% of the GDP but generated 22.0% of emissions. Provinces with both high emission intensity and high per capita emissions are mainly concentrated in the north. The results also imply that the formulation of emission reduction policies should differentiate regions according to their specific characteristics to achieve the most effective results.

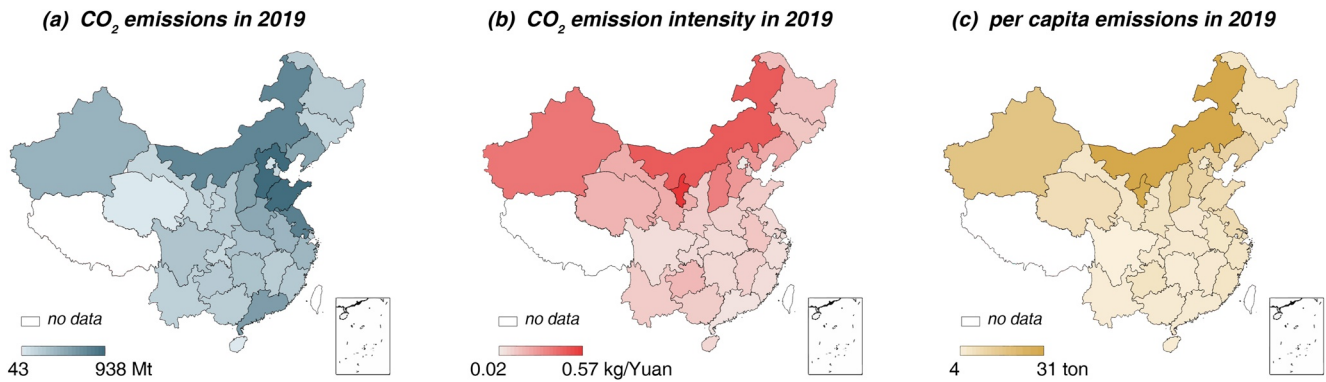


Figure 2. Carbon dioxide (CO₂) emissions of China's provinces in 2019.

As shown in Figure 1b, the NBS has frequently revised national-level energy statistics, resulting in a continuous increase in energy consumption data. The 2019 data revised the total energy consumption upward by 0.6% in 2014 and by 1.6% in 2017 compared with the 2014 data. From 2013 to 2017, the total energy consumption increased, with an average annual growth rate of 2.3% in the 2019 data, from an estimated growth rate of 1.8% in the 2014 data. In terms of fuel types, these gaps were mainly due to the coal consumption data in various data versions. In 2017, national-level coal consumption contributed 72.9% of the total variance between the 2019 data and 2014 data, while oil, natural gas, and new energy (e.g., renewable energy, hydrogen energy, and biogas) accounted for 25.1%, 0.8%, and 1.3%, respectively. It is worth noting that although the latest national-level coal consumption data were revised upwards by around 0.9–2.0% annually compared with the 2014 data, its share in the energy mix kept decreasing from 65.8% (in 2014) to 56.8% (in 2020). The new 2019 data increased national CO₂ emissions by an average of 0.3% from 2014 to 2017 compared with the 2014 data. However, these corrections still failed to resolve the inconsistency between national and aggregated provincial data. As a result, the provincial aggregated emissions (10.88 Gt) in 2019 were 11.1% higher than the national emissions (9.80 Gt), while emissions from raw coal combustion contributed 76.2% of this discrepancy.

3.2. Sectoral Scope 1 and 2 Emissions

We further calculate China's scope 1 and 2 sectoral carbon emissions from 2000 to 2019 at both national and provincial levels.

As for scope 1 direct emissions, the majority of China's carbon emissions were contributed by secondary industry, especially six energy-intensive sectors. Electricity and Heat Generation discharged around half of the national total emissions. Ferrous Metal Manufacturing contributed 18.9%, Nonmetal Mineral Production 11.4%, Chemical Materials Production 1.7%, Petroleum Manufacturing 1.8%, and Nonferrous Metals Manufacturing 0.7% of national emissions in 2019.

Scope 2 accounts re-allocate indirect emissions caused by purchased electricity and heat consumption to the consumers. China's total scope 2 electricity emissions were always negative from 2000 to 2019, indicating that more carbon emissions were embodied in electricity exports than those in imports. Nonferrous Metals Manufacturing triggered most of the scope 2 electricity emissions (10.1%) due to its high electricity consumption, followed by Ferrous Metal Manufacturing (9.8%), Other Services (9.5%), and Urban Household Consumption (8.8%) in 2019. China's total scope 2 heat emissions caused by heat supply and demand are balanced at the national level. As the largest contributors to scope 2 heat emissions, Chemical Materials Production induced 1.81 Gt CO₂, Urban Household Consumption triggered 1.57 Gt CO₂, Petroleum Manufacturing and Textile Industry emitted 0.79 Gt CO₂ in 2019 (Figure 3).

The combination of scope 1 with scope 2 accounts provides a perspective for sectoral emissions re-allocation. For example, Chemical Materials Production discharged 1.64 Gt direct CO₂ in 2019, but its allocated (i.e., direct and indirect) emissions increased by 4.75 Gt (2.94 Gt from purchased electricity use and 1.81 Gt from purchased heat use), accounting for 6.5% of the national total. Carbon emissions from Nonmetal Min-

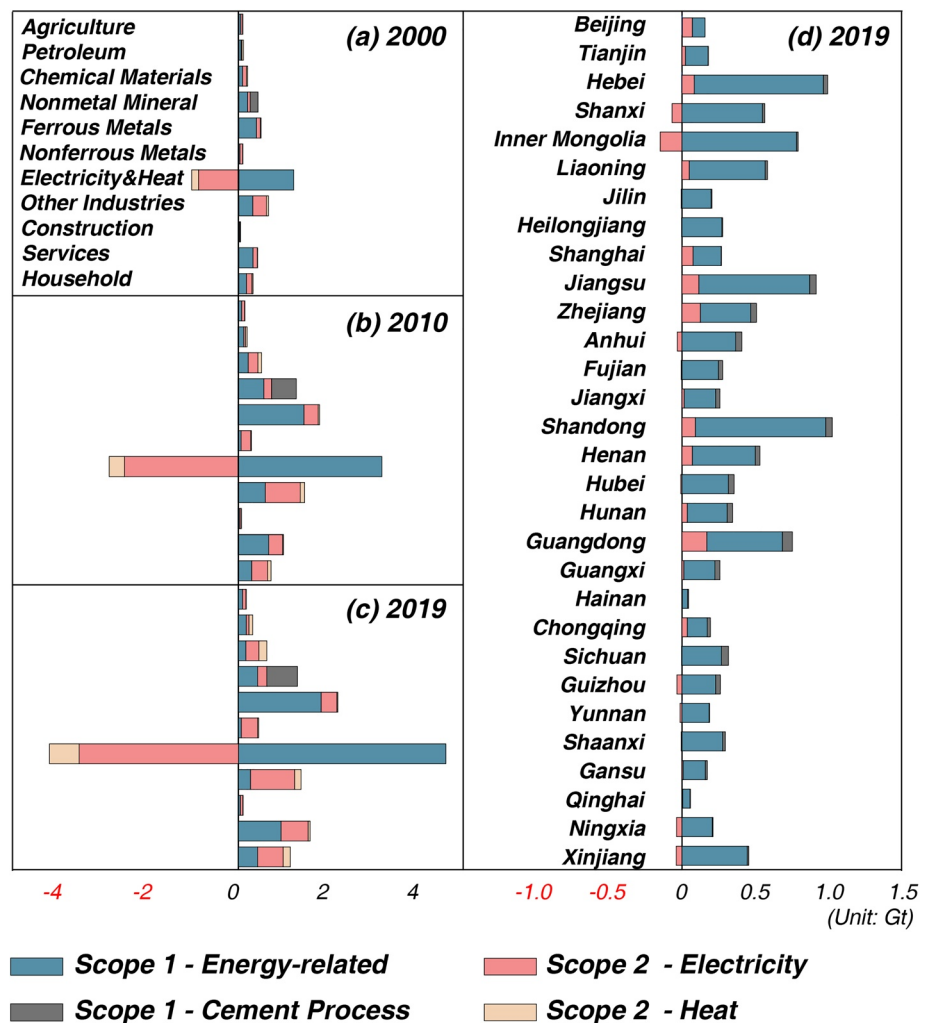


Figure 3. China's scope 1 and 2 sectoral carbon emissions in 2000 (a), 2010 (b), and 2019 (c); Provincial scope 1 and 2 sectoral carbon emissions in 2019 (d).

eral Production in 2019 were 51.7% (6.81 Gt) for cement production, 32.7% (0.43 Gt) for fossil fuel use, 15.4% (0.20 Gt) for purchased electricity use and 0.2% (0.003 Gt) for purchased heat use. Its combined emissions declined at an average annual rate of 3.4% since peaking in 2014, mainly due to China's policies of eliminating outdated capacity since 2012 (NDRC, 2018b). The combined emissions from Services were 67.8% and Household Consumption 171.8% higher than their respective scope 1 emissions in 2019. In detail, Transportation, as the main emitter in Services, contributed 8.5% (0.83 Gt) of the national emissions in 2019, of which 88.0% were caused by fossil fuel combustion, 11.4% came from purchased electricity use and 0.6% came from purchased heat use. Over the past decade, China has cultivated the world's largest production and consumption market for electric vehicles. Scope 2 electricity emissions in Transportation have grown rapidly at an annual rate of 7.9% between 2009 and 2019, but fossil fuel-related emissions have dominated. In other words, there is still a long way to go to achieve near-zero emissions in Transportation. Supporting new energy vehicles and encouraging shared transportation is one of the ways to go.

Due to the intricate transmission of electricity and heat between regions, the advantages of combined emission accounts are more prominent in provincial inventories. For example, in 2019, the electricity consumption in Zhejiang Province contributed 0.13 Gt CO₂ emissions, causing its combined emissions (0.51 Gt) to be 32.9% higher than its scope 1 emissions (0.38 Gt). In contrast, the combined emissions in Inner Mongolia (0.64 Gt) were reduced by 19.3% compared to its scope 1 emissions (0.79 Gt) in the same year, mainly due to its electricity supply to other regions. On the other hand, the aggregated scope 2 emissions from 30 prov-

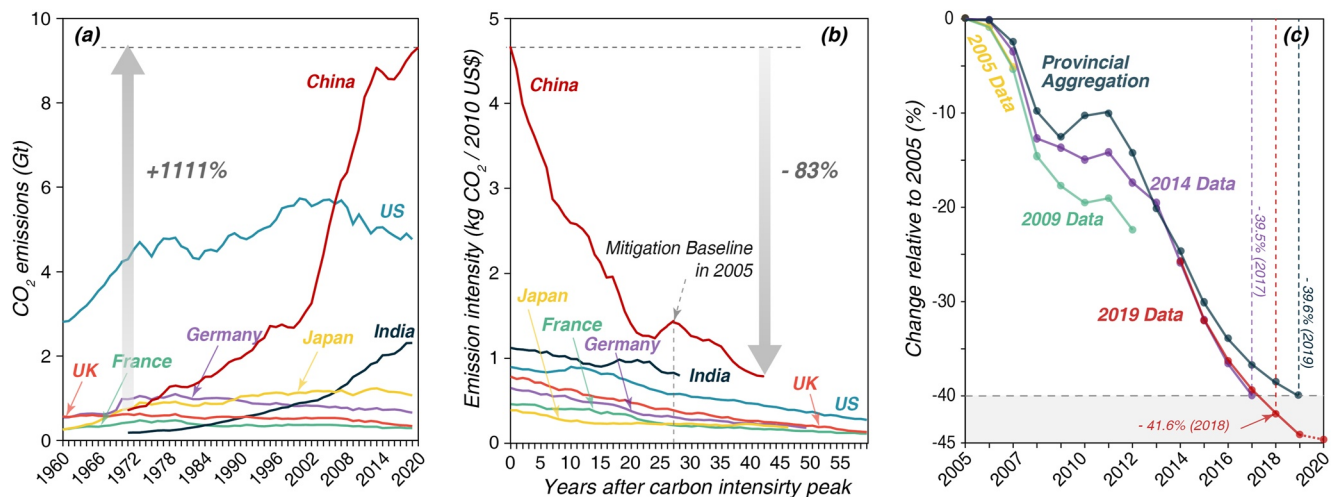


Figure 4. Comparison of energy-related carbon dioxide (CO₂) emissions and emission intensity. (a) CO₂ emissions of selected countries; (b) the decline of emission intensity after peaking for China and selected countries; (c) changes of China's emission intensity relative to the 2005 level among different data versions. Note: value added is in constant US dollars of 2010; Data for the US, the UK, France, Germany, Japan, and India were obtained from the International Energy Agency.

inces were 0.61 Gt, while the national data were -0.009 Gt in 2019, which once again proves the huge gap between China's energy statistics at different scales.

3.3. The Achievement of China's Climate Change Targets

Based on the updated inventories, we discuss and analyze the achievement of China's climate change mitigation targets and evaluate the implications of the revisions in the energy statistics on these targets.

Figure 4a shows that China's carbon emissions have significantly increased by 1,111% over the past 50 years, making China the world's largest emitter since 2006. Compared with other countries, China has experienced rapid industrialization in only 30 years, through massive exploitation and utilization of resources and radical institutional reforms (Jin, 2008). With the technological revolution, serious environmental problems followed. Learning from lessons of western countries, China has placed great emphasis on reducing its emission intensity. As shown in Figure 4b, its carbon intensity dropped by 83% from the intensity peak in 1978–2020. By contrast, Japan, the US, the UK, France, and Germany took decades to achieve a 50% reduction in emission intensity from their peak, and India has only reduced its carbon intensity by 29% from its intensity peak in 1991–2019. Nevertheless, China's carbon intensity is still 701% higher than France, 203% higher than the US, and 0.6% higher than India in 2019. China still has a long way to go to catch up with western countries in terms of carbon intensity reduction. All advanced economies have experienced a period of rapid development followed by a stage of slowing economic growth, and China is no exception (Qi et al., 2016). The Chinese government has issued a series of policies in efforts to pay close attention to environmental issues while ensuring economic development through decarbonizing the energy mix and industrial transformation (Guan et al., 2018; Qi et al., 2016; Zheng et al., 2019). These current actions provide opportunities for cleaner energy technologies to promote long-term sustainable development.

The official revisions of energy consumption data aim at more accurate accounting. In this context, it is necessary to evaluate the implications of China's climate change mitigation targets. We calculated the changes in emission intensity relative to the mitigation baseline (i.e., emissions intensity in 2005) for various data versions, as shown in Figure 4c. As listed in Table 1, Due to the 2014 data revision, the mitigation baseline was revised up by 5.1% compared with the 2009 data and by 10.8% with the 2005 data. As a result, the intensity reduction requirement to meet the 2020 target (i.e., a 40–45% reduction of carbon intensity by 2020 compared with the 2005 level) increased from 0.55–0.62 kg/2010US\$ in the 2005 data to 0.58–0.65 kg/2010US\$ in the 2009 and 0.61–0.68 kg/2010US\$ in the 2014 data. The requirement to meet the 2030

Table 1
Implications of the Energy Statistics Revisions on China's Carbon Intensity (kg CO₂ per 2010 US\$)

Data version	2014 data	2009 data	2005 data	Provincial aggregation
Mitigation baseline in 2005	1.52	1.44	1.37	1.56
Requirement to achieve 40% target	0.61	0.58	0.55	0.63
Requirement to achieve 45% target	0.68	0.65	0.62	0.70
Requirement to achieve 65% target	0.99	0.94	0.89	1.02

target (i.e., a more than 65% reduction of carbon intensity by 2030 compared with the 2005 level) increased from 0.89 kg/2010US\$ in the 2005 data to 0.94 kg/2010US\$ in the 2009 data to 0.99 kg/2010US\$ in the 2014 data. According to the revised energy statistics, the challenge to fulfill these pledges has increased. For example, in the 2014 data version, China achieved a 39.5% intensity reduction in 2017 from the 2005 level, while in the 2019 data version, the figure became 39.1%. It is worth noting that at the national level, the intensity reduction reached 41.6% in 2018% and 44.0% in 2019 from the 2005 level, meaning that the 2020 mitigation target was achieved ahead of schedule. Compared with the previous three revisions, the impact of the latest revision on carbon intensity is significantly lower, reflecting that China's energy statistics system is being gradually improved. However, there were still significant discrepancies of (−1.2%–3.6%) between national and provincial aggregation results. Reliable energy statistics and accurate carbon emissions accounting are essential for setting reasonable reduction targets and for the allocation of environmental responsibilities. Such discrepancies bring a series of challenges for China's path toward carbon neutrality, as well as for global research on climate change. It is necessary for China to find out the real reasons behind the inconsistency of energy statistics between the provincial and national levels and thus eliminate the phenomenon of local over-reporting and national under-reporting (Guan et al., 2012; Zheng et al., 2018).

3.4. Comparisons With Other Estimates and Uncertainties

Considering the importance of uncertainty assessment in emissions accounting, we investigate the variances in China's CO₂ emissions provided by different sources and quantify energy-related emissions by varying activity data and emission factors.

As mentioned in Section 3.1, China's CO₂ emission inventories vary considerably according to different versions of energy statistics. Such variances were also found in the inventories by many international research institutes (shown in Figure 5). For example, the maximum discrepancy between estimations was 1.74 Gt (17.8%) in 2019. The highest estimate (11.53 Gt) by EDGAR included both energy-related emissions and process-related emissions from the production of various industrial products. The lowest estimate (9.83 Gt) by BP only included energy-related emissions, but was still 7.8% higher than our estimates.

The basic data used for carbon accounting by these institutes are opaque. There are three explanations for such large variances. First, there are some variances in the activity data used. Although China's energy statistics are revised from time to time based on the results of the National Economic Census, some scholars still reported that it may be under-reporting, especially in raw coal consumption (Guan et al., 2012; Zheng et al., 2018). The current bottom-up energy accounting system in China requires highly accurate and reliable foundational data from manufacturers at a smaller scale, such as at the city or county level (Zheng et al., 2018). The statistics department and manufacturers in China are often pressured to provide data “to fit” some political purposes, as described by Guan et al. (2012). In this case, the activity data versions adopted by these institutes seem to be inconsistent. Second, there are some variances in the emission factors used. China is a large country with varying geological formations, resulting in variations in carbon content, calorific value, and oxygenation efficiency of different types of fuels. The default emission factors recommended by the IPCC do not correspond to the actual survey values in China (Liu et al., 2015). Third, there is some variation in accounting boundaries. Some inventories focus only on CO₂ emissions from fossil fuel combustion and did not consider or only partially consider (e.g., for cement) process-related emissions, resulting in lower estimates.

To quantify the uncertainties of our energy-related emission accounts, we used the Monte Carlo approach. The red-shaded area in Figure 5 represents the 97.5% confidence intervals for the carbon emissions calculat-

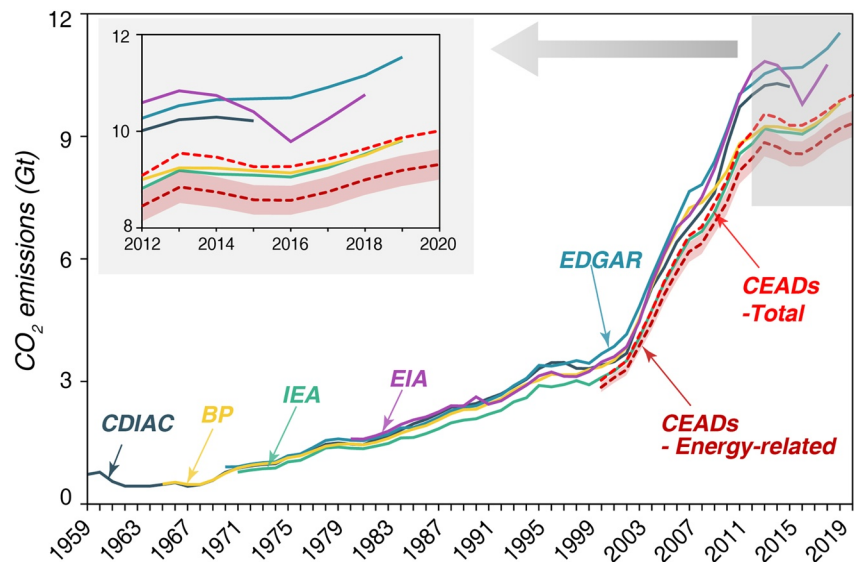


Figure 5. Comparison of China's carbon dioxide (CO_2) emissions by different institutes. Data source: Carbon Dioxide Information Analysis Centre (CDIAC) (Boden et al., 2016); British Petroleum (BP) (BP, 2020); International Energy Agency (IEA) (IEA, 2020); U.S. Energy Information Administration (EIA) (EIA, 2020); Emissions Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2020); Carbon Emission Accounts and Datasets for emerging countries (CEADs, this study). Note: All datasets include energy-related emissions. Emissions by CDIAC and CEADs-Total include cement production process-related emissions, and emissions by EDGAR include industrial process-related emissions from cement, steel, chemicals, and urea production.

ed in this study. We found that the uncertainties of the energy-related CO_2 emission inventories calculated in this study are roughly (-3.48% , 3.46%) in 2019 with a 97.5% confidence interval. IPCC (2006) estimated that the uncertainty for countries with less well-developed energy statistic systems may be on the order of $\pm 10\%$, whereas the range for the countries with good energy collection systems is $\pm 5\%$ (Friedlingstein et al., 2020; Marland, 2008). Similarly, Olivier and Peters (2002) estimated that emissions from Organization for Economic Co-operation and Development (OECD) countries may have an uncertainty of 5%–10%, and 10%–20% for other countries. These show that the uncertainties of our CO_2 emission inventories are much lower than the international average, which is attributed to the most up-to-date activity data we adopted and the actual measurement-based emission factors evaluated by Liu et al. (2015).

4. Conclusions

This study compiled China and its 30 provinces' CO_2 emissions using the latest revised national energy statistics and evaluated the implications of China's climate change mitigation targets. Specifically, we calculated combined scope 1 and scope 2 emissions from fossil fuel combustion, cement production, purchased electricity, and heat consumption from 2000 to 2019 at both national and provincial levels. This study found that the source of variation in China's carbon emissions is not only due to the correction of energy statistics, but also other reasons such as differences in emission factors, accounting approaches, and system boundaries.

Combining scope 1 and scope 2 emissions, a combined accounting approach developed in this study provides a new perspective for the allocation of sectoral and regional carbon emissions. At the national level, the sectoral, combined emissions differ from their corresponding scope 1 direct emissions, mainly due to differences in electricity and heat consumption. For example, Chemical Materials Production discharged 1.64 Gt direct CO_2 in 2019, but its combined emissions increased by 4.75 Gt, accounting for 6.5% of the national total. Because of the intricate supply demand relationships of electricity and heat between regions, provincial, combined emissions show greater heterogeneity than respective scope 1 emissions. Scope 2 accounts reveal a larger gap in energy statistics between national and provincial levels. We emphasize that

emission reduction policies need to be adapted to local conditions requiring accurate smaller-scale energy statistics and CO₂ emission accounts.

Reliable and transparent energy statistics and emissions inventories are crucial for the formulation and evaluation of climate change mitigation targets. China's efforts to tackle climate change have attracted global attention. Our accounts show that the revisions of energy data have caused significant impacts on China's CO₂ emissions inventories. This study reveals that these retrospective revisions provide opportunities for more accurate accounting, reflecting that China's energy statistics system has been gradually improved. According to national-level CO₂ emission accounts, in 2018, China has already achieved the goal of reducing its emission intensity by 40–45% compared with the 2005 level. Nevertheless, China's carbon intensity is still 701% higher than France, 203% higher than the US, and 0.6% higher than India in 2019. China still has a long way to go to catch up with western countries in terms of carbon intensity reduction. On the other hand, inconsistencies between national and provincial aggregated data declined but still exist after several rounds of revisions. For example, the national emissions showed a temporary peak around 2013, while the provincial aggregated data does not show such a peak. The current inconsistency has brought obstacles to assessing emission trends. However, from a long-term perspective, it does not matter whether China's emission temporarily peaked in 2013. What is important is that under the new normal of a slowdown in economic growth, China needs long-term efforts to promote changes in energy mix and industrial transformation, which is a necessity for achieving climate change mitigation targets.

China is still in the process of industrialization and urbanization, and therefore facing a series of challenges on the road toward net-zero emissions. The first challenge for policymakers is to promote a systemic reform of its energy statistics. Suggestions for the reform of the energy statistics system, such as collecting data through more on-site surveys and using remote sensing technologies, have been extensively discussed in previous studies (Guan et al., 2012; Han, Lin, et al., 2020; Han, Zeng, et al., 2020). On the other hand, decarbonizing the energy mix could be carried out by reducing the dependence on coal consumption, supporting renewable energy technologies through subsidies and carbon pricing, and accelerating the construction of smart energy systems to maximize energy utilization (Lund et al., 2017). Overall, China's decarbonization of the energy mix cannot be accomplished overnight, it will inevitably undergo a long-term process.

Data Availability Statement

The energy statistic data are obtained from the China Energy Statistics yearbook (NBS, 2020) and the provincial corresponding statistical yearbooks. The imported electricity data are collected from the UN Comtrade Database (<https://comtrade.un.org/data/>) and China Electricity Statistics Yearbook 2020 (China Electricity Council, 2020). The emission factors in energy-related emission accounts are summarized in Liu et al. (2015). The country-specific electricity generation emission factors data are from the Definitive Emission Factor Database (Brander et al., 2021). The China-specific heat generation emission factor is from China Carbon Trading Market website (<http://www.tanjaoyi.com/article-914-1.html>). The GDP data are collected from The World Bank website (<https://data.worldbank.org/indicator/NY.GDP.MKTP.KD>). All the data and results developed in this study can be downloaded freely from Carbon Emission Accounts and Data sets for emerging countries (CEADs). The national inventories are available at <https://www.ceads.net/data/nation/> and the provincial inventories are available at <https://www.ceads.net/data/province/>.

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