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Review

A representative CO_2 emissions pathway for China toward carbon neutrality under the Paris Agreement's 2 °C target

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Abstract

In 2021, China updated its nationally determined contributions (NDCs) under the Paris Agreement, which prompts a more accurate measurement of its emissions inventory and a reasonable pathway toward carbon neutrality by 2060. This study reviews the estimates using the bottom-up emissions factor method or the top-down atmospheric CO_2 concentration inversion method to derive China's CO_2 emissions inventory and finds that CO_2 emissions from energy combustion and industrial processes in Chinese mainland range from 11.3−12.0 $GtCO_2$ in 2021. Based on a comprehensive review of pathways proposed by domestic and international studies and an analysis of the origins of their differences, we proposed the Tsinghua-CMA pathway that coordinates the 2 °C global temperature rise control target with China's current CO_2 emissions status and mitigation policies. The pathway requires China's CO_2 emissions to peak around 2028−2029 at about 12.8 $GtCO_2$, then decline steadily to about 11.2 $GtCO_2$ in 2035, 3.6 $GtCO_2$ in 2050, and 0.9 $GtCO_2$ in 2060. Compared to a reference scenario without updated NDCs, this pathway would result in an economic cost of about 0.9% cumulative GDP between 2020 and 2060, only 1/4−1/3 of the cost associated with pathways that align with the 1.5 °C target. We recommended that China improves emissions accounting by cross-validating bottom-up and top-down approaches and regularly updating the pathway toward carbon neutrality while maintaining consistency with its evolving CO_2 emissions inventory, policy trends, and global CO_2 emission budget updates.

Keywords: CO_2 emissions inventory; Emissions accounting; Bottom-up emissions factor; Top-down inversion; Emissions pathway; Carbon neutrality; 2 °C target

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1. Introduction

The Paris Agreement has established a global goal to address climate change: limiting the increase in average global surface temperature to well below 2 °C above pre-industrial levels and striving for a limit of 1.5 °C. It requires achieving carbon neutrality by the second half of this century (Zhang et al., 2022; UNFCCC, 2016). As of March 2023, 133 countries have announced carbon-neutral targets, covering about 88% of global emissions (Wang et al., 2023). Among these countries, more than 90 countries, including China, the

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European Union, the United States, and India, have formally presented their carbon neutrality targets through legislation, policy documents, and political commitments. These countries account for about 80% of global greenhouse gas emissions. Carbon neutrality has become an international consensus (Climate Watch, 2023).

China has officially set its target for carbon neutrality and is calling for an appropriate pathway to reduce CO_2 emissions as soon as possible. In 2021, the Chinese government released a guiding document outlining China's dual carbon goal, achieving peak carbon emissions and neutrality (XNA, 2021). It aims to achieve harmonious coexistence between humans and nature while building a shared future for humanity. Subsequently, the State Council and all the relevant ministries released policies on implementing the dual carbon goal, constituting China's '1 + N' policy framework for carbon peaking and carbon neutrality, together with the guiding document.

To effectively implement these policies, it is necessary to have accurate data on the current emissions inventory and reasonable pathways toward reducing emissions until 2060. This information will also be crucial for energy transformation modeling and climate policy analysis. However, there are currently discrepancies in estimates from different studies regarding China's CO_2 emissions inventory (Zhong et al., 2023). Additionally, the range of decarbonization pathways proposed by domestic and international studies varies widely due to differing socioeconomic and technological assumptions (California-China Climate Institute and Lawrence Berkeley National Laboratory, 2021). Therefore, this study will focus on the following three questions: 1) What is the current status of China's CO_2 emissions, and why are there discrepancies in estimates? 2) How and why do different institutions propose varying CO_2 emissions pathways for China towards carbon neutrality? 3) What would be an appropriate representative CO_2 emissions pathway for China to achieve its dual carbon goal? This paper provides a comprehensive discussion of CO_2 emission accounting methods and an analysis of China's CO_2 emissions status quo. Based on a comprehensive review of pathways proposed by domestic and international studies and an analysis of the origins of their differences, we proposed the Tsinghua-CMA pathway that aligns with the global temperature rise control target and China's dual carbon goal.

2. China's CO_2 emissions inventory in 2021

After China announced the dual carbon goal in 2020, more studies emerged to compile China's CO_2 emissions inventory in 2021, as understanding the status quo of CO_2 emissions is important for developing pathways and strategies toward carbon neutrality. This study focuses on CO_2 emissions from energy combustion and industrial processes in Chinese mainland, consistent with China's current NDCs. We discuss the characteristics of two mainstream emissions accounting methods (bottom-up emissions factor method and top-down atmospheric CO_2 concentration inversion method) and compare CO_2 emissions in 2021 estimated by different studies. We show that applying a consistent scope is critical for the comparison.

2.1. Bottom-up emissions factor method

The emissions factor method is the most commonly applied emissions accounting method (Yu and Tan, 2023). It is essentially the sum of the products of the activity level and emissions factors for each emissions source, according to the emissions inventory (IPCC, 2006). This method is simple, straightforward, and easy to understand as long as some forms of activity and emissions factor data are ready to use. However, since emissions factors usually vary temporally and spatially even for the same source type and using one single emissions factor is prone to significant biases (Zhao et al., 2012; Rypdal and Winiwarter, 2001), at the country level, uncertainties with the emissions factor method can reach 10%−40% (Marland, 2008; Peylin et al., 2013).

Several studies calculated CO_2 emissions from energy combustion and industrial processes in Chinese mainland in 2021, with a range of 11.6−12.9 $GtCO_2$. We first adopt CO_2 emissions factors of coal, oil and gas, and industrial process of products for China from our author team and their collaborators' latest work (Guo et al., 2023a) and apply the activity level data in 2021 from the National Bureau of Statistics of China (NBSC National Bureau of Statistics of China, 2022), which would lead to 11.6 $GtCO_2$. Among them, CO_2 emissions from energy combustion were about 10.3 $GtCO_2$, and that from industrial processes were 1.3 $GtCO_2$. These numbers were close to the estimate from the International Energy Agency (IEA, 2022) based on the latest CO_2 emissions factors following the 2006 IPCC Guidelines (IPCC, 2006) (11.9 $GtCO_2$), among which emissions from fuel combustion were about 10.6 $GtCO_2$ (IEA, 2023) and emissions from industrial processes were about 1.3 $GtCO_2$.

We note that two recent studies provided significantly higher estimates and explain why. Li et al. (2023c) calculated that CO_2 emissions were about 12.9 $GtCO_2$, using the greenhouse gas emissions inventory by sector, technology, fuel, and raw material. We believe this study might overestimate CO_2 emissions from China's power sector. According to the China Electricity Council (China Electricity Council, 2022), CO_2 emissions per unit of thermal power generation in 2021 were about 828 g $(kW\ h)^{-1}$, and thermal power generation was 5.66 PW h. Therefore, CO_2 emissions from the power sector were about 4.7 $GtCO_2$, significantly lower than 6.1 $GtCO_2$ from Li et al. (2023c). If this 1.4 $GtCO_2$ difference in the power sector were deducted, Li et al. (2023c)'s estimate would also be approximately 11.6 $GtCO_2$. The Emissions Database for Global Atmospheric Research (EDGAR) used CO_2 emissions factors from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and estimated China's CO_2 emissions were about 12.5 $GtCO_2$ in 2021 (Crippa et al., 2022). We believe their overestimate is because the IPCC's recommended emissions factors were higher than the actual numbers in China. Liu et al. (2015) surveyed China's fossil fuel quality and cement process and found that the EDGAR had systematically overestimated

China's CO_2 emissions. The difference was due primarily to the emissions factors used to estimate emissions from coal combustion, as Liu et al. (2015)'s measurements indicated that the factors applicable to China's coal were about 40% lower than the default values recommended by the IPCC (2006). Similarly, Ding and Zhang (2022) found that the total CO_2 emissions in China using local emissions factors were generally 10%−15% lower than those calculated using the IPCC CO_2 emissions factors. Therefore, if the EDGAR's overestimate was about 10%, China's CO_2 emissions would be 11.3 $GtCO_2$ in 2021.

Some other studies only estimated China's CO_2 emission from energy combustion in 2021. For example, British Petroleum (British Petroleum, 2022) adopted IPCC emissions factors and excluded the uncombusted share of fossil fuels from IEA's statistics. Their results showed that China's CO_2 emissions from energy combustion were about 10.5 $GtCO_2$. Since CO_2 emissions from the industrial process in 2021 were about 1.3 $GtCO_2$, according to IEA (2023), the estimate from BP would be about 11.8 $GtCO_2$. The Carbon Monitor (2023) and the Global Carbon Project (GCP) (Friedlingstein et al., 2022) calculated the CO_2 emissions from energy combustion and cement production based on a diverse range of activity data and emissions factors, and their estimates were 11.2 $GtCO_2$ and 11.5 $GtCO_2$, respectively. Given that CO_2 emissions from the industrial process of cement production were about 0.8 $GtCO_2$ during 2019 and 2020 (Yu and Tan, 2023) and if it remained the same in 2021, CO_2 emissions from other industrial processes would be 0.5 $GtCO_2$ when cement industrial process emissions were deducted from the total industrial process emissions (1.3 $GtCO_2$) according to the IEA (2023). Therefore, with this amount of CO_2 emissions from other industrial processes accounted for, CO_2 emissions from energy combustion and industrial processes would be about 11.7 $GtCO_2$ for the CM and 12.0 $GtCO_2$ for the GCP.

2.2. Top-down atmospheric CO_2 concentration inversion method

The IPCC (2019) proposed the top-down method in the Guidelines for National Greenhouse Gas Inventories. It assimilates ground-based and satellite-based atmospheric CO_2 observations using atmospheric transport models to invert carbon source-sink variations. This method is less affected by human disturbance and has high time resolution. The accuracy and resolution of this method depend on available CO_2 observations and are affected by multiple factors, including sensor precision and the uncertainty in atmospheric transport models (Wang et al., 2022).

Some studies used the atmospheric CO_2 concentration inversion method to quantify the global CO_2 emissions in 2021, but only a few studies provided estimates for emissions in China. At the global level, according to the World Meteorological Organization's systematic observations and analyses (WMO, 2022), the global average CO_2 mole fraction in 2021 was $(415.7 \pm 0.2) \times 10^{-6}$. The result showed that the increase in CO_2 from 2020 to 2021 was equal to that observed from 2019 to 2020 and larger than the average annual growth rate over 2010−2020. At the country level, Li et al. (2023b) used bottom-up multi-resolution emissions inventories of China and top-down inversion of surface stations observation data from the World Meteorological Organization to obtain daily changes in China's CO_2 emissions from 2019 to 2022. However, the study did not provide the absolute level of China's total CO_2 emissions in 2021. Zhong et al. (2023) obtained the total anthropogenic CO_2 emissions of approximately 13.1 $GtCO_2$ in 2021 from 32 provinces and autonomous regions in China by assimilating the atmospheric CO_2 concentration monitoring inversion of the National Greenhouse Gas Observation Network (Guo et al., 2023b). The CO_2 emissions from human and animal respiration were about 1 $GtCO_2$, and the CO_2 emissions from Hong Kong, Macao, and Taiwan of China were about 0.2 $GtCO_2$. After deducting the above emissions, Zhong et al. (2023) obtained Chinese mainland's total CO_2 emissions from energy combustion and industrial processes of about 11.9 $GtCO_2$.

In summary, we find that the two methods (emissions factor method and atmospheric CO_2 concentration inversion method) generated comparable results and can potentially cross-validate each other to improve accuracy in the future. Estimates for CO_2 emissions from energy combustion and

Table 1
Estimated CO_2 emissions in China in 2021 from different studies ($GtCO_2$).

Study	Original value	Adjusted value using a consistent scope[a]	Method
Institute of Energy, Environment and Economy, Tsinghua University (Guo et al., 2023a)	11.6	11.6	Emissions factor method
IEA (2022)	11.9	11.9	Emissions factor method
Li et al. (2023c)	12.9	11.6	Emissions factor method
EDGAR (Crippa et al., 2022)	12.5	11.3	Emissions factor method
British Petroleum (2022)	10.5	11.8	Emissions factor method
Carbon Monitor (2023)	11.2	11.7	Emissions factor method
GCP (Friedlingstein et al., 2022)	11.5	12.0	Emissions factor method
Zhong et al. (2023)	11.9	11.9	Atmospheric CO_2 concentration inversion method

Note: [a] CO_2 emissions from energy combustion and industrial processes in Chinese mainland are accounted.

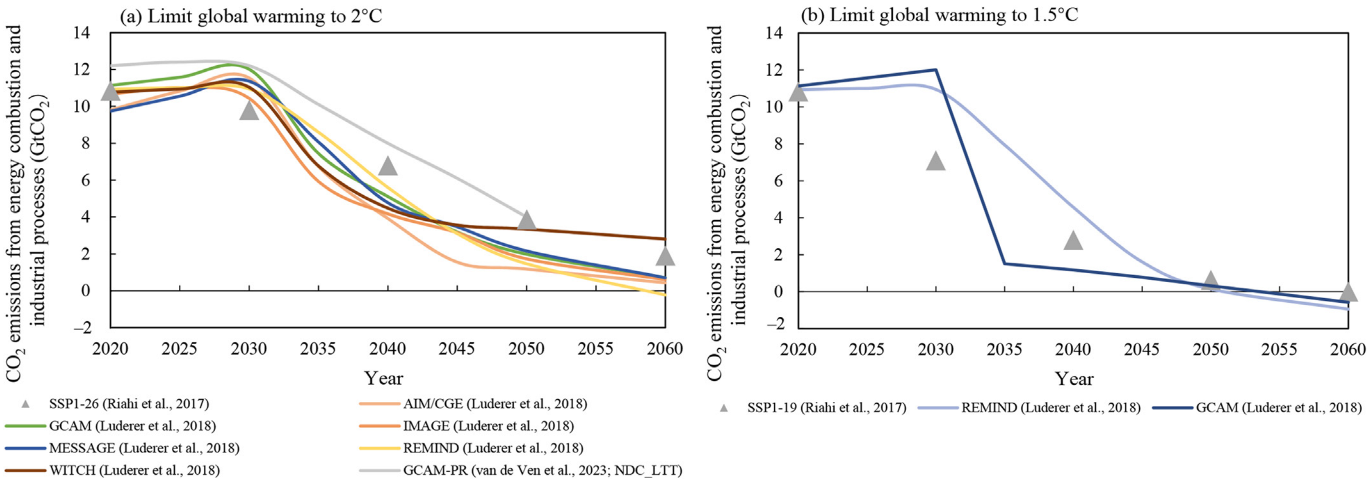

Fig. 1. Pathways for CO_2 emissions from energy combustion and industrial processes in Chinese mainland proposed by international institutions.

industrial processes in Chinese mainland in 2021 are between 11.3 and 12.0 Gt if a consistent scope is applied, as shown in Table 1. In the rest of this study, we adopt the value of 11.9 $GtCO_2$, which is cross-validated by emissions factor method (IEA, 2022) and atmospheric CO_2 concentration inversion method (Zhong et al., 2023), as a starting point to derive China's CO_2 emissions pathways toward carbon neutrality, with CO_2 emissions from energy combustion as 10.6 $GtCO_2$ and that from industrial processes as 1.3 $GtCO_2$.

3. CO_2 emissions pathways for China toward carbon neutrality

Several studies by both domestic and international institutions have already put forward China's CO_2 emissions pathways toward carbon neutrality. Most studies by international teams mainly adopt the perspective of controlling the global temperature rise within 2 or 1.5 °C and then allocate an emissions budget for China (Riahi et al., 2017; Luderer et al., 2018; Vrontisi et al., 2018). Hence, these emissions pathways are not necessarily aligned with China's near-term emissions reduction target or do not fully consider policy feasibility. For many studies by domestic institutions (Ding et al., 2022; Cai et al., 2021; Wang et al., 2021), although these aspects are considered, they did not apply economic models to fully evaluate their proposed pathways or use the most updated emissions inventory numbers, as reviewed below.

3.1. Studies by international institutions

Arguably, the most influential CO_2 emissions pathways that aim to control the global temperature rise within 2 °C are based on the relatively sustainability-focused Shared Socioeconomic Pathways (SSP1). Based on SSP1-19 and SSP1-26, which could roughly control the temperature rise at 1.5 °C and 2 °C, respectively, Riahi et al. (2017) proposed two CO_2 emissions (from energy combustion and industrial processes) pathways for China. These pathways only provide emissions every ten years and lack information on peaking years and values, as shown in Fig. 1.

According to the assumption that there is no international emissions trading, but emissions reduction occurs at the most cost-effective place and time, Luderer et al. (2018) and Vrontisi et al. (2018) published two influential articles and put forward CO_2 emissions (from energy combustion and industrial processes) pathways that can limit global warming to 1.5−2 °C for all major countries/regions, based on simulation results from mainstream international modeling teams, including AIM/CGE, GCAM, IMAGE, MESSAGE, REMIND, WITCH, POLES, and IMACLIM.[2] Since POLE and IMACLIM had their starting points (emissions value in 2020) substantially off compared to our estimated value discussed above (about 11 $GtCO_2$), we exclude them from further discussion in the next section. Some pathways assume that China peaked its emissions in 2020 (contradicting the current situation), so we exclude them from further discussion. In addition, we only keep pathways that can limit warming within 2 °C or 1.5 °C with a chance greater than 67%, meaning that pathways that have a control target with a chance of 50% are not discussed further for a consistent comparison. With these exclusion rules described above (these rules are applied in our analysis in Section 3.2), Fig. 1 shows that these remaining pathways are consistent with China's goal of peaking emissions by 2030 and achieving carbon neutrality by 2060. Under the 2 °C target, the range of China's CO_2

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[2] AIM/CGE model was developed by the Japan Center for Social and Environmental Systems Research. GCAM model was developed by the Joint Global Change Research Institute. IMAGE model was developed by the Environmental Protection Agency of Ireland. MESSAGE model was developed by the International Institute for Applied Systems Analysis (IIASA). REMIND model was developed by the Potsdam Institute for Climate Impact Research in Germany. WITCH model was developed by RFF-CMCC European Institute on Economics and the Environment (EIEE). POLES model was developed by the European Union Joint Research Center. IMACLIM model was developed by CIRED, Ecole des Ponts ParisTech.

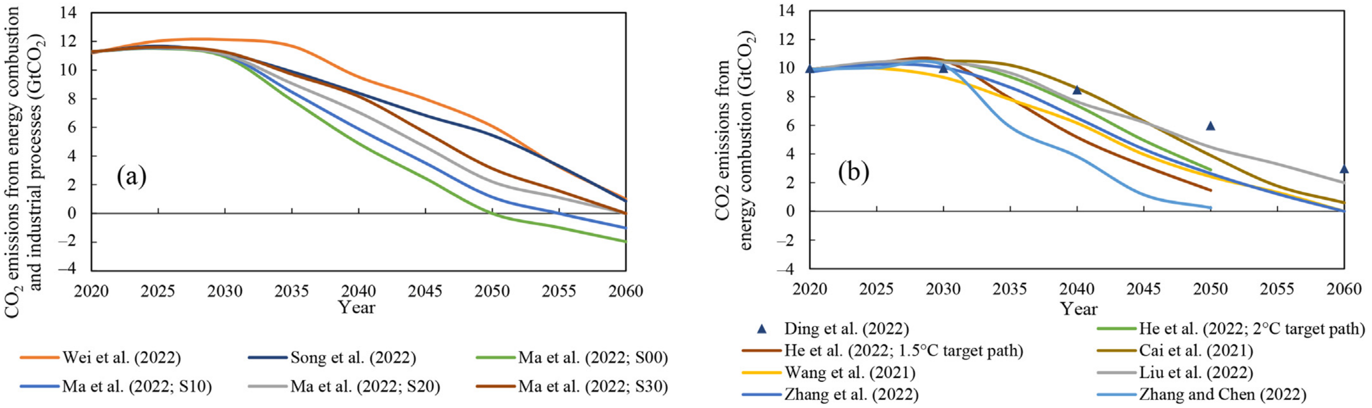

Fig. 2. Pathways for CO_2 emissions in Chinese mainland proposed by domestic institutions, (a) from both energy combustion and industrial processes, and (b) from energy combustion only.

emissions is 1−4 $GtCO_2$ in 2050 and 0−3 $GtCO_2$ in 2060; while under the 1.5 °C target, China's CO_2 emissions would need to achieve near-zero by 2050 and become negative by 2060, which is more aggressive than China's current goal of achieving carbon neutrality by 2060. Hence, we focus on pathways that correspond to the 2 °C target for further discussion.

China announced the dual carbon goal in 2020, but new international studies on China's transition pathways after that are limited. van de Ven et al. (2023) used four diverse integrated assessment models, including GCAM-PR, GEMINI-E3, MUSE, and TIAM-Grantham[3] to assess CO_2 emissions trajectories based on national policies and pledges after COP26, combined with a simple climate model to assess the temperature implications. The result shows that achieving stated long-term targets (LTTs) among all countries is the only option for keeping temperature increase well below 2 °C. Pathways proposed by GEMINI, MUSE, and TIAM all assume that China peaked its emissions in 2020 (contradicting the current situation), so we exclude them from further discussion. Under GCAM-PR's NDC_LTT pathway (NDCs with LTTs), China would peak in around 2025 at 12.4 $GtCO_2$ and reduce to 12.2 $GtCO_2$ in 2030, 8.0 $GtCO_2$ in 2040, and further to 4.0 $GtCO_2$ in 2050, as shown in Fig. 1a. Another notable study is the IEA (2021a) roadmap to carbon neutrality for China, released in 2021. It indicated that China's energy-related CO_2 emissions would plateau between 2026 and 2030, decrease rapidly from 10.1 $GtCO_2$ in 2030 to 3.4 $GtCO_2$ in 2040, and reach finally net zero emissions by 2060.[4] We deem that the pathway is aggressive as the period of fastest emission reduction occurs between 2030 and 2040, while it is without precedent as no major economy can dramatically reduce its CO_2 emissions within a decade after reaching the peak. A review by the California-China Climate Institute and Lawrence Berkeley National Laboratory (California-China Climate Institute and Lawrence Berkeley National Laboratory, 2021) also showed recent international studies on mid-century emissions transition scenarios for China mostly overlooked this fact and projected rapid declines in energy-related CO_2 emissions between 2030 and 2040. With the same exclusion rules applied, pathways discussed in this review report are excluded for further comparison (not shown in Fig. 1).

3.2. Studies by domestic institutions

Unsurprisingly, many domestic institutions proposed CO_2 emissions pathways for China after the dual carbon goal was released, as shown in Fig. 2. For example, Ding et al. (2022) from the Chinese Academy of Sciences proposed that China's pathway toward carbon neutrality can be divided into four stages measured in energy-related CO_2 emissions: peaking emissions at the level of about 10 $GtCO_2$ by 2030, reducing emissions to about 8.5 $GtCO_2$ by 2040, further reducing emissions to about 6.0 $GtCO_2$ by 2050, and controlling emissions to 2.5−3.0 $GtCO_2$ by 2060, as carbon sinks can offset at that time. He et al. (2022) from Tsinghua University proposed pathways for 2 °C and 1.5 °C target from 2020 to 2050 (2 °C target path and 1.5 °C target path). Both pathways would peak CO_2 emissions at around 10.5 $GtCO_2$ before 2030 and reduce gradually to 2.9 $GtCO_2$ and 1.5 $GtCO_2$ in 2050, respectively. Wei et al., 2022 from the Beijing Institute of Technology used the bottom-up model C3IAM/NET to evaluate different CO_2 emissions pathways toward carbon neutrality (though they did not disclose their cost estimates). Their central pathway (medium-demand−high-speed transformation−long-platform period, displayed in Fig. 1a) projected that China's CO_2 emissions from energy combustion and industrial processes would peak in 2028−2029, with a level of about 12.2 $GtCO_2$, and emissions in 2060 would be

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[3] The GCAM-PR model, The GEMINI-E3 model, the MUSE model, and the TIAM-Grantham model are developed by the Joint Global Change Research Institute, Ecole Polytechnique Fédérale de Lausanne, Switzerland, the Imperial College London, and McGill University and GERAD, Montreal, Canada, respectively.

[4] Since all the pathways displayed in Fig. 1 account for CO_2 emissions from both energy combustion and industrial processes, we do not show the IEA pathway in Fig. 1. However, we include it for comparison with other pathways that only account for energy-related CO_2 emissions in Fig. 4b.

about 2.1 $GtCO_2$. Cai et al. (2021) from the Environmental Planning Institute, the Ministry of Ecology and Environment proposed an energy-related CO_2 emissions pathway that would peak around 2027—2028 at the level of about 10.6 $GtCO_2$ and then reduce to about 3.9 $GtCO_2$ in 2050 and around 0.6 $GtCO_2$ in 2060. Wang et al. (2021) from the Economic and Technological Research Institute, China Petroleum Corporation, projected that China's energy-related CO_2 emissions would peak around 2025, maintain a plateau period of about five years, and then reduce to around 2.4 Gt by 2050 and zero emissions by 2060.

Several studies took a step further and applied energy-economic models to evaluate the economic burden of proposed pathways toward carbon neutrality. Some of them estimated the rising cost of energy supply. For example, based on a review of international forecasts, including British Petroleum (2020), IEA (2020), Global Shell (2018), and Equinor (2020), Song et al. (2022) from Tsinghua University proposed that CO_2 emissions will peak around 2025 by about 12 $GtCO_2$ and reduce to about 6 $GtCO_2$ in 2050 and about 1 $GtCO_2$ in 2060. They used a bottom-up energy system model to analyze the cost and showed that overall energy costs would increase by 16% to achieve carbon neutrality. Ma et al. (2023) from China University of Petroleum and Tsinghua University reviewed some recent studies (Huang et al., 2020; He et al., 2020; IEA, 2021b; Zhao et al., 2021; Shao et al., 2022) and concluded that China's emissions pathway toward 2030 is relatively predictable, with CO_2 emissions from fossil fuel combustion and industrial processes reaching a peak level of about 11 $GtCO_2$ in 2030; however, there are high uncertainties toward carbon neutrality by 2060. They applied an energy-economic model, GCAM-TU, to estimate the energy system cost of four illustrative scenarios that reduce CO_2 emissions from fossil fuel combustion and industrial processes to 3, 2, 1, and 0 $GtCO_2$ in 2050 (namely scenario S30, S20, S10, and S00), which were equivalent to 3.99%, 4.10%, 4.34% and 4.48% of GDP in 2050, respectively. We note that Ma et al. (2023) need to update their pathways because their projected CO_2 emissions peak level was already passed in 2021. Zhang and Chen (2022) from Tsinghua University designed three mitigation scenarios with peak times around 2020, 2025, and 2030, respectively, and used the Monte Carlo method to generate 3000 cases in each scenario and a bottom-up model to analyze the impact on energy cost. To facilitate comparison, we only focus on cases that peak CO_2 emissions around 2030 at 10.4 Gt and display a pathway that connects the average emissions values of these 1000 cases every five years in Fig. 2b. In these cases, the cumulative energy system costs related to additional investment, maintenance, and operation would be 3.3%—3.6% of GDP between 2020 and 2050.

Finally, some studies applied economy-wide models to estimate the overall economic burden of achieving the carbon neutrality target. Duan et al. (2019) from the Chinese Academy of Sciences calculated the global and China's energy-related CO_2 emissions budget corresponding to the 2 °C and 1.5 °C temperature control targets under two probability levels (50% and 67%, respectively) based on their selected emissions budget allocation principles. An integrated assessment model (CE^3METL) was then used to generate four optimal CO_2 emissions pathways with four exogenous cumulative CO_2 emission constraints and endogenous social carbon cost. For the pathway for the 2 °C target with a probability of 50%, China would peak its energy-related CO_2 emissions by 2030 with a level of about 11.1 $GtCO_2$, still maintain at the level over 8.0 $GtCO_2$ by 2050, and rapidly reduce to near-zero by 2060, with a cumulative GDP loss by 2060 not more than 2%. As mentioned above, we only keep pathways that can limit warming within 2 °C or 1.5 °C with a chance greater than 67%, so we exclude it from further discussion. The other three pathways required China to peak its emissions around 2020 (the cumulative GDP loss would be 2.5—3.0 times higher), so we exclude them from further discussion. Duan et al. (2021) further assessed China's efforts to pursue the 1.5 °C warming limit by conducting a multi-model study, cooperating with modeling teams, including AIM, GCAM, IMAGE, POLES, REMIND, WITCH, and CE^3METL. According to their research, China's CO_2 emissions need to peak around 2020 and continue to decrease to −1.94—2 $GtCO_2$ in 2050, and the accumulated policy costs may amount to 2.8%—5.7% of GDP by 2050. We do not display these pathways in Fig. 2 either because they require China to peak around 2020.

Liu et al. (2022) from the Chinese Academy of Sciences simulated four suites of emissions reduction policies to achieve carbon neutrality by 2060, including carbon pricing, energy efficiency improvement, renewable energy, and electrification enhancement, in a dynamic computable general equilibrium model. They projected that China's energy-related emissions would peak at less than 10.4 $GtCO_2$ before 2029 and decrease to less than 2 $GtCO_2$ in 2060. Compared to a scenario without these policies, the cumulative GDP losses from 2020 to 2060 would be around 2.5%—3.5%. Zhang et al. (2022) from Tsinghua University also proposed an emissions pathway and applied a dynamic computable general equilibrium model for the cost evaluation. They projected that China's energy-related CO_2 emissions would peak around 2027—2028 at less than 10.5 $GtCO_2$. In 2030, CO_2 emissions would slowly decrease to 10 $GtCO_2$ and then gradually decrease to achieve net zero emissions until 2060. It estimated that China's cumulative GDP losses from 2020 to 2060 would be around 1.1% compared to the reference scenario.

4. Tsinghua-CMA CO_2 emissions pathway for China toward carbon neutrality

This section proposes an appropriate representative pathway, the Tsinghua-CMA pathway, for China toward carbon neutrality that coordinates the global temperature rise control target with China's current CO_2 emissions status and mitigation policies. We apply an economy-wide computable equilibrium model, the China-in-Global Energy Model (C-GEM), developed by the Institute of Energy, Environment and Economy, Tsinghua University (Zhang et al., 2022), to evaluate its economic feasibility.

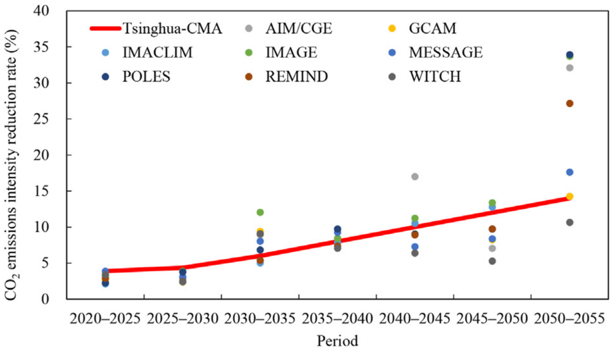

Fig. 3. Annual CO_2 emissions intensity reduction rate for the world (selected pathways in Luderer et al. (2018) and Vrontisi et al. (2018)) and China (the Tsinghua-CMA pathway).

4.1. Design of the pathway

To materialize an emissions pathway based on the dual carbon goal, we need to pinpoint the level of CO_2 emissions through 2060, commonly with a time step of five years. Given that China has formulated CO_2 emissions reduction targets in its recent five-year plans in the form of CO_2 emissions intensity reduction, we also derive the Tsinghua-CMA pathway by assuming five-year CO_2 emissions intensity decline rates.

The 14th Five-Year Plan has already confirmed a target of reducing CO_2 emissions intensity by 18% between 2020 and 2025 (about 3.9% annually). For the post-2025 annual emissions intensity reduction rate, we refer to the global yearly average emissions intensity reduction rate in Luderer et al. (2018) and Vrontisi et al. (2018), shown in Fig. 1, to propose a pathway consistent with global emissions reduction targets. Specifically, we calculate the annual emissions intensity reduction rates every five years. The results are shown in Fig. 3, which suggest that the global CO_2 emissions intensity reduction rates should be 2.0%−4.0% per year between 2020 and 2025, 2.5%−4.0% per year between 2025 and 2030, 5.0%−12.0% between 2030 and 2035, and then reach 10.0%−34% between 2050 and 2055. Since most of these pathways assume that the world will achieve carbon neutrality by 2060, we only show the emissions intensity reduction rates through 2055. Therefore, we propose stepped annual CO_2 emissions intensity reduction rates for China (see Table 2), which are 3.9% between 2020 and 2025 (18% in five years), 4.4% between 2025 and 2030 (20% in five years), then start with 6% between 2030 and 2035, and increase by two percentage points every five years until it reaches 14% between 2050 and 2055, and further to 16% between 2055 and 2060. Fig. 3 shows that this trajectory is within the range of global annual CO_2 emissions intensity reduction rates in Luderer et al. (2018).

As reviewed above, some existing pathways only account for CO_2 emissions from energy combustion. We also put forward an energy-related CO_2 emissions pathway for comparison under the assumption that the CO_2 emissions intensity reduction rates are the same for both CO_2 emissions from energy combustion and industrial processes.

As shown in Fig. 4a, under the Tsinghua-CMA pathway, China's CO_2 emissions from energy combustion and industrial processes are expected to peak during 2028−2029 at about 12.8 $GtCO_2$, then decline steadily to 11.2 $GtCO_2$ in 2035, further decline to 3.6 $GtCO_2$ in 2050, and then to 0.9 $GtCO_2$ in 2060, which could be well offset by carbon sink in China to achieve carbon neutrality, as Guo et al. (2023a), Zhong et al. (2023), Pu et al. (2022) and Wei et al., 2022 all estimated that China's carbon sink could reach 1−2 $GtCO_2$ in 2060. Potential carbon sink surplus leaves room for offsetting remaining non-CO_2 greenhouse gases at that time. As for China's CO_2 emissions from energy combustion (as shown in Fig. 4b), it would peak at around 11.4 $GtCO_2$ during 2028−2029, decrease to 10.0 $GtCO_2$ in 2035, further to 3.2 $GtCO_2$ in 2050, and finally reduce to 0.8 $GtCO_2$ in 2060. The Tsinghua-CMA pathway is located centrally within the envelope of other pathways after 2030.

4.2. Evaluating the economic impact of the pathway

We use our in-house energy-economic general equilibrium model, the C-GEM (see Li et al. (2023a), Zhang et al. (2022), and Zhao et al. (2022) for detailed model descriptions and cases of policy analyses), to estimate the economy-wide cost of implementing the Tsinghua-CMA pathway as CO_2 emissions constraints. The model has represented key low-carbon, zero-carbon, and negative-carbon technologies. By dynamically adjusting the production and consumption structure, it can characterize characteristics of China's economic transformation toward high-quality development (Huang, 2023).

The result shows that China's cumulative GDP from 2020 to 2060 would be 0.9% lower compared to a reference scenario representing the climate policy stringency before China released the dual carbon goal, as discussed in Zhang et al. (2022). Compared to the carbon neutrality pathway in Zhang et al. (2022), the economic cost of the Tsinghua-CMA pathway is slightly lower as emissions in later years are assumed to be higher.

To analyze the economic impact of pathways to meet the 1.5 °C target, we choose to evaluate the SSP1-19 pathway proposed by Riahi et al. (2017) and pathways for the 1.5 °C target by GCAM and REMIND in Luderer et al. (2018) and Vrontisi et al. (2018), which all are shown in Fig. 1b. Again, these pathways are implemented as CO_2 emissions constraints in the C-GEM. Since CO_2 emissions under the SSP1-19

Table 2
Annual average CO_2 emissions intensity reduction rate (% per year) assumed in the Tsinghua-CMA pathway.

Year	2020−2025	2025−2030	2030−2035	2035−2040	2040−2045	2045−2050	2050−2055	2055−2060
Reduction rate	3.9	4.4	6.0	8.0	10.0	12.0	14.0	16.0

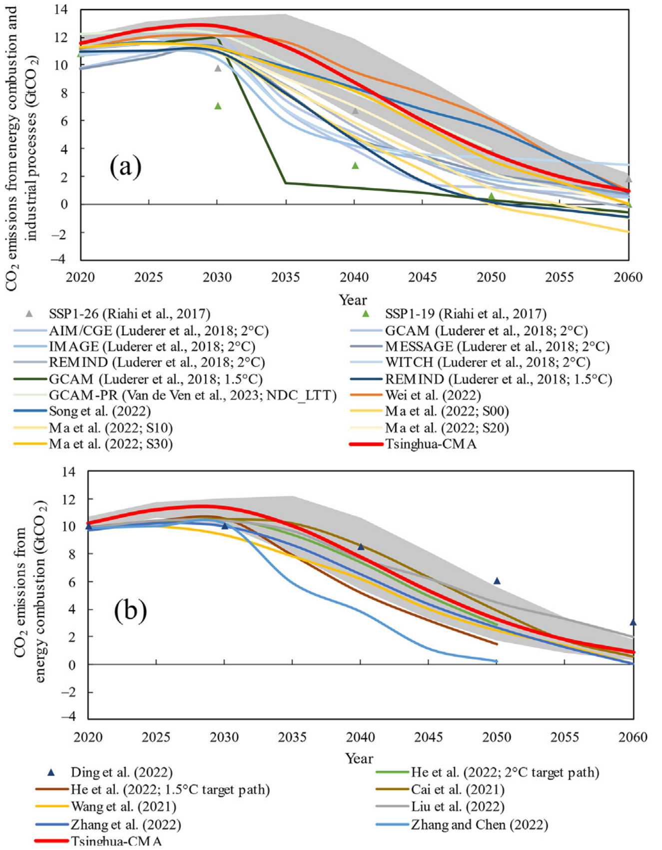

Fig. 4. Comparison of China's CO_2 emissions pathways toward carbon neutrality, (a) from both energy combustion and industrial processes, and (b) from energy combustion only (The gray area represents a possible range of the Tsinghua-CMA pathway, considering uncertainties discussed in Section 4.3).

pathway need to peak immediately and rapidly decrease to 7 $GtCO_2$ in 2030 and almost zero in 2050, the accumulative GDP from 2020 to 2060 under the SSP1-19 pathway would be three times higher than the Tsinghua-CMA pathway. Similarly, both pathways by the GCAM and REMIND would cause an accumulative GDP loss about four times higher. In other words, we estimate that China's GDP losses to achieve the 1.5 °C target would be about 3−4 times that of the Tsinghua-CMA pathway, which we deem policy-infeasible so far.

4.3. A range for the Tsinghua-CMA pathway considering uncertainties in key parameters

Economic growth and emissions reduction rates are two key factors determining China's future CO_2 emissions. To explore the impacts of underlying uncertainties of these two parameters, we consider two additional sets of GDP growth rates (high-growth and low-growth) and CO_2 emissions intensity reduction rates (fast-reduction and slow-reduction), as shown in Table 3. Since a typical national CO_2 emissions inventory adopts 5% as the uncertainty range (UNFCCC, 2019), we also use 5% as a deviation relative to our base rates for GDP growth and CO_2 emissions intensity reduction to create these additional two sets of parameters for our uncertainty analysis.

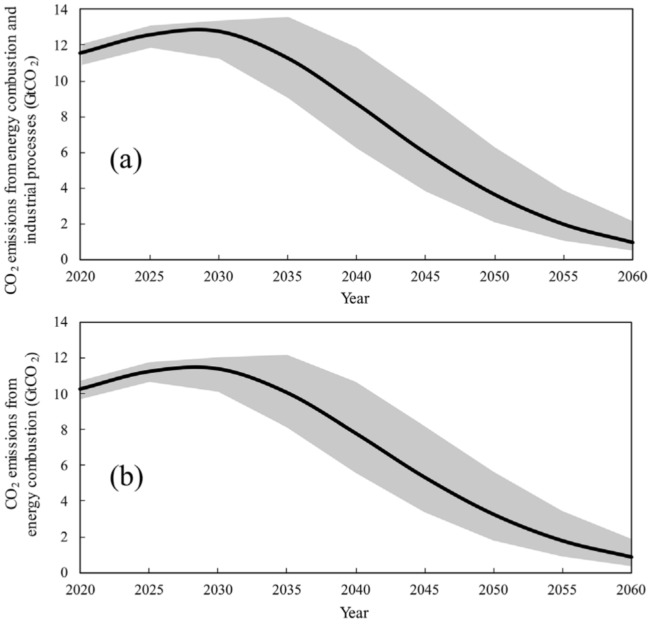

Fig. 5. The possible range of the Tsinghua-CMA pathway (The black lines represent the Tsinghua-CMA pathway, and the gray area represents a possible range of the Tsinghua-CMA pathway).

As shown in Fig. 5a, if economic growth slows down and emissions reduction is more aggressive, China's CO_2 emissions from energy combustion and industrial processes may peak in 2026 at around 12.1 $GtCO_2$; if the economic growth is higher and emissions reduction is less aggressive, peaking would be delayed with a higher level. The range of CO_2 emissions is 11.3−13.5 $GtCO_2$ in 2030, 2.0−6.3 $GtCO_2$ in 2050, and 0.4−2.1 $GtCO_2$ in 2060. As for China's CO_2 emissions from energy combustion, as shown in Fig. 5b, the range is 10.1−12.1 $GtCO_2$ in 2030, 1.8−5.6 $GtCO_2$ in 2050, and 0.4−1.9 $GtCO_2$ in 2060.

Table 3
The range of annual GDP growth rate and CO_2 intensity reduction rate (unit: %).

Rate		2020−2025	2025−2030	2030−2035	2035−2040	2040−2045	2045−2050	2050−2055	2055−2060
Annual GDP growth rate	Base	5.8	4.8	3.8	3.3	3.0	2.9	2.9	2.8
	High-growth	6.1	5.4	4.5	3.5	3.2	3.0	3.0	3.0
	Low-growth	5.5	4.6	3.6	3.1	2.9	2.8	2.7	2.6
Annual average CO_2 intensity reduction rate	Base	3.9	4.4	6	8	10	12	14	16
	Fast-reduction	3.9	6	8	10	12	14	16	18
	Slow-reduction	3.9	4	4	6	8	10	12	14

5. Conclusion

This study examines two main methods for deriving China's CO_2 emissions inventory: the bottom-up emissions factor method and the top-down atmospheric CO_2 concentration inversion method. When applying a consistent scope for accounting, estimates for CO_2 emissions from energy combustion and industrial processes in Chinese mainland in 2021 using these two methods are comparable, ranging from 11.3 to 12.0 $GtCO_2$. We adopt the value of 11.9 $GtCO_2$, which is cross-validated by the emissions factor method and atmospheric CO_2 concentration inversion method as a starting point to establish a representative CO_2 emissions pathway toward carbon neutrality for China, known as the Tsinghua-CMA pathway. This pathway is proposed after reviewing various pathways proposed by domestic and international studies and presenting the origins of their differences. The Tsinghua-CMA pathway aims to peak CO_2 emissions around 2028–2029 and steadily reduce them to approximately 0.9 $GtCO_2$ by 2060, aligning with the target of limiting global warming to 2 °C. At that time, any remaining CO_2 emissions could be offset by China's carbon sink. To assess its economic impact, we utilize an economy-wide energy-economic model and find that achieving carbon neutrality under the Tsinghua-CMA pathway is comparatively feasible and incurs lower cumulative costs than other pathways aligned with a target of limiting global warming to 1.5 °C.

To ensure timely tracking and updating of the pathway in the future, we recommend continuous improvement of CO_2 emission accounting methods through more accurate measurement of relevant activity levels and emission factors for bottom-up approaches. For top-down approaches, enhancing the monitoring system and inversion techniques is crucial. Encouraging cross-validation between these two methods to enhance the accuracy of emissions inventory is also important. When updating the pathway, careful consideration should be given to maintaining consistency with China's evolving CO_2 emissions inventory, policy trends, and updates on global CO_2 emission budgets. It is worth noting that one limitation of this study is the lack of discussion on non-CO_2 greenhouse gases in our proposed pathway. Further research is needed to address this aspect. Regional and sectoral pathways are also important directions for future research.

CRediT authorship contribution statement

Da Zhang: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. Xiao-Dan Huang: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. Jun-Ting Zhong: Writing – review & editing, Methodology, Formal analysis, Data curation. Li-Feng Guo: Writing – review & editing, Validation, Resources. Si-Yue Guo: Writing – review & editing, Validation, Resources, Methodology, Investigation, Conceptualization. De-Ying Wang: Writing – review & editing. Changhong Miao: Writing – review & editing. Xi-Liang Zhang: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. Xiao-Ye Zhang: Writing – review & editing, Validation, Supervision, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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