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Original Research

Toward greenhouse gas neutrality: China's post-2030 transition pathway and policy

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A B S T R A C T

Global climate targets require massive economic transformations to achieve greenhouse gas (GHG) neutrality by mid-century. China, as the world's largest emitter, has pledged to peak carbon dioxide (CO_2) emissions before 2030 and achieve carbon neutrality before 2060. Current domestic policies primarily target the 2030 CO_2 peaking objective, whereas the specific scope and actionable measures for the 2060 neutrality goal remain unclear. However, the critical differences in socioeconomic and technological pathways between realizing CO_2 neutrality versus comprehensive GHG neutrality are not yet well understood. Here we show that achieving GHG neutrality by 2060 demands unprecedented, cross-sectoral mitigation efforts far exceeding those required for CO_2 neutrality. Using a multi-model integrated framework, we demonstrate that GHG neutrality requires a 100% elimination of energy-related CO_2 emissions, compared with a 92% reduction under CO_2 neutrality. Furthermore, non-CO_2 emissions must be slashed by 60% instead of 50%, and the technical demand for carbon capture must expand from 1.3 to 1.9 gigatonnes of CO_2. Reaching this target requires a 15% reduction in total GHG emissions by 2035 and an 85% reduction by 2050 relative to 2030 levels. The findings indicate the necessity of a 2035-focused medium-term climate strategy to connect current policies with long-term objectives. Implementation of these comprehensive roadmaps is essential for directing the broader economy toward sustainable global climate governance.

1. Introduction

The year 2025 shattered global climate records as one of the warmest years in modern history [1]. However, a significant gap remains between near- and medium-term global ambitions and the long-term temperature goals of 2 °C and 1.5 °C set in the Paris Agreement. Current national policies are putting the Earth on a path to a 3 °C temperature rise this century [2]. Meanwhile, domestic climate change policies have given way to issues such as economic recovery and energy security due to the global economic downturn, intensifying geopolitical conflicts, and the decline of multilateralism. At past Climate Change Conferences and Group of 20 Summits, global leaders called on countries to enhance their Nationally Determined Contributions (NDCs) for 2035, accelerate concrete actions, and achieve global carbon neutrality by mid-century [3,4].

As the world's largest carbon dioxide (CO_2) emitter and the second-largest economy, China's decarbonization efforts and policies are crucial to tackling global climate change risks. In 2020, China announced pledges to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060, known as the dual-carbon

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goals. These commitments were subsequently written into China's 2021 NDC update [5]. In this report, the Chinese government clarified that the scope of the carbon peaking target includes only CO_2. In addition, China has committed to a series of measurable targets by 2030. Its Long-Term Low-Greenhouse Gas Emission Development Strategy to the Middle of This Century sets a target of over 80% of energy consumption from non-fossil sources by 2060 [6]. Meanwhile, the scope of China's climate policy targets beyond 2030, especially the 2060 carbon-neutrality pledge, remains unclear.

These global commitments have simultaneously translated into domestic policies that focus on delivering the 2030 ambition. In 2021, the central government released the 1+N climate policy package, outlining systematic strategies, policies, and actions for the dual-carbon goals [7]. More than 30 interconnected policies strike a careful balance between targets, actions, and enabling conditions to peak CO_2 emissions before 2030. At the same time, the definition and content of carbon neutrality by 2060 remain unclear in domestic policies. Different ministries have differing opinions and interpretations of the 2060 carbon-neutrality goal. Then, at the Baku Climate Change Conference in November 2024, for the first time, China's vice premier announced that the 2035 emission reduction targets in the next round of the NDCs would be economy-wide and cover all greenhouse gas emissions [8].

China must initiate debates on consistent medium- and long-term targets and policy frameworks after 2030 [9]. However, few studies have sought to bridge the gap between systemic transition and policy discussions by connecting near-term policy targets to medium- and long-term goals. One report indicates that a significant gap exists between current policy and long-term targets and that fossil fuels will still account for 40% of China's energy mix in 2050 despite an enormous shift toward green energy [10]. Early macro studies employed engineering–economic optimization models to evaluate decarbonization pathways and technology portfolios [11–14]. Annual energy outlooks from influential industrial institutions further enrich the scenario landscape by offering contrasting assumptions on geopolitical evolution, policy shifts, and technological progress, thereby illustrating the uncertainties embedded in the energy transition pathway [15–18]. Recent studies have used sector-specific modeling to refine assessments of technology feasibility and mitigation costs across energy-intensive industries, such as aluminum, electricity generation, cement, and steel [19–22], as well as across subnational scales, such as cities and industrial parks [23,24]. Integrated assessment studies have increasingly embedded climate mitigation within multidimensional sustainability frameworks and quantified co-benefits for air quality, health, food systems, and sustainable development goals (SDG) progress [25–29], thus highlighting the broader societal implications of decarbonization scenarios and reinforcing the need for a coherent, multisectoral policy design.

Against this backdrop, an important question emerges: What are the differences in the pathways between carbon neutrality and greenhouse gas (GHG) neutrality, and what do these differences imply in the policy context? This study addresses these critical gaps by connecting systematic pathway comparison with policy discussion to inform targets after 2030. Clarifying the difference between carbon neutrality and GHG neutrality is crucial to fostering domestic consensus, facilitating policymaking, advancing the Global South's mitigation ambitions and actions, and upholding China's role as a leader and trusted partner in global climate governance.

This paper is organized as follows. Section 2 describes the research design, scenario setting, and methods. Section 3 elaborates on significant results, including emission trajectories, decarbonization pathways, sectoral decompositions, energy transition, technological demand, and additional efforts from CO_2 neutrality to GHG neutrality. Section 4 discusses the characteristics and limitations of this study. Section 5 presents the paper's conclusions and policy recommendations.

2. Research design, scenario setting, and methods

2.1. Research design and guidelines

This study is framed by the dual objectives of achieving China's socialist modernization goals and meeting the global temperature-rise control targets under the Paris Agreement, while aligning timelines and integrating policy targets. The Socialist Modernization Strategy is China's predominant design for its medium-to long-term development, with goals over two stages: becoming a moderately prosperous society by 2035 and a great modern socialist country by 2050 [30]. ‘Beautiful China’ first appeared as an environmental and ecological vision in the report of the 18th National Congress in 2012 [31] and was further elaborated and enriched in regulations and plans in the subsequent years. From the 20th National Congress in 2022, Beautiful China, with periodic environmental targets and focus areas such as green development, environmental pollution control, ecosystem conservation, and achieving the dual carbon goals, was proposed as the national strategy for environmental and ecological governance, and aligns with the timeline of the Socialist Modernization Strategy [32,33].

China's long-term policy framework for carbon neutrality was issued in 2021 and serves as a guideline within the 1+N climate policy package. The document, entitled “Opinions on Completely, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon Peaking and Carbon Neutrality,” covers both carbon peaking and carbon neutrality, and the timeframe from 2021 to 2060 is divided into three periods: 2021–2025, 2026–2030, and 2031–2060 [7]. It specifies staged goals across five key aspects: (1) building a green, low-carbon, and circular economic system; (2) improving energy efficiency; (3) increasing the share of non-fossil energy consumption; (4) reducing carbon dioxide emissions; and (5) enhancing the ecosystem carbon sink. At the 20th National Congress in 2022, the environment, ecology, and carbon-neutrality targets were integrated into the Beautiful China Strategy, further positioning Beautiful China as the environmental dimension of the Socialist Modernization Strategy (Table 1).

The timeline and targets for medium- and long-term policies on carbon neutrality should align with domestic strategies and the global climate governance agenda, which includes achieving global GHG neutrality by the second half of this century and updating the NDCs every five years. Based on this assumption, this study divided the timeframe for carbon neutrality into three phases. From now until 2035, the policy target is to peak CO_2 emissions before 2030 and significantly reduce emissions by 2035. The phase from 2035 to 2050 is for deep decarbonization to realize the potential of all measures with technical and economic feasibility by 2050. The third phase, from 2050 to 2060, strives for carbon neutrality. In addition, the long-term strategic targets for economic, environmental, and climate change define the boundary of the research framework.

2.2. Scenario setting

In this research, the scenario setting before 2030 aligns with China's 2021 NDC update [5] and is consistent with the definition and scope of the carbon peaking target. For the scenario setting after 2030, this study considers two kinds of policy targets for

Table 1
Alignment of medium- and long-term targets in national strategies.

Category	Strategy	Policy targets			Reference
		2035	2050	2060	
Overall development	Socialist Modernization Strategy	A moderately prosperous society	A modern socialist country	None	[30]
Environment and ecology	Beautiful China Strategy	Green production and lifestyles, a decline in carbon emissions after peaking, and environmental improvement	Enhanced ecological civilization, green development and lifestyles, deep decarbonization in key sectors, and a healthy environment	None	[31–33]
Carbon neutrality	Opinions	None	None	Carbon neutrality, over 80% of energy consumption from non-fossil sources	[7]

Note:(1) The timeframe for “Socialist Modernization Strategy” and “Beautiful China Strategy” is from 2020 to 2050. Therefore, there are no policy targets for 2060 for these two strategies.(2) “Opinions” refers to the document entitled “Opinions on Completely, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon Peaking and Carbon Neutrality.” The timeframe for “Opinions” spans from 2021 to 2060, with policy targets set for the years 2025, 2030, and 2060.

2060: carbon neutrality and GHG neutrality. Two scenarios were designed to compare sectoral differences and additional efforts to achieve GHG neutrality versus carbon neutrality. Considering the inertia of economic and social development, this study assumes that CO_2 and GHG emissions in the two scenarios follow the same trajectories until 2035, after which decarbonization accelerates at different rates due to their respective emission-reduction targets. Most of the data have been updated to 2024, and the simulation period is from 2020 to 2060 at five-year intervals. Meanwhile, the assumptions regarding economic growth, technology costs, and energy-efficiency progress are similar across scenarios, which align with the timelines of the Paris Agreement, Beautiful China, and the Socialist Modernization Strategy.

CO_2 neutrality scenario. This scenario's long-term target is to achieve net zero CO_2 emissions by 2060. The CO_2 neutrality scenario aims to peak CO_2 emissions before 2030 and reach CO_2 neutrality before 2060, using carbon sinks to offset the remaining CO_2 emissions by 2060, while acknowledging residual non-CO_2 GHG emissions at that time. This scenario is driven primarily by technological and socioeconomic factors.

GHG neutrality scenario. This scenario's long-term target is to achieve net zero GHG emissions by 2060. The GHG neutrality scenario aims to peak CO_2 emissions before 2030, achieve CO_2 neutrality and a deep reduction in greenhouse gas emissions by 2050, and reach GHG neutrality by 2060, with carbon sinks used to offset residual non-CO_2 emissions. This scenario is driven mainly by ambitious domestic policies and favorable global collaboration. The assumptions for the large-scale deployment of decarbonization technologies are roughly five years earlier than those under the CO_2 neutrality scenario and include the use of direct carbon capture technology.

2.3. Methods

This study used a multimodel framework to simulate China's overall decarbonization pathways, combining top–down and bottom–up approaches (Fig. 1). For the years before 2035, the study used a typical top–down approach. The overall trajectories of the economy, energy, and carbon emissions before 2035 were outlined in related planning and strategies, including the Socialist Modernization Strategy, the 1+N climate policy package, and the 14th Five-Year Plan (FYP). Therefore, energy consumption and carbon emissions in key years were estimated based on the anticipated economic scale by 2035 and expectations of the project's steering committee for the target year's carbon-intensity reduction objective. The energy mix was determined based on the literature and the experts' expectations.

For the years after 2035, the study employed a bottom–up approach, using models to simulate transition pathways in end-use sectors. First, electricity demand, energy consumption, and direct CO_2 emissions were calculated using sectoral models covering the industrial, building, and transport sectors. Next, the sum of electricity consumption across end-use sectors was used as an input to the model to optimize decarbonization pathways for the power sector. Moreover, the production and consumption of biomass and hydrogen were analyzed independently with consumption data from end-use sectors. Finally, data from various sectors were synthesized to estimate total energy consumption, energy mix, and carbon emissions. Two balances—total energy consumption and overall energy structure—were used to calculate and iterate between the top–down and bottom–up models [13]. The specific calculation process was as follows.

At the macro level, given the current gross domestic product (GDP) growth rate and potential optimization of the energy structure, the overall economy's total energy consumption and CO_2 emissions are projected to decline at a rate similar to recent declines in carbon intensity. At the macro level, the balance of total energy supply and consumption is met in equation (1):

$$\lambda = 1 - \frac{\dfrac{E_{t+T} \times \sum_i e_{i,t+T} \times \alpha_i}{D_{t+T}}}{\dfrac{E_t \times \sum_i e_{i,t} \times \alpha_i}{D_t}} \tag{1}$$

where E stands for total energy consumption; e stands for energy structure; D stands for gross domestic product; i stands for the consumption of different energy types (coal, oil, natural gas, and non-fossil energy); t and $t+T$ stand for different years, respectively; α stands for emission factor; and λ stands for the declining rate of carbon intensity.

At the sectoral level, sectors such as industrial, building, transport, and electric power are subject to bottom–up sectoral modeling, which needs to meet the balance between electricity consumption (end-use sectors and electrolytic hydrogen production) and overall electricity production at the economic level:

$$P_{c,j} = \sum_{j=1}^{3} P_{p,j} + P_{h,j=4} \tag{2}$$

where $P_{c,j}$ stands for power consumption, $P_{p,j}$ stands for power production; $P_{h,j}$ stands for electricity used for hydrogen production; j stands for the terminal sector; and $j = 1, 2, 3$, and 4 stand for

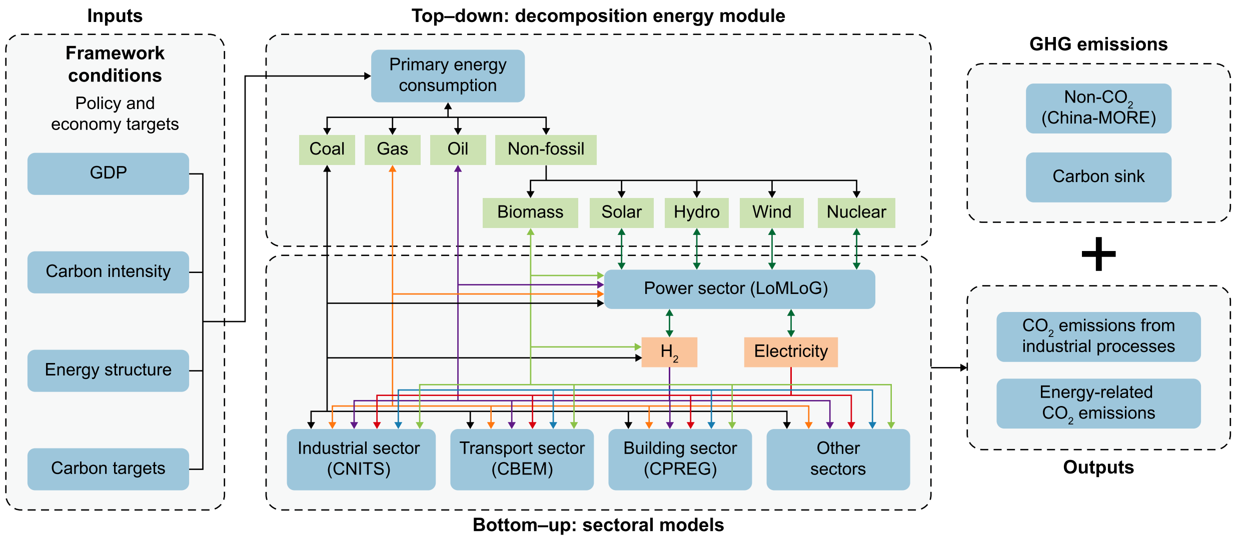

Fig. 1. Multimodel framework for the transition pathway study. LoMLoG: Long-term Multi-region Load-dispatch Grid-structure-based model [34]. CNITS: Carbon Neutrality Oriented Industrial Technology Scenario model [35]. CBEM: China Building Energy Model. [36]. CPREG: China Provincial Road Transport Energy Demand and GHG Emissions Analysis model [37]. China-MORE: China Multigas Optimal Reduction Evaluation model [38]. GDP: gross domestic product.

industrial, building, transport, and power, respectively. Power consumption on the production side of the power sector primarily comprises auxiliary power and line losses.

Hydrogen is emerging as a critical solution for decarbonizing end-use applications that defy straightforward electrification. Meanwhile, hydrogen production technologies will evolve from coal-based hydrogen to coal with carbon capture and storage (CCS) technologies, biomass hydrogen, and water electrolytic hydrogen. The balance between hydrogen production and consumption is as follows:

$$\sum_{j=1}^{3} H_{\mathrm{c},j} = \sum_{k=1}^{4} H_{\mathrm{p},k} \tag{3}$$

where $H_{\mathrm{c},j}$ stands for hydrogen consumption; $H_{\mathrm{p},k}$ stands for hydrogen production; k stands for different technologies for hydrogen production; and k = 1, 2, 3, and 4 stand for hydrogen production from coal-based technology, coal-based technology with carbon capture and storage (CCS) facilities, biomass-based technology, and water electrolytic technology, respectively.

Currently, biomass is widely used across the industrial, building, transport, and power sectors. In the medium to long term, biomass consumption in the industrial, transport, and power sectors will increase slowly, while consumption in the building sector will decrease. Biomass hydrogen production is assumed to be commercially utilized by 2040. The balance between biomass consumption and supply is as follows:

$$B_{\mathrm{c}} = \sum_{j=1}^{4} B_{\mathrm{s},j} + B_{\mathrm{h}} \tag{4}$$

where B_{c} stands for biomass consumption; $B_{\mathrm{s},j}$ stands for biomass supply in the industrial, building, transport, and power sectors; B_{h} stands for biomass used for hydrogen production.

In addition to balancing the production and consumption of electricity, hydrogen, and biomass, the overall energy structure of the economy should align with the combined energy consumption of all sectors, which is the energy structure balance:

$$E_{t,i} = E_t \times e_i = \sum_{j=1}^{4} E_{t,i,j} \tag{5}$$

For non-CO_2 emissions, a technology-specific bottom–up model is used to simulate CH_4, N_2O, and F-gas emissions from key anthropogenic sources. The carbon sink from forestry is used to offset the remaining emissions [34,35]. Finally, the total greenhouse gas output is the sum of energy-related CO_2 emissions, industrial processes CO_2 emissions, non-CO_2 emissions, and the carbon sink:

$$G = G_{\mathrm{CO_2\_E}} + G_{\mathrm{CO_2\_P}} + G_{\mathrm{Non-CO_2}} - G_{\mathrm{S}} \tag{6}$$

where G stands for total greenhouse gas emissions, $G_{\mathrm{CO_2\_E}}$ stands for energy-related CO_2 emissions, $G_{\mathrm{CO_2\_P}}$ stands for the CO_2 emissions from industrial processes, $G_{\mathrm{Non-CO_2}}$ stands for non-CO_2 emissions, and G_{S} stands for the carbon sink. The published literature on sectoral modeling and related research results is outlined in references [36–40].

3. Results

3.1. Emission trajectories

The GHG trajectories in the two scenarios were divided into three phases (Fig. 2). Generally, CO_2 and GHG emissions in the two

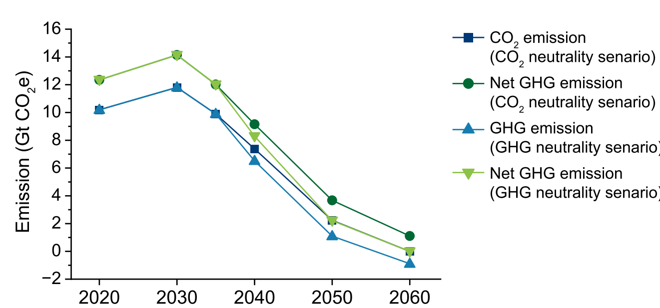

Fig. 2. CO_2 and net greenhouse gas (GHG) emission trajectories under the two scenarios.

scenarios follow similar paths through 2035, after which they diverge between 2035 and 2060. From now until 2030, the target for this phase is to peak CO_2 emissions as soon as possible while capping CO_2 emissions at 12.8 Gt CO_2 and GHG emissions at 15 Gt CO_2 equivalent (CO_2e). After 2030, significant reductions in emissions are expected, including approximately 15% of CO_2 emissions and 10% of non-CO_2 emissions by 2035, which translates to a 15% reduction in net GHG emissions, with offsets from carbon storage and the carbon sink in forests.

From 2035 to 2050, the target of this phase is deep decarbonization. Under the CO_2 neutrality scenario, net GHG emissions are expected to reach 75% below peak by 2050, equivalent to an annual reduction of 4%. Meanwhile, CO_2 emissions are expected to decrease by 75%, and non-CO_2 emissions are required to decrease by 40% by 2050. Steeper reductions are expected under the GHG neutrality scenario rather than under the CO_2 neutrality scenario. Net GHG emissions are expected to reach approximately 85% below peak, equal to an annual reduction of 4.7%. CO_2 emissions should also reach an 85% reduction, and non-CO_2 emissions must achieve a 50% reduction by 2050. The annual scale of GHG emissions reduction is projected to reach 400–500 million tonnes of CO_2e.

The third phase, from 2050 to 2060, aims for carbon or GHG neutrality. Under the CO_2 neutrality scenario, net CO_2 emissions are expected to reach net zero through offsets from carbon sinks. Meanwhile, net GHG emissions, CO_2 emissions, and non-CO_2 emissions are projected to decrease by approximately 90%, 90%, and 50%, respectively, compared with their peak levels. A residual of 1.11 Gt CO_2e of GHG emissions remains. Under the GHG neutrality scenario, while net GHG and CO_2 emissions are expected to reach net zero, non-CO_2 emissions must be reduced by more than 60%. Large-scale deployment of negative-carbon technologies is necessary in both scenarios; however, approximately 0.6 Gt CO_2e of additional capture capacity is required under the GHG-neutrality scenario (Table 2). In general, the carbon sink of forestry is used to offset residual CO_2 emissions from energy-related activities and industrial processes under the CO_2 neutrality scenario, as well as non-CO_2 emissions under the GHG neutrality scenario.

3.2. Economy-wide decarbonization pathway

The pathways in the two scenarios encompass all economic sectors (Figs. 3 and 4). Before 2030, energy-related CO_2 accounts for more than 78% of total emissions, with the industrial and power sectors the largest emitters, each accounting for approximately 30%. Non-CO_2 emissions contribute approximately 15%, and industrial process emissions account for approximately 7%. From 2035 to 2050, the decarbonization of the energy system and

Table 2
Comparison of emissions and sinks under two scenarios (Unit: Gt CO_2e).

Category	2035	CO_2 neutrality scenario		GHG neutrality scenario	
		2050	2060	2050	2060
CO_2 emissions	10.8	3.2	0.9	2.0	0.0
Energy-related CO_2 emissions	10.5	4.2	2.2	3.4	1.9
CCS & DACCS	−0.3	−1.2	−1.3	−1.5	−1.9
Industrial process CO_2 emissions	0.6	0.1	0.0	0.1	0.0
Non-CO_2 gas emissions	2.1	1.4	1.1	1.1	0.9
Carbon sink	−0.9	−0.9	−0.9	−0.9	−0.9
Net GHG emissions	12.0	3.7	1.1	2.2	0.0

Note: Carbon sink data refer only to the forest ecosystem. GHG, greenhouse gas; CCS, carbon capture and storage; DACCS, direct air carbon capture and storage.

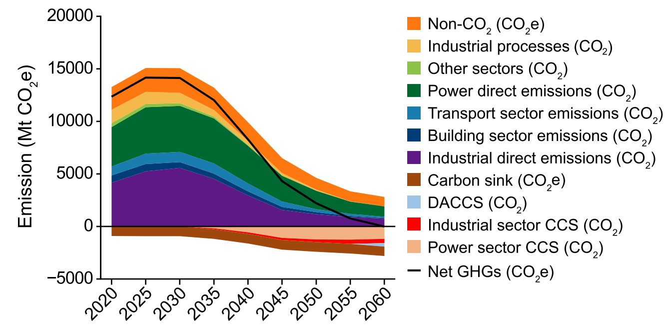

Fig. 3. Emission structure under the greenhouse gas (GHG) neutrality scenario. DACCS: direct air carbon capture and storage; CCS: carbon capture and storage.

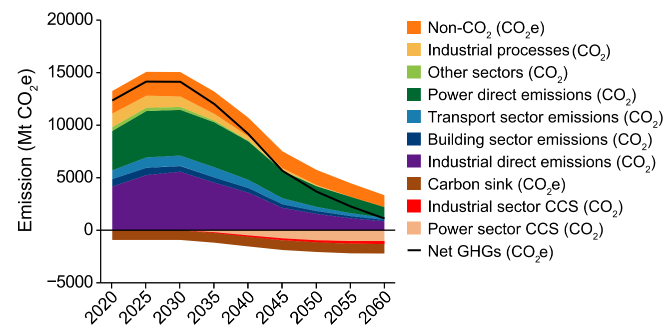

Fig. 4. Emission structure under the CO_2 neutrality scenario. GHG: greenhouse gas.

industrial processes should be further accelerated, with CO_2 emissions decreasing by 65–70% and 90%, respectively. The power and industrial sectors are expected to contribute more than 80% of the reduction in energy-related CO_2 emissions. By 2060, under the GHG neutrality scenario, non-CO_2 emissions are expected to account for more than 90% of total GHG emissions, while CO_2 emissions from energy-related and industrial processes are projected to reach near-net-zero levels. There will still be approximately 0.5 Gt CO_2e of residual emissions from hard-to-abate sectors, including the industrial, building, and transport sectors. For overall balance, forestry carbon sinks (900 million tonnes) can offset emissions from residual non-CO_2 and hard-to-abate sectors, and the energy system could reach net-zero with 1.9 Gt CO_2 of CCS and direct air carbon capture and storage (DACCS).

Non-CO_2 emissions must peak before 2030, in parallel with CO_2 emissions, and must be capped below 2.5 Gt CO_2e. Compared with 2030, non-CO_2 emissions are expected to decline by 10% by 2035 and by 50% and 60% by 2060 in the two scenarios (Supplementary Table S1). Across sectors, the industrial, energy, and agricultural sectors contribute more than 90% of the total emissions (Fig. 5). Under the GHG neutrality scenario, the industrial sector's emissions are expected to decline from approximately one-third to approximately 5% by 2060, driven by lower-cost technologies. The energy sector's emissions are expected to decrease from 25% to approximately 10% by 2060, driven by reduced fossil fuel consumption, particularly coal. Owing to the large area of rice and scattered crop cultivation and livestock breeding, the agricultural sector is expected to become a hard-to-abate source of non-CO_2 emissions, with its emissions contribution increasing over the long term, from 35% in 2025 to 78% in 2060. While the waste sector's emissions contribution remains relatively stable, emissions need to reach a two-thirds reduction over the long term compared with 2030.

3.3. Sectoral decomposition of dual-carbon targets

The policy targets for carbon peaking and carbon neutrality should be broken down by sector and aligned with the planning of various ministries. From now until 2035, the policy focus is to peak CO_2 emissions before 2030 and to significantly reduce GHG emissions by 2035. End-use sectors must reach their peak emissions between 2025 and 2030, and non-CO_2 emissions should also peak during this period (Fig. 6). In addition, the energy sector's CH_4 emissions peaked in 2014, following the closure of 70% of coal mines [41]. By 2035, the end-use sectors should cut their emissions by 10% to 30%. In contrast, the power sector's emissions may remain flat due to the rising demand driven by the swift electrification of end-use sectors.

From 2035 to 2050, the policy focus is on deep decarbonization through the application of all technically and economically feasible measures. Under the GHG neutrality scenario, the 2050 targets aim for nearly zero CO_2 emissions. Emissions from the industrial and power sectors need to decrease by 85% or more, while emissions from the transport and building sectors should decline by 70% due to higher technology costs. Meanwhile, the non-CO_2 sector can achieve only a 50% reduction due to rapid increases in technology costs.

Between 2050 and 2060, the policy focus will be on achieving GHG neutrality. Energy-related CO_2 emissions must reach net zero, while non-CO_2 emissions should be reduced by more than 60%. The power sector should achieve net zero by approximately 2055 and transition to a negative-emissions sector by 2060. There will still be approximately 0.5 Gt CO_2e of emissions remaining from hard-to-abate sectors, including industrial, building, and transport, and additional direct air carbon capture and storage (DACCS) technologies will be required to offset them.

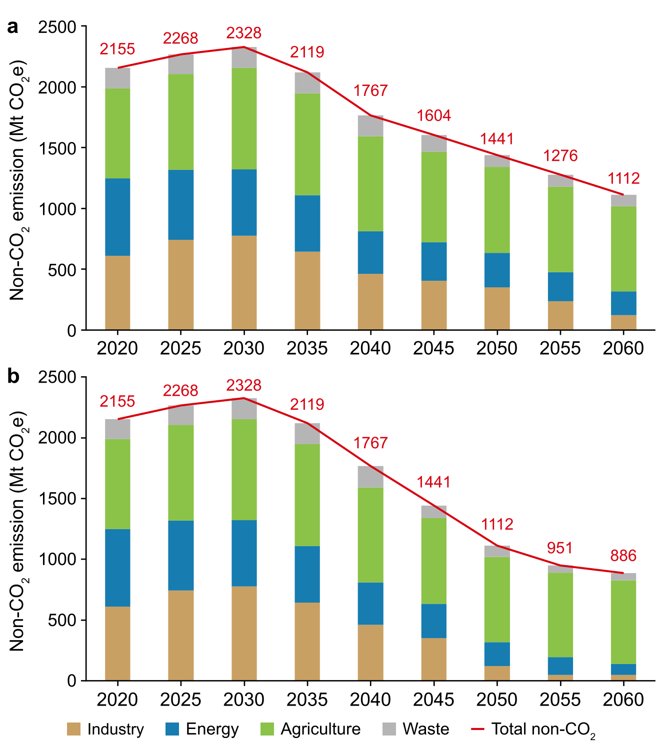

Fig. 5. Sectoral non-CO_2 emissions under the CO_2 and greenhouse gas (GHG) neutrality scenarios. **a**, CO_2 neutrality scenario. **b**, GHG neutrality scenario. Values above the bars indicate the total non-CO_2 emissions.

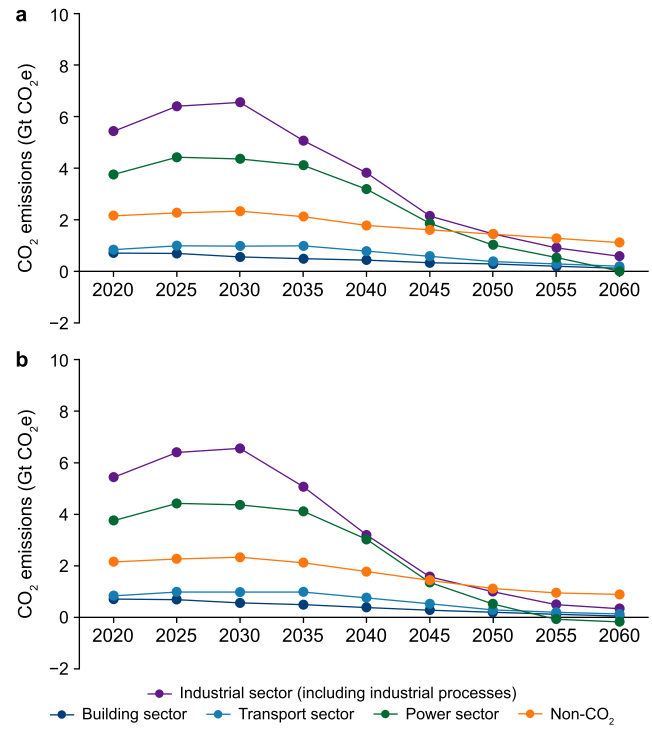

Fig. 6. Sectoral CO_2 and non-CO_2 emission trajectories under the CO_2 and greenhouse gas (GHG) neutrality scenarios. **a**, CO_2 neutrality scenario. **b**, GHG neutrality scenario. Sectoral emissions include only direct emissions and exclude indirect emissions from electricity and heat consumption.

3.4. Energy system transformation

Energy-related CO_2 emissions, including emissions from both the energy supply and end-use sectors, accounted for 77% of China's total GHG emissions (excluding land use, land-use change, and forestry) in 2021 [42]. In both scenarios, primary energy consumption is expected to peak at 7.5 billion tce in 2035 and then decline by approximately 20% by 2060 (Supplementary Table S2–S5). In the future, primary energy consumption will be dominated by clean electricity. By 2060, electricity demand is expected to reach 18,700 GW-hours (GWh), roughly 2.5 times the 2020 level. As the share of fossil fuels declines rapidly, non-fossil electricity is expected to be the backbone of primary energy consumption over the long term, reaching 29% by 2030, 39% by 2035, 75% by 2050, and 85% by 2060 under the GHG neutrality scenario (Supplementary Table S4).

Fossil fuel supply and consumption are expected to peak during the 15th FYP period (2025–2030), with a gradual decline thereafter. Coal will play a crucial role in securing energy supply in the short term and will account for peak consumption during the 15th FYP period, as its share of primary energy consumption is expected to decline to 46% by 2030, 39% by 2035, 12% by 2050, and well below 10% by 2060 under the GHG neutrality scenario. Oil consumption will peak during the 15th FYP period due to the rapid electrification of road and rail transport, with its share of primary energy consumption expected to fall to 15.5% by 2030, 6.3% by 2050, and 5% by 2060 under the GHG neutrality scenario. Natural gas consumption is expected to peak before 2040 and then gradually decline after 2045, reaching 4% by 2060 under the GHG neutrality scenario. Meanwhile, the significant use of coal, oil, and gas will transition from fuel to industrial feedstock.

The decarbonization of end-use sectors will be driven by

Table 3
Electrification rates of end-use sectors and electricity demand under the GHG-neutrality scenario.

Year	Electrification rate				Total electricity demand (gigawatt-hours)
	Industrial sector	Building sector	Transport sector	End-use sector	
2020	25.3%	42.4%	3.7%	25.1%	7500
2030	26.3%	56.3%	12.3%	29.5%	12,800
2035	31.0%	62.2%	16.9%	34.8%	15,500
2050	50.5%	80.6%	38.9%	57.6%	18,300
2060	54.9%	88.8%	43.7%	63.6%	18,700

electrification, with hydrogen and energy efficiency also key measures. In 2020, energy consumption in the end-use sectors was still dominated by direct fossil fuel use, accounting for 72% of total consumption, while electricity accounted for only 25% (Table 3). Electricity is expected to replace fossil fuels rapidly and dominate final energy consumption over the long term, reaching 30% by 2030, 57% by 2050, and 64% by 2060 under the GHG neutrality scenario. The building sector will have the highest share and the fastest pace of electrification, as electricity is an economic and reliable solution for most energy consumption needs, such as cooling, heating, cooking, and entertainment. Energy efficiency improvement (energy intensity) also needs to be maintained at a higher level than during the 14th FYP period, with an average annual rate of 2.6% by 2030, 3.7–4.5% by 2050, and 2% by 2060.

In the long term, the energy system will be highly integrated and primarily powered by electricity, with a mix of energy sources, including renewables, storage, hydrogen, nuclear, and a small share of fossil fuels (Fig. 7). Hydrogen and biomass are key energy carriers and clean feedstocks for aviation, shipping, and industrial uses, among others. Under the GHG neutrality scenario, the share of hydrogen and biomass is projected to rise from 5% in 2020 to 18% in 2050 and 23% in 2060. With trends in miniaturization, intelligence, and multifunctionality, nuclear power is expected to supply around 10% of primary energy by 2060. Furthermore, nuclear plants supply heating, generate steam, and produce green hydrogen with excess electricity.

3.5. Demand for carbon removal

In this study, carbon removals are mainly land-based, including 850–920 million tonnes CO_2e from forest carbon sinks, complemented by 1320–1920 million tonnes CO_2 of industrial removals by 2060. Carbon capture technologies are essential in both scenarios. Carbon capture, utilization, and storage (CCUS) technology should be widely deployed after 2030, with its CO_2 capture capacity expected to reach approximately 270 million tonnes by 2035. Under the GHG neutrality scenario, the carbon capture capacity is estimated to be approximately 1.5 billion tonnes of CO_2 in 2050 and 1.9 billion tonnes in 2060.

Carbon removal technologies will be used mainly in the power sector and in hard-to-abate sectors, which are well-suited to concentrated carbon capture. Under the GHG neutrality scenario, for the power sector, CCS is expected to capture 170 million tonnes of CO_2 from coal-fired plants by 2035 and 740 million tonnes from coal-fired plants, 170 million tonnes from gas-fired plants, and 270 million tonnes from biomass plants by 2060 (Fig. 8). For the industrial sector, carbon capture technology will gradually be applied across steel, cement, chemical, and other sectors, capturing 100 million tonnes of CO_2 by 2035 and 400 million tonnes by 2060. DACCS technologies will be scaled up significantly under the GHG neutrality scenario, with a capture capacity of 340 million tonnes of CO_2 in 2060.

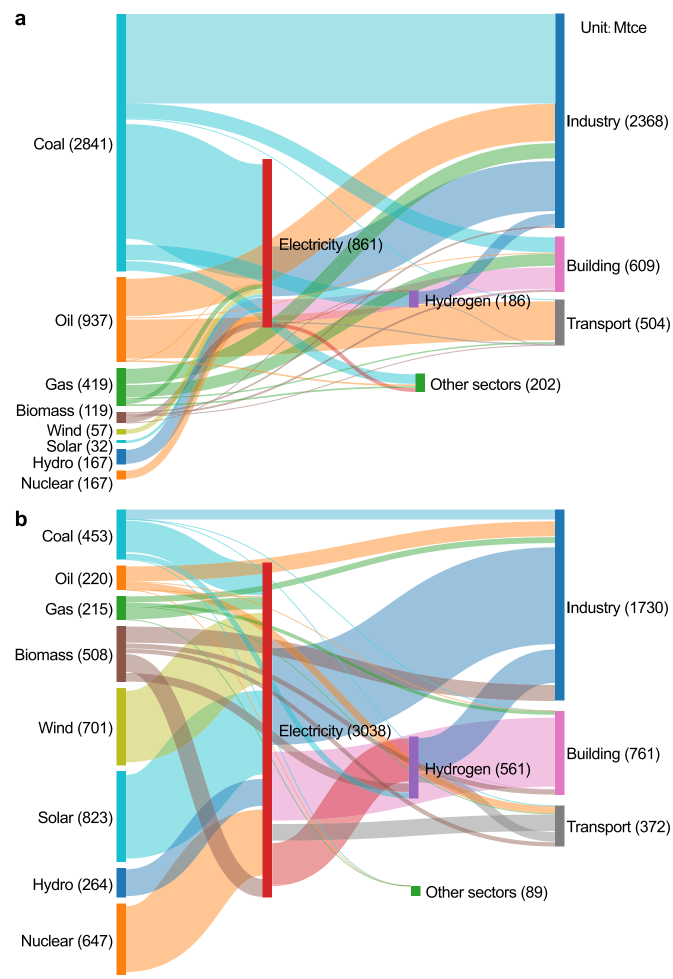

Fig. 7. Transformation of energy flows. **a**, Energy balance in 2020. **b**, Energy balance in 2060 under the greenhouse gas (GHG) neutrality scenario. Values in parentheses show the energy at each node (unit: Mtce), including primary energy supply (on the left), secondary energy converted from primary sources (electricity and hydrogen in the middle), and final consumption in end-use sectors (on the right). The links depict energy flows between sectors, with widths corresponding to their magnitudes.

3.6. From CO_2 neutrality to GHG neutrality: additional efforts

Achieving GHG neutrality by 2060 will require significantly greater sectoral emission reductions than those outlined under the CO_2 neutrality scenario (Supplementary Table S6–S7). Under the CO_2 neutrality scenario, approximately 0.89 billion tonnes of residual CO_2 will remain by 2060 (Fig. 9). However, under the GHG neutrality scenario, energy-related CO_2 emissions must reach net zero by 2060, which requires reducing an additional 245, 62, 65, and 175 Mt of CO_2 emissions from the industrial, building, transport, and power sectors, respectively. In addition, DACCS must

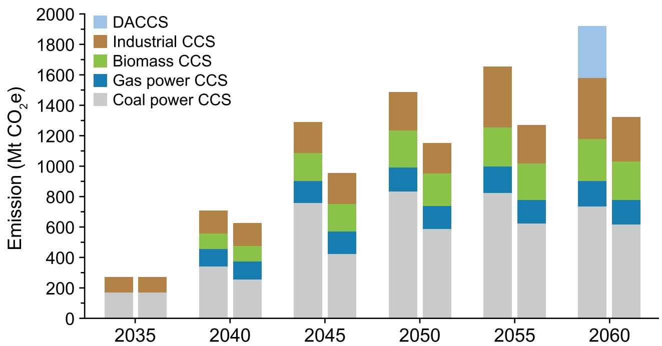

Fig. 8. Deployment of carbon capture and storage (CCS) and carbon dioxide removal technologies under the CO_2 and greenhouse gas (GHG) neutrality scenarios. For each year, the left bar shows the GHG-neutrality scenario, and the right bar shows the CO_2-neutrality scenario. DACCS: direct air carbon capture and storage.

capture 340 Mt of residual CO_2 emissions.

Additional efforts are evident in other indicators. On the energy supply side, the share of non-fossil fuels must rise from 82% to 85% when comparing the CO_2-neutrality scenario with the GHG-neutrality scenario. On the consumption side, the electrification rate needs to increase from 59% to 64% between the two scenarios, and there will be a greater need for residual emission reductions in end-use sectors. From a sectoral perspective, the power sector must reach net zero by 2055 under the GHG neutrality scenario, five years earlier than under the CO_2 neutrality scenario, and it will become a negative-emissions sector by 2060. Non-CO_2 emissions reduction efforts need to rise from 50% of the peaking level under the CO_2 neutrality scenario to 60% under the GHG neutrality scenario. Finally, an additional 510 Mt CO_2 (including 340 Mt CO_2 from DACCS) of carbon capture capacity is required by 2060 under the GHG neutrality scenario.

4. Discussion

This study uses a decarbonization target-driven approach for pathway simulation, maximizing technological potential while leaving hard-to-abate sectors for 2050 from a technoeconomic perspective. The technological assumptions are based on the current understanding of commercialized or emerging technologies without accounting for uncertainties surrounding disruptive technologies, such as DACCS. The technology cost curves are derived from general knowledge of past technologies or the existing literature, which may not capture abrupt changes in technology or the market, particularly technologies dominated by a single market. For instance, in China's domestic market, the share of new energy vehicles rose from 31.6% in 2023 to 45.3% in 2024, while the cost of power batteries fell by over 30% in 2024. With the rapid electrification of road transportation, oil consumption is expected to peak around 2025, approximately 3–5 years earlier than this study predicts.

In this study, uncertainty is considered separately within the sectoral models (electricity, industrial, transport, building, non-CO_2), which are based on the principle of cost optimization. Major sources of uncertainty include technological mixes and behavioral variables, such as transportation travel intensity and cooking demand. In the multimodel framework, the top–down approach and the bottom–up sectoral simulations are combined via a soft link. Due to the limitations of this method, the authors did not perform an uncertainty analysis of the final results. This is also a limitation of this method.

This study focuses on policy scenarios and pathways under favorable assumptions about international collaboration, which may not fully reflect future trends and complexities in a highly uncertain world and a rapidly changing China. For example, recent studies have sought to quantify the spillovers of escalating geopolitical fragmentation [43–45]. Domestically, this translates into heightened energy security priorities, slower GDP growth, supply-chain constraints, higher technology costs, reduced oil and gas imports, prolonged reliance on coal, and greater reliance on CCUS and resource recycling [16–18]. One study suggested that the deployment scale of CCUS would reach 2.5 billion tonnes by 2060 [16]. Meanwhile, new digital infrastructure, such as data centers and EV charging, has become a major source of uncertainty about energy demand. Recent studies have suggested that the digital infrastructure's electricity demand by 2060 may reach 10% of total electricity consumption, thereby pushing total electricity demand to 20,000–22,600 GWh, which is significantly higher than assumed by this study [16,18]. This uncertainty underscores the importance of demand-side efforts and the optimization of flexibility alongside supply-side clean energy expansion [46].

5. Conclusion and policy implications

This study explored China's transition pathway and policies after 2030 by comparing CO_2 neutrality with GHG neutrality. The findings indicate that achieving GHG neutrality by 2060 requires much deeper emissions reductions than achieving CO_2 neutrality alone. Specifically, compared with CO_2 neutrality, GHG neutrality by 2060 requires increasing energy-related CO_2 reductions from 92% to 100%, lowering non-CO_2 emissions from 50% to 60%, and expanding the demand for carbon capture from 1.3 to 1.9 Gt CO_2. In addition, achieving net zero energy-related CO_2 emissions by 2060 requires substantial cross-sector efforts, with further reductions of 245, 62, 65, and 175 Mt in the industrial, building, transport, and power sectors, respectively. Moreover, DACCS needs to sequester 340 Mt of residual CO_2 emissions.

This study also provides a comprehensive vision beyond 2030. To achieve GHG neutrality, China must peak CO_2 emissions before 2030, reduce GHG emissions by 15% before 2035, cut GHG emissions by 85% by 2050 compared with 2030, and reach GHG neutrality by 2060. Electrification will be the primary approach to decarbonizing end-use sectors, resulting in a steady increase in electricity demand through 2060, which is expected to be 2.5 times higher than in 2020. Therefore, the power sector is projected to be the last sector to reach carbon peaking and achieve carbon

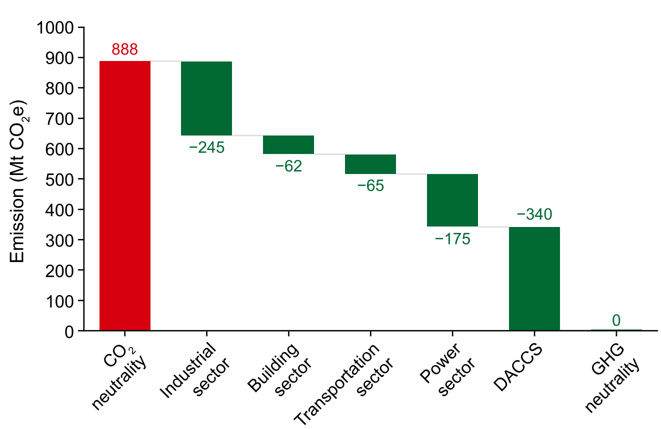

Fig. 9. Additional sectoral efforts in energy-related CO_2 emissions from CO_2 neutrality to greenhouse gas (GHG) neutrality. The first and last bars represent total emissions in the CO_2 and GHG neutrality scenarios, while the second through sixth bars show the incremental emission reductions requested for each sector.

neutrality by 2055, approximately 20 years later than the target set by many developed countries. In addition, specific attention needs to be paid to areas where deep emission reductions are difficult to achieve, to crucial technologies such as CCS and hydrogen, to the circular economy, and to guidance on low-carbon lifestyles across society.

Developing a medium-term climate strategy for 2035 is crucial to bridging the phases of carbon peaking and achieving carbon neutrality. This strategy should steer the economy and society toward GHG neutrality by setting emissions-reduction targets and a roadmap, defining sector-specific objectives and actions, and coordinating efforts across key decarbonization technologies. It should promote a circular economy and a low-carbon society while ensuring that the strategy's timelines and goals align with China's broader development and environmental policies. Moreover, the strategy needs to connect the domestic strategy with global climate governance. Beyond climate mitigation, it should address climate adaptation, risks, resilience, and justice, drawing on insights from economics, society, industry, technology, resources, geopolitics, and other relevant fields.

CRediT authorship contribution statement

Ershun Du: Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Wenjuan Dong:** Writing – original draft, Formal analysis, Conceptualization. **Zheng Li:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Jiankun He:** Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Xiu Yang:** Writing – review & editing, Resources, Project administration, Investigation. **Weirong Zhang:** Writing – review & editing, Supervision, Software, Formal analysis, Data curation. **Hailin Wang:** Validation, Software, Methodology, Formal analysis, Data curation. **Tianduo Peng:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation. **Shiyan Chang:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation. **Qing Tong:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation. **Bin Hu:** Writing – review & editing, Validation, Formal analysis, Data curation. **Alun Gu:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation. **Xunmin Ou:** Validation, Software, Methodology, Formal analysis, Data curation. **Yujuan Fang:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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