RESEARCH ARTICLE

Can China achieve its climate pledge: a multi-scenario simulation of China’s energy-related CO₂ emission pathways based on Kaya identity

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Abstract
China is currently in the process of the middle and late stage of industrialization, and energy-related CO₂ emissions have reached 10 Gt. This paper models energy consumption and related CO₂ emissions and analyzes the development trends of various driving factors of CO₂ emissions, explicitly considering China’s economic and social development goals in the medium- and long-term. Different scenarios for 2020–2060 are projected based on the Kaya identity. Energy consumption will peak at 6,200 Mtce in 2035 in the BAU scenario with the energy-related CO₂ emissions peaking at 11.1 Gt in 2026–2027 advanced by the rising non-fossil energy share, while energy consumption and CO₂ emissions in the accelerated transition scenario would be potentially reduced by 300 Mtce and 300–400 Mt respectively. In the BAU scenario, the net CO₂ emissions will remain around 2,000 Mt in 2060, after removing 1,800 Mt by CCS/CCUS, indicating that China needs to enhance its post-2030 policy to deliver the carbon neutrality pledge. Steady energy efficiency improvement, radical industrial and energy restructuring are three key driving forces for carbon neutrality.

Keywords Energy consumption · Carbon neutrality · Carbon dioxide peaking · Mitigation scenarios · Kaya identity

Introduction
The reform and opening-up policy and the boom of heavy industry have accelerated China’s economic growth, while also promoting increased energy consumption (Lin et al. 2016). In 2019 (Fig. 1), China’s total primary energy consumption reached 4,875 million tonne coal equivalent (Mtce), accounting for 24.3% of the world, with an average annual growth rate of 6.4% as of 2002 (National Bureau of Statistics 2021). There are two main sources of CO₂ emissions, energy consumption and industrial processes, with the former producing far more CO₂ than the latter (National Development and Reform Commission 2021) (Fig. 2). As a major consumer of primary energy, China is also the main driver for increasing CO₂ emissions worldwide: in 2020, China’s energy consumption generated 9,899 Mt CO₂ emissions, accounting for 30.7% of global CO₂ emissions. The CO₂ produced by burning much fossil energy has accelerated the process of global warming, posing a serious threat to global climate security. For contributing to global climate governance and sustainable development, China must propose a practical and effective Chinese pathway to address the climate issues (Yuan et al. 2014b).

The signing of the Paris Agreement has led China to pay high attention to the environmental and ecological impact of energy consumption and CO₂ emissions. Since the 11th Five-Year Plan (FYP), China has released several national determined contributions (NDC) targets to promote the process of energy conservation and emission reduction: 20% reduction of energy intensity of the economy during 2005–2010, 40–45% reduction of GDP CO₂ intensity during 2005–2020, and a 15% non-fossil energy share target by 2020 (State Council of China 2006). Statistics from previous years show that these goals have been achieved ahead of schedule (Goldman 2021; National Bureau of Statistics 2021). In September 2020, China announced that it would strive to
reach peak CO₂ emissions by 2030 and carbon neutrality by 2060 (State Council of China 2020a). To successfully achieve them, China has adopted stronger policies and measures since the 14th FYP, which proposed the updated NDC target that increases the proportion of non-fossil energy to 25% by 2030 and over 65% reduction of CO₂ intensity for GDP growth during 2005–2030.

The environmental Kuznets curve (EKC) shows an approximately inverted “U” curve between per capita CO₂ emissions and per capita GDP (Grossman and Krueger 1991). To test the EKC hypothesis, many scholars investigated whether there is an inflection point in the curve of per capita CO₂ emissions vs. per capita GDP in various countries. Richmond and Kaufmann (2006) found limited evidence for the existence of EKC in OECD countries, but for other countries, GDP and CO₂ emissions are still significantly positively correlated. Although the EKC has been confirmed in some developing countries, Gill et al. (2018) argued that deteriorating global environment cannot wait for the EKC inflection point if developing countries keep following the EKC curve. Developing countries should be proactive in addressing environmental issues by releasing policies to promote the use of renewable energy, which is also the starting point of China’s climate pledge.

For China, studies have confirmed the existence of the EKC hypothesis (Ibanez et al. 2019; Tenaw and Beyene 2021). According to Xu and Song (2010), there is a positive “U” curve between per capita GDP and per capita CO₂ emissions in the western region of China, while there is an inverted “U” curve in the whole country and its eastern and central regions, but industrial structure and energy structure may affect the position and shape of the curve in the short term. Thus, Xia and Wang (2020) considered the impact of energy consumption intensity and energy structure and found that EKC exists in China when considering structural mutation and the process of industrialization and economic growth have a significant positive effect on CO₂ emissions.

To sum up, EKC can be detected in China, but traditional EKC cannot accurately describe China’s CO₂ emissions and some additional factors are essential to model CO₂ emissions (Lin and Jiang 2009). Accurate CO₂ emissions projections can help assess the emission reduction process and formulate timely policies. Table 1 is a brief overview of literature on China’s CO₂ emissions.

Although China’s energy conservation and emission reduction efforts have been quite effective over the past decades, China still emitted nearly 10 Gt energy-related CO₂ emissions in 2020, and its inflection point of the EKC has not yet arrived (Riti et al. 2017). Existing literature have revealed future trends for China’s CO₂ emissions that will grow slowly to a peak and then gradually decline, the timing and the height of the peak differ (Xiao et al. 2021; Zhou
| Ref.         | Methodology                                                                 | Findings                                                                 | Comment                                                                                      |
|-------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Yue et al. (2010) | Used the Kaya identity based on the projection of China's GDP and GDP CO₂ emission intensity in 2050. | CO₂ emissions reach 2.4–3.3 Gt in 2050.                                  | The proportion of different energy types in energy demand is not taken into account. The forecast accuracy is low. |
| Dai et al. (2010) | Designed different energy demand and carbon emission scenarios based on IPAC model and CGE model. | Without strong climate policies, China’s CO₂ emissions will continue to increase to 12.2 Gt in 2050. | The simulation of energy use focuses on the power generation sector. And it does not explicitly model changes in the energy mix. |
| Ge et al. (2018) | Constructed a sub-sectoral refinement model using the Kaya identity. | In the BAU scenario, China’s CO₂ emissions will reach a peak at 14,134±906 Mt in 2040. If China’s NDC targets are considered, its CO₂ emissions will reach a peak at around 11,277±643 Mt in 2030. | The analysis focuses on the impact of energy intensity on CO₂ emissions by sector. And it does not consider the impact of urbanization and income. |
| Xu et al. (2020) | Proposed three energy consumption trends and a simple decomposition model that decomposed energy consumption into its quantity and structure to predict CO₂ emissions. | CO₂ emissions will not peak in the BAU scenario and they will peak at 10.69 Gt in 2030 in the planned energy structure scenario. In the low-carbon energy structure scenario, the peak will occur in 2025 at the value of 10.37 Gt. | Only energy consumption and energy share are considered. Neither industrial structure nor residential life is taken into account. |
| Cai et al. (2021) | Used a combination of top-down and bottom-up approaches to build China’s carbon emission pathway under the carbon neutrality target. | China’s CO₂ emissions will reach a peak of 10.6 Gt around 2027, and they will be 10.5 Gt in 2030 after a plateau period of 5 to 7 years. | The scenario is singular. Factors relevant to residents’ life are not taken into account. |
| Zhou et al. (2021) | Used the energy-economics-emission module in GCAM and set three future emissions scenarios: an NDC scenario, a 2 °C temperature rise target scenario, and a 1.5 °C temperature rise target scenario. | By 2030, under the NDC, T20, and T15 scenarios, the CO₂ emissions are projected to be 10.53, 9.51, and 7.69 GtCO₂. By 2050, they are predicted to be 9.45, 6.31, and 0.81 GtCO₂. By 2100, they are projected to be 4.91, −1.78, and −1.92 GtCO₂. | Converting energy consumption demand using 2015 as the base year does not reflect updated policies impact on the development trend of the relevant parameters. |
et al. 2021). In addition, the successful implementation of the carbon peaking and carbon neutrality targets needs to be assessed in the context of China’s changing policy dynamics. The interest of this study is as follows: how factors such as population, economy, energy mix, industrial structure, industrial energy intensity, urbanization, and residential life will evolve under the guidance of China’s recently declared social-economic policies and NDC targets; how the energy-related CO₂ emissions will change; whether China is on the track of its climate pledge; and what are the focus factors for achieving the carbon neutrality target.

More drivers can be taken into account when combining the Kaya identity with scenario simulations to calculate CO₂ emissions. At the same time, reasonable scenario simulations can effectively reflect the impact of policies and targets on social development and help to accurately assess the potential for achieving carbon dioxide peaking and carbon neutrality targets driven by existing policies.

The Kaya identity and scenario simulations have been employed in selected literature to study China’s CO₂ emissions, but most existing literature only analyzed historical data to test the drivers of CO₂ emissions in the past (Chen et al. 2018; Ma et al. 2021; Steckel et al. 2011). In contrast, Yuan et al. (2014a) proposed to project China’s energy consumption and CO₂ emissions up to 2050, focusing on the international comparative analysis to examine whether the path of China’s economy and CO₂ emissions fits with that of developed countries. In addition, some literature have narrowed the study from the national level to a particular industry, and used the Kaya identity and scenario simulations to investigate the impact of drivers on future peak CO₂ emissions from the industry (Huo et al. 2021) or to assess the reduction potential of CO₂ emissions in the industry (Lin and Tan 2017), but their studies are not comprehensive to consider the drivers of CO₂ emissions.

The contribution of this paper is 3-fold. First, this paper focuses on the projection of CO₂ emissions within the time horizon of the carbon neutrality target, taking into account a number of newly released social-economic policies and targets. Second, it is more comprehensive than previous studies in that it takes into account a variety of drivers covering the economy, population, energy, production, and residential life when decomposing CO₂ emissions using the Kaya identity. Third, it uses the LMDI method to analyze the prediction results and test the factors that have the greatest impact on achieving the carbon neutrality target, which helps to formulate reasonable policies to promote the achievement of the carbon neutrality target. The remainder of this paper is organized as follows. The “Methodology” section introduces the research methodology. The “Driving factors of energy-related CO₂ emissions in China” section presents the historical trajectory of driving factors and sets assumptions for the scenarios. The “Scenario results” section reports the results. The “Conclusion and policy implications” section concludes the paper with policy implications.

Methodology and data

Kaya identity

In this paper, we use the Kaya identity equation for calculating CO₂ emissions. The Kaya identity takes into account four factors to calculate total carbon emissions: population, GDP per capita, energy use per unit of GDP, and carbon emissions per unit of consumed energy. To accurately predict energy use, we make a difference between use for production and use in household. The main influencing factors for production energy use are energy intensity and industry structure, while the main influencing factors for residential energy use are residential income and urbanization. With the advancement of the urbanisation process, the proportion of residential energy consumption would be gradually increasing. At the same time, it is essential to decompose the energy consumption of production to express the impact of industrial restructuring and energy efficiency improvement. Hence, we adapt the equation as follows:

\[
T_E = GDP \times \frac{E_P}{GDP} + gdp \times \frac{ER}{gdp}
\]  

(1)

Where \(E_P\) is production energy consumption and \(E_R\) is residential energy consumption, \(gdp\) indicates GDP per capita.

\[
\frac{E_P}{GDP} = \sum SiEi
\]  

(2)

The primary energy used for production can be expressed as the sum of GDP, products of all output shares in the economic structure \(S_i\) (primary, secondary, tertiary), and their energy intensities \(EI_i\).

\[
\frac{ER}{gdp} = \frac{eU}{IU} \times \frac{IU}{gdp} \times P \times RU + \frac{eR}{IR} \times \frac{IR}{gdp} \times P \times (1 - RU)
\]  

(3)

The calculation of residential energy consumption is further composed of two parts, urban and rural energy consumption. We choose urbanization \(R_U\) and total population \(P\) to express the differences of the urban and rural population. Residential consumption, of which energy consumption is an important part, is subject to the status of rural disposable per capita income \((I_d)\) and urban disposable per capita income \((I_R)\)—for example, in cities with high per capita income levels, household energy consumption is dominated by electricity and natural gas, while in the countryside, the main source of energy consumption is still coal (Liu et al. 2015)—so we
add them as an intermediate variable between per capita GDP and residential energy consumption per capita to reflect the effect of income on per capita urban energy consumption ($e_u$) and rural energy consumption ($e_r$).

$$C = TEC \times \sum (E_{i,f})$$

(4)

Carbon emission factors of fuel and their shares in primary energy consumption can be expressed by $e_f$ and $E_i$. Based on Eq. (4), we can calculate the total carbon emissions ($C$) under different energy development pathways (Yuan et al. 2014a).

Scenario simulation

Before calculating CO$_2$ emissions with the Kaya identity, we construct alternative scenarios to simulate the trends of eight CO$_2$ emission drivers. By combining existing policies and NDC targets, the pathways of these drivers and their impact on CO$_2$ emissions are assessed. Table 2 describes the different scenarios for each driver in detail.

Data sources

The datasets used and/or analyzed during this study are collected from the China Statistical Yearbook, including population, GDP, industrial structure, industry and household energy consumption, urbanization rate, resident income, and energy mix over the period 2000–2020 (National Bureau of Statistics 2021). The time horizon for scenario projection is set at 2021–2060 with 5 years as a projection step, considering China’s FYP policy cycle. All the modeling work is conducted with Microsoft Office Excel.

Driving factors of energy-related CO$_2$ emissions in China

Population

Population of China during 2000–2020

The total population of China was 1,267 million in 2000 and grew to 1,412 million in 2020, with a net growth rate of 11.4%, while its growth rate has gradually slowed down. China’s rate of natural increase was 7.58‰ in 2000, but fell to 3.32‰ in 2019. In 2020, affected by the COVID-19 epidemic, it dropped to an all-time low of 1.45‰ (Fig. 3). The factor contributing to the decline in growth rate is the persistently low total fertility rate. Even though China proposed the “universal two-child” policy in 2015 to stimulate fertility, the pull effect of it on total population has not achieved the expected effect from the data so far in 2017. Since 2017, the total number of annual neonates in China has continued to decline, which in 2020 hit a record low of 10.04 million. The accumulation of compensatory fertility from the “two-child” policy has been released, and there is a clear lack of momentum in the growth of China’s population.

Projection of total population in China during 2021–2060

The fertility willingness of fertile women is gradually declining due to changes in marriage views and family patterns and inadequate policies to support childbearing in China, which is reflected in the process of the “universal two-child” policy. Studies to project population of China (Energy Transitions commission 2020; STC (State Information Center) 2021) generally agree that China’s population will continue to grow at a lower rate in the short term under the current fertility level, which will experience negative population growth after reaching a peak of 1.420–1.450 million between 2025 and 2030, and decrease to 1,350–1,400 million in 2050. With the implementation of the “three-child” policy in 2021 and enhancement of the fertility policy, the fertility rate may rebound; however, the effect is only to delay the peak year by a few years and slightly increase the peak population, which does not fundamentally reverse the trend of negative population growth in China in the future. According to the National Population Development Plan (2016–2035) (State Council of China 2017), combined with findings of researches, we expect China’s population to gradually decline after peaking at about 1,450 million around 2030, and be 1,330 million in 2060 (Fig. 4).

GDP growth in China, 2000–2020

China’s GDP was 2.23 trillion US$ in 2000, and by 2020, it reached 11.83 trillion US$ (in 2010 constant price), with an average annual growth rate of 7.20%. Up to 2007, China’s GDP growth rate had shown a trend of year-on-year increase. In 2008, due to the impact of the global financial crisis, China’s GDP growth rate had a large decline; however, as the effects of the economic crisis receded, it rebounded slightly in 2010. After 2010, the GDP growth rate began to decrease year by year, which had fallen from 10.64% in 2010 to 6.11% in 2019. The outbreak of the COVID-19 epidemic led to a worldwide shutdown of economy in 2020; although China was the only economic entity with positive growth worldwide, its growth rate is well below the level in previous years (Fig. 5). While China’s GDP growth rate has declined, it is still higher than developed countries, and there is plenty of room for GDP growth in the future.
Projection of GDP growth in China, 2021–2060

China’s economy is shifting from high-speed development to high-quality development. It is generally accepted by national and international research institutions (Asian Development Bank 2021; IMF(International Monetary Fund) 2021; OECD(Organisation for Economic Co-operation and Development) 2020) that while China’s GDP will grow in the future, the growth rate will decline in a wavy pattern due to the increase in the amount of new capital required to the unit of output as a result of technological progress and the decrease in the efficiency of investment. Decline in population growth rate and aging society will also lead to a lack of growth momentum in the economy. With the restoration of social activities in the post-COVID-19 era, the GDP growth rate of China will increase significantly in 2021 and return to pre-epidemic levels during the 14th FYP. By quantifying China’s development goal of basically realizing socialist modernization by 2035, and taking into account the experience

| Driver                | Scenario          | Description                                                                 |
|-----------------------|-------------------|-----------------------------------------------------------------------------|
| Population            | Baseline          | Based on the National Population Development Plan (2016–2035), scenario simulation is conducted in conjunction with the results of existing researches, considering only one scenario. |
| GDP                   | Baseline          | Since there is a clear target for the development of China’s economy, we assume only one development scenario for GDP, which is simulated by quantifying China’s development target of basically realizing socialist modernization by 2035, combining the experience of developed countries and the results of relevant researches. |
| Industrial structure  | Baseline          | It is an extension of the existing trend of industrial restructuring considering China’s updated NDC targets. Researches from Energy Transitions commission and World Resources Institute China are used for the simulation. |
|                       | Acceleration      | China’s transition to a service economy will occur at a faster pace than the trend under NDC targets. |
| Energy Intensity      | Baseline          | The baseline scenario is the energy intensity reduction trend that meets updated NDC targets. |
|                       | Acceleration      | The acceleration scenario fully considers that China will achieve new NDC targets ahead of schedule, as it did in the past decade, with a greater decrease in energy intensity. |
| Urbanization          | Low speed         | Urbanization is slower than the plan. |
|                       | Baseline          | Assume that the urbanization process is in line with the projections of State Council of China and DESA, meets the development targets of the 14th FYP, and continues to extend on this basis. |
|                       | High speed        | Socio-economic development lead to further increase in labor force and urbanization is happening faster than the plan. |
| Resident income       | Low speed         | Resident income growth below expected targets. |
|                       | Baseline          | Considering the implementation of China’s rural revitalization strategy, assumption is made by combining the experience of high-income countries and the historical trend of China. |
|                       | High speed        | With the accelerated promotion of the rural revitalization strategy and the rapid development of the economy, the growth rate of resident income will further increase. |
| Household energy consumption | Baseline | Considering the development targets of China, we assume that China’s per capita household energy consumption in rural still has much room for growth in the short term, while urban energy consumption will gradually reduce with the further increase in the terminal electrification rate. |
|                       | Acceleration      | An acceleration scenario is provided for comparative analysis which takes into account the implementation of various energy conservation policies. |
| Energy consumption    | Business as usual (BAU) | The baseline scenario is a reflection of Chinese government’s plans, and the 25% NDC target is set as the share of non-fossil energy in the baseline scenario by 2030. |
|                       | Low-carbon (LC)   | The low-carbon scenario considers that new NDC targets will be achieved ahead of schedule, and China will promote a higher share of renewables than baseline through more effective policy support. |
of developed countries, we assume a GDP growth rate of 8.2% in China in 2021; an average annual GDP growth rate of 6.3% in 2022–2025, 5.2% in 2026–2030, and 4% in 2031–2035; and GDP per capita will reach 22,000 US$ by 2035; hence, the core goal of doubling GDP compared to 2020 will be achieved. In 2036–2040, the average annual GDP growth rate will be 3.5%, 3.3% in 2041–2045, 3% in 2046–2050, 2.5% in 2051–2055, and 2% in 2056–2060. Under this scenario, China’s GDP is projected to be $51.83 trillion in 2060, and per capita GDP will reach 39,000 US$, which is 4.8 times the per capita GDP of 8,182 US$ in 2019, in line with the development trend in China (Fig. 6).

**Industrial structure**

**Evolution of China’s industrial structure, 2000–2020**

We plotted the evolution of China’s industrial structure from 2000-2020 (Fig. 7). The share of primary industry decreased year by year, from 14.68% in 2000 to 7.65% in 2020. The share of secondary industry also showed a declining trend, which declined from 45.54% in 2000 to 37.82% in 2020, and its leading position in the economic structure has gradually been replaced by tertiary industry. Transforming development pattern requires radical economic restructuring. The prosperous development of China’s economy in the past
Fig. 5. GDP and its growth in China, 2000–2020

Fig. 6. Projection of GDP in China, 2021–2060

Fig. 7. Industrial structure in China, 2000–2020
decades relied on secondary industry as support, while the tertiary industry will be the most important driver of China’s economic growth in the future. Since 2012, tertiary industry has become the leader of China’s economy, and it has maintained a high growth rate trend, with the share increasing from 39.79% in 2000 to 54.53% by 2020.

**Projection of China’s industrial structure, 2021–2060**

According to World Bank, in the industrial structure of the USA, Britain, and other developed countries in 2019, primary industry generally accounted for less than 1%, tertiary industry accounted for 70–75%, while secondary industry accounted for only about 20%. China is in a transition from the middle to the late stage of industrialization. It is expected that with industrial restructuring, the proportion of secondary industry will decline; at the same time, taking into account Chinese national conditions, to continuously maintain economic development for such a large economic entity, China still needs part of secondary industry as a support. Therefore, based on the experience of the developed countries, which are in the late stage of industrialization, and combined with relevant researches (Energy Transitions commission 2020; World Resources Institute China 2020), two development scenarios are provided in Table 3.

### Energy intensity

**Change of energy intensity in China, 2009–2018**

China has been working for the past few years to reduce energy intensity to address growing environmental concerns. Energy intensity is steadily decreasing in China, driven by the target of 16% reduction in energy intensity by 2015 compared to 2010, which is proposed in the 12th FYP. Over the past 40 years, China’s energy intensity has decreased by an average of more than 4% per year, a cumulative reduction of nearly 84%, with significant results in energy conservation, and a rapid enhancement in energy efficiency. The data from 2009 to 2018 show that secondary industry, which consumed

| Year | Primary industry | Secondary industry | Tertiary industry |
|------|------------------|--------------------|-------------------|
|      | Baseline | Acceleration | Baseline | Acceleration | Baseline | Acceleration |
| 2020 | 7.65%    | 37.82%      | 54.53%   |             |           |             |
| 2025 | 6.50%    | 35.00%      | 57.70%   | 60.70%      | 62.50%    |             |
| 2030 | 5.50%    | 33.80%      | 60.70%   | 63.70%      | 66.00%    |             |
| 2035 | 5.00%    | 31.30%      | 63.70%   | 66.00%      | 69.00%    |             |
| 2040 | 4.70%    | 29.00%      | 66.30%   | 69.00%      | 69.00%    |             |
| 2045 | 4.40%    | 27.00%      | 68.60%   | 72.00%      | 72.00%    |             |
| 2050 | 4.10%    | 25.50%      | 70.40%   | 74.90%      | 77.70%    |             |
| 2055 | 3.80%    | 24.00%      | 72.20%   | 77.70%      | 77.70%    |             |
| 2060 | 3.50%    | 23.00%      | 73.50%   | 80.00%      |           |             |

**Fig. 8.** Industry energy consumption in China, 2009–2018
the most energy during the production process, reduced its share in primary energy consumption year by year (Fig. 8), and the energy intensity of secondary industry has decreased from 0.16 to 0.09 kgce/RMB in the past ten years.

**Projection of energy intensity for China, 2019–2060**

According to international comparison, China’s energy intensity is still 1.5 times that of the world average, and might have a lot further to decrease. With the advancement of China’s energy revolution, secondary industry will see a wide range of energy transition such as replacing coal and gas with electricity. The shrinkage of energy-intensive heavy industry and the rise of high-technology industry will make the energy intensity of second industry continue to decline, but the room is limited. Meanwhile, the development goals of the 14th FYP mentioned that energy consumption per unit of GDP will be lowered by 13.5% from the 2020 level, and in 2030 will be lowered by 30% (State Council of China, 2021). We use the above development goals as the basis for our assumptions about the average annual rate of reduction in energy intensity based on the pace of previous adjustments. This study provides two scenarios that consider the effectiveness of energy efficiency policies and the industry structure transition. The outbreak of the COVID-19 epidemic leads to empty load operations in many industries. By analyzing the data, there is no significant decrease in energy intensity between 2020 and 2019, so we assume that the energy intensity of each industry in 2020 is the same as in 2019 (Table 4).

**Urbanization**

**China’s urbanization during 2000–2019**

China’s urbanization rate has been increasing since 2000, with growing from 36.22% in 2000 to 60.60% in 2019. China’s urban population overtook the rural population in 2011,

### Table 4 Projection of energy intensity improvement in China, 2019–2060

| Period       | Annual decrease rate of PI Baseline | Annual decrease rate of PI Acceleration | Annual decrease rate of SI Baseline | Annual decrease rate of SI Acceleration | Annual decrease rate of TI Baseline | Annual decrease rate of TI Acceleration |
|--------------|-------------------------------------|----------------------------------------|------------------------------------|----------------------------------------|------------------------------------|----------------------------------------|
| 2014–2018    | 1.36%                               | 3.79%                                  | 4.08%                             |                                        |                                    |                                        |
| 2019         | 0.00%                               | 1.00%                                  | 3.50%                             | 3.70%                                  | 3.70%                             | 4.00%                                  |
| 2020         | -                                   | -                                      | -                                 | -                                      | -                                 | -                                      |
| 2021–2025    | 0.00%                               | 1.00%                                  | 3.30%                             | 3.50%                                  | 3.50%                             | 3.80%                                  |
| 2026–2030    | 0.00%                               | 1.00%                                  | 3.00%                             | 3.20%                                  | 3.20%                             | 3.50%                                  |
| 2031–2035    | 0.00%                               | 1.00%                                  | 3.00%                             | 3.20%                                  | 3.20%                             | 3.50%                                  |
| 2036–2040    | 0.00%                               | 1.00%                                  | 2.80%                             | 3.00%                                  | 3.20%                             | 3.50%                                  |
| 2041–2045    | 0.00%                               | 1.00%                                  | 2.80%                             | 3.00%                                  | 3.20%                             | 3.50%                                  |
| 2046–2050    | 0.00%                               | 1.00%                                  | 2.60%                             | 2.80%                                  | 3.20%                             | 3.50%                                  |
| 2051–2055    | 0.00%                               | 1.00%                                  | 2.60%                             | 2.80%                                  | 3.20%                             | 3.50%                                  |
| 2056–2060    | 0.00%                               | 1.00%                                  | 2.40%                             | 2.60%                                  | 3.20%                             | 3.50%                                  |

Fig. 9. Urbanization in China, 2000–2019
indicating that China's urbanization process has reached the medium and later stage (Fig. 9).

**Projection of China's urbanization rate, 2020–2060**

The phase regular pattern of urbanization reveals its process from slow development in the early stage to rapid development in the middle stage and then to slow development in the later stage (Wang et al. 2020). China is currently in the rapid development stage of urbanization rate of 30–70%. As urbanization enters the later stage, its growth rate will continue to slow down and then stabilize. The 14th FYP sets the development target of reaching a 65% urbanization rate in 2025. National Population Development Plan (2016–2035) (State Council of China 2016) estimated that the urbanization rate of China’s resident population will reach 70% in 2030, and United Nations Department of Economic and Social Affairs (DESA) (2013) predicted that China’s urbanization rate will reach 71% in 2030 and 80% in 2050. According to the above projections and the changes in China’s urbanization rate over the past decades, we propose three scenarios in Table 5: the low-speed scenario, the baseline scenario, and the high-speed scenario.

**Resident income**

**Change of resident income in China, 2013–2020**

From 2013 to 2020, the per capita residential income of urban increased 1.66 times from 26,467 to 43,834 RMB, and the rural resident income increased from 9,430 to 17,131 RMB, an increase of 1.82 times. The urban-rural income gap has been reduced from 2.81:1 in 2013 to 2.56:1 in 2020, which indicates that the gap between urban and rural income is narrowing along with GDP growth in China (Fig. 10).

**Projection of resident income in China, 2021–2060**

To describe the growth of per capita residential income, we define the income elasticity coefficient for forecasting. The income elasticity coefficient is equal to the ratio of change in per capita residential income related to change per capita GDP. The income elasticity coefficient approaches 1 when the per capita Gross National Income (GNI) reaches a critical point of the high-income group and will continue to decline as income grows further. According to the standard from World Bank, per capita GNI higher than 12,535 USD is considered a high-income level, and per capita GNI of China is 10,343.6 USD in 2020, which is approaching the critical point of the high-income group. Meanwhile, the implementation of China’s rural revitalization strategy will narrow the urban-rural income gap, and the growth rate of rural residential income will be higher than urban. Therefore, we propose three development scenarios to report annual average
elasticity coefficients for urban and rural residential income at 5-year intervals based on the experience of developed countries and the past trend in China: low-speed scenario, baseline scenario, and high-speed scenario (Table 6).

**Household energy consumption**

**Change in household energy consumption in China, 2000–2016**

Along with economy and income growth, household energy consumption has grown in China, as reflected in data from 2009 to 2016 (Fig. 11): the share of household energy consumption in total primary energy consumption in 2009 was 10.46%, which grew to 12.81% in 2016. Due to the difference in per capita residential income, per capita energy consumption in urban households was always higher than rural households from 2009 to 2016, but the gap was decreasing. In the urban household, the per capita energy consumption grows slowly because the consumption concept of high-income groups is changing and low-carbon lifestyle is more in line with the national development trend. However, in the rural, the transformation of the consumption concept has not started, and the further increase of residential income will increase the household energy consumption, which will soon exceed the level of per capita household energy consumption in urban.

**Projection of household energy consumption in China, 2017–2060**

We define the energy consumption elasticity coefficient, which is the ratio of per capita energy consumption growth to per capita GDP growth, to make assumptions about energy consumption in urban and rural household, and we use data of Beijing, which is the relatively developed region in China, as a reference (Pang 2020). The urban and rural per capita residential income in Beijing in 2019 is 73,849 RMB and 28,928 RMB, and the per capita household energy consumption in the same period is 775.5 kg

### Table 6: Projection of income elasticity coefficients in China, 2021–2060

| Period         | Urban income elasticity coefficient | Rural income elasticity coefficient |
|---------------|------------------------------------|-----------------------------------|
|               | Low speed | Baseline | High speed | Low speed | Baseline | High speed |
| 2014–2020     | 1.10      |          |           | 1.40      |          |           |
| 2021–2025     | 1.05      | 1.10     | 1.15      | 1.35      | 1.40     | 1.45      |
| 2026–2030     | 1.00      | 1.05     | 1.10      | 1.30      | 1.35     | 1.40      |
| 2031–2035     | 0.95      | 1.00     | 1.05      | 1.25      | 1.30     | 1.35      |
| 2036–2040     | 0.90      | 0.95     | 1.00      | 1.20      | 1.25     | 1.30      |
| 2041–2045     | 0.85      | 0.90     | 0.95      | 1.15      | 1.20     | 1.25      |
| 2046–2050     | 0.80      | 0.85     | 0.90      | 1.10      | 1.15     | 1.20      |
| 2051–2055     | 0.75      | 0.80     | 0.85      | 1.05      | 1.10     | 1.15      |
| 2056–2060     | 0.70      | 0.75     | 0.80      | 0.95      | 1.00     | 1.10      |

**Fig. 11.** Per capita household energy consumption in China, 2000–2016
and 850.8 kg, which maintains a stable fluctuation, with elasticity coefficient ranging from 0.6 to 0.2. Beijing’s urbanization rate was 86.6% in 2019, which led to a limited increase of its per capita energy consumption in rural households. Considering the development targets of China, we assume a baseline path that China’s per capita household energy consumption in rural still has much room for growth in the short term, and the coefficient would be as large as 1, while the elasticity coefficient of urban energy consumption would be below 0.6. However, with the further increase in the terminal electrification rate, the elasticity coefficient will become gradually small. Meanwhile, an acceleration scenario is provided for comparative analysis which takes into account the implementation of various energy conservation policies (Table 7).

### Table 7 Projection of household energy consumption elasticity coefficients in China, 2017–2060

| Period       | Urban elasticity coefficient | Rural elasticity coefficient |
|--------------|------------------------------|------------------------------|
|              | Baseline | Acceleration | Baseline | Acceleration |
| 2011–2016    | 0.60     | 1.00         | 1.10     | 1.05         |
| 2017–2019    | 0.60     | 0.55         | 1.10     | 1.05         |
| 2020–2025    | 0.60     | 0.55         | 1.10     | 1.05         |
| 2026–2030    | 0.50     | 0.45         | 1.00     | 1.00         |
| 2031–2035    | 0.50     | 0.45         | 0.80     | 0.75         |
| 2036–2040    | 0.40     | 0.40         | 0.60     | 0.60         |
| 2041–2045    | 0.40     | 0.40         | 0.40     | 0.40         |
| 2046–2050    | 0.30     | 0.30         | 0.20     | 0.20         |
| 2051–2055    | 0.20     | 0.20         | 0.10     | 0.10         |
| 2056–2060    | 0.10     | 0.10         | 0.10     | 0.10         |

### Fig. 12. Primary energy consumption structure in China, 2010–2020

Energy consumption

#### Change in China’s energy structure, 2010–2020

China’s resource endowment is rich in coal and lack of oil and less gas, which has led to coal being the main source of energy supply in China for a long time. With China’s growing concern about climate issues, it has embarked on the energy transition to address the environmental pollution caused by overuse of fossil fuels. Data from 2010 to 2020 show that the energy transition process, which focuses on the substitution of coal by natural gas and non-fossil energy, is beginning to bear fruit (Fig. 12): the share of coal in primary energy consumption decreased from 69.2 to 56.8%; the share of natural gas increased from 4.0 to 8.4%; and non-fossil energy increased from 9.4 to 15.9%.

#### Projection of Primary energy structure in China, 2021–2060

Considering China’s resource endowment, the future energy mix will show the process of replacing coal by oil and gas as the main energy and replacing fossil energy by non-fossil energy. As oil consumption will shift from the transportation sector, with a large share of oil consumption, to the chemical sector in the future, and considering the energy security issues brought about by international political competition, we project that oil consumption will gradually decline after slight fluctuations during 2020–2025. Energy in China’s New Era (State Council of China 2020b) points out that during the 14th FYP period, non-fossil energy and natural gas will be promoted as the main energy of incremental energy consumption, and natural gas consumption is expected to peak during 2035–2040 and then show a downward trend. As for non-fossil energy, China’s updated NDC target states that the share of non-fossil energy will reach 25% in 2030.
The Energy Production and Consumption Revolution Strategy 2016–2030 (National Development and Reform Commission 2017) predicts that the share of natural gas will reach 15% in 2030 and the share of non-fossil energy will be more than half in 2050. Based on the above projections and new NDC targets, two energy consumption scenarios are assumed in conjunction with the pace of past adjustments (Table 8).

Results and discussion

Scenario hypothesis

The trend of population and GDP growth we consider is only one scenario by quantifying China’s 2035 and 2050 long-term development goals, while the scenario of energy mix is analyzed separately after calculating total energy consumption, and the combination of other five factors will result in different scenarios, and we choose 14 energy consumption scenarios for analysis, as shown in Table 9.

We set three main scenarios according to urbanization and the growth of residential income, and within each main scenario, 4–5 sub-scenarios are set based on different development scenarios of industrial structure, energy intensity, and household energy consumption, in which $S_{11}$–$S_{14}$ are low-speed scenarios, $S_{21}$–$S_{25}$ are baseline scenarios, and $S_{31}$–$S_{35}$ are accelerated transition scenarios.

Energy consumption

Based on our scenario assumptions and research methodology, we project the energy consumption in China for 2020–2060 under various scenarios (Fig. 13), and the details are shown in Appendix A (Table A.1).

Under the low-speed scenarios, when both industrial structure and energy intensity are in the baseline scenario ($S_{11}$), China’s energy consumption is expected to peak in 2035 at 6,261 Mtce and will reach 5,478 Mtce in 2060. In $S_{12}$, due to accelerating the pace of industrial restructuring, the peak would be reduced by 131 Mtce, and energy consumption will drop to 4,927 Mtce in 2060. In $S_{13}$, compared to the $S_{11}$ scenario, energy consumption will have a peak

### Table 8 Projection of primary energy structure for China, 2021–2060

| Year | BAU Coal Oil Gas Non-fossil | Low-carbon Coal Oil Gas Non-fossil |
|------|-----------------------------|-----------------------------------|
| 2020 | 56.80% 18.90% 8.40% 15.90%  | 48.00% 18.50% 11.50% 22.00%      |
| 2025 | 50.50% 17.50% 11.50% 20.50%  | 42.00% 17.00% 14.00% 27.00%      |
| 2030 | 44.50% 15.50% 15.00% 25.00%  | 35.50% 15.50% 15.00% 34.00%      |
| 2035 | 38.50% 14.00% 17.50% 30.00%  | 28.50% 12.50% 16.00% 43.00%      |
| 2040 | 33.00% 12.50% 18.00% 36.50%  | 21.50% 10.00% 13.50% 55.00%      |
| 2045 | 28.00% 11.50% 17.50% 43.00%  | 16.00% 8.00% 11.00% 65.00%      |
| 2050 | 24.00% 11.00% 15.00% 50.00%  | 12.00% 6.00% 8.50% 73.50%      |
| 2055 | 21.00% 10.50% 13.50% 55.00%  | 8.00% 5.00% 6.00% 81.00%      |
| 2060 | 18.00% 10.00% 12.00% 60.00%  | 8.00% 5.00% 6.00% 81.00%      |

### Table 9 The overall description on scenario setting

| Scenario                | $S_{11}$ | $S_{12}$ | $S_{13}$ | $S_{21}$ | $S_{22}$ | $S_{23}$ | $S_{24}$ | $S_{25}$ | $S_{31}$ | $S_{32}$ | $S_{33}$ | $S_{34}$ | $S_{35}$ |
|-------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Industrial structure    | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        |
| Urbanization            | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        |
|                       | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        |
| Resident income         | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        |
| Energy intensity        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        |
| Household energy        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        | ✓        |

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decline of 214 Mtce because of strengthening energy efficiency improvement, with the peak appearing five years earlier (in 2030), and energy consumption will be 4,987 Mtce in 2060. In the $S_{14}$ scenario, China’s energy consumption will be 5,930 Mtce in 2030 and decline to 4,502 Mtce in 2060 due to combined effect of energy efficiency improvement and industrial restructuring.

Under the baseline scenarios, when both industrial structure and energy intensity are in the baseline scenario ($S_{21}$), China’s energy consumption is expected to peak at 6,248 Mtce in 2035 and will reach 5,446 Mtce in 2060, which is slightly smaller than that in $S_{11}$. Under the $S_{22}$ scenario and the $S_{23}$ scenario, the peak of China’s energy consumption will decrease by 132 Mtce and 208 Mtce, and peak in 2035 and 2030, respectively, in 2060, energy consumption will drop to 4,895 Mtce and 4,955 Mtce. In $S_{24}$, peak energy consumption will appear in 2030 at 5,923 Mtce, and decline to 4,471 Mtce in 2060. The comparison of $S_{21}$ and $S_{25}$ reveals the contribution of household energy consumption: in $S_{25}$, peak energy consumption will be 42 Mtce less than that in $S_{21}$ due to lower household energy consumption, and energy consumption in 2060 will drop to 5,397 Mtce.

For the accelerated transition scenarios, $S_{31}$ and $S_{32}$ scenarios consider different household energy consumption, and the peak energy consumption of $S_{31}$ will be 42 Mtce higher than that of $S_{32}$, with the peak appearing in 2035. The peak energy consumption under $S_{33}$, $S_{34}$, and $S_{35}$ will be 6,061 Mtce in 2035, 6,005 Mtce in 2030, and 5,888 Mtce in 2030, respectively. In 2060, energy consumption will reach 4,809 Mtce, 4,870 Mtce, and 4,385 Mtce.

$S_{11}$, $S_{21}$, and $S_{31}$ reveal the impact of different urbanization and residential income on energy consumption. Low-speed growth of urbanization and residential income will lead to an increase in energy consumption, and the peak energy consumption of $S_{11}$ will be higher than that of $S_{21}$ and $S_{31}$, but the difference is not significant, which is 13 Mtce and 14 Mtce, and the peak appears in 2035 for all scenarios. In 2060, energy consumption of $S_{11}$ will be 32 Mtce higher than $S_{21}$ and 36 Mtce higher than $S_{31}$.

By analyzing the results of the scenario assumptions, we can find that urbanization, residential income, and household energy consumption have a slight impact on the peak energy consumption, while the industrial restructuring and energy intensity have more remarkable impact. When both industrial structure and energy intensity are in the baseline scenario, energy consumption would peak at around 6,200 Mtce in 2035. Further analysis reveals that energy intensity has a larger impact on energy consumption than industrial restructuring: when only industrial restructuring is in an acceleration scenario, energy consumption will peak at about 6,100 Mtce in 2035; while only energy intensity is improved in higher speed, energy consumption will peak at about 6,000 Mtce in 2030. If both variables develop in acceleration assumption, energy consumption is expected to peak in 2030 at about 5,900 Mtce.

**CO₂ emissions**

By considering the energy consumption and emission factors of each scenario, we calculated CO₂ emissions during 2020–2060 under the BAU scenario and low-carbon scenario of energy structure (Fig. 14), and the details are shown in Appendix A (Table A.2 and Table A.3).

Under the primary energy mix envisioned by China (BAU scenario), $S_{11}$, $S_{21}$, $S_{25}$, $S_{31}$, and $S_{32}$ have higher CO₂ emissions due to lower energy efficiency and slower industrial restructuring, and still have around 4,400 Mt of CO₂ emissions in 2060. Compared with the above five scenarios, the
CO₂ emissions of $S_{12}$, $S_{22}$, and $S_{33}$ will decline, by accelerating the pace of industrial restructuring, and it will reach 3,991 Mt, 3,965 Mt, and 3,895 Mt respectively in 2060. The $S_{13}$, $S_{23}$, and $S_{34}$ scenarios have CO₂ emissions of 4,040 Mt, 4,014 Mt, and 3,944 Mt in 2060 due to higher energy efficiency. When both energy intensity and economic structure are in accelerated transition scenarios, which are $S_{14}$, $S_{24}$, and $S_{35}$ scenarios, CO₂ emissions will be lower, reaching 3,647 Mt, 3,621 Mt, and 3,551 Mt in 2060.

In the low-carbon scenario, CO₂ emissions are significantly reduced compared to the baseline scenario. $S_{11}$, $S_{21}$, $S_{25}$, $S_{31}$, and $S_{32}$ scenarios will have CO₂ emissions approaching 2,100 Mt in 2060; CO₂ emissions in 2060 under $S_{12}$, $S_{22}$, and $S_{33}$ are expected to fall below 2,000 Mt, which is 1,872 Mt, 1,860 Mt, and 1,827 Mt, respectively; under $S_{13}$, $S_{23}$, and $S_{34}$ scenarios, CO₂ emissions will reach 1,895 Mt, 1,883 Mt, and 1,850 Mt in 2060; in $S_{14}$, $S_{24}$, and $S_{35}$, CO₂ emissions will be further reduced, reaching 1,711 Mt, 1,699 Mt, and 1,666 Mt in 2060.

In order to obtain the specific year of peak and peak CO₂ emissions more precisely, we calculated the CO₂ emissions of China in 2020–2030 under each scenario by refining the data points (Fig. 15), and the details are shown in Appendix A (Table A.4 and Table A.5).

Under the BAU scenario, CO₂ emissions from $S_{11}$, $S_{21}$, $S_{25}$, $S_{31}$, and $S_{32}$ will peak in 2027 at 11,000–11,100 Mt. The peak years of CO₂ emissions under $S_{12}$, $S_{22}$, and $S_{33}$ scenarios will be advanced to 2026, and the peaks will decrease to around 10,900 Mt. CO₂ emissions in $S_{13}$, $S_{23}$, and $S_{34}$ will also peak in 2026, with peaks of 10,927 Mt, 10,922 Mt, and 10,881 Mt. Under $S_{14}$, $S_{24}$, and $S_{35}$ scenarios, CO₂ emissions will peak in 2026 at 10,700–10,800 Mt.

In the low-carbon scenario, all scenarios will peak in 2026, and with a slightly reduced peak compared to the BAU scenario. The CO₂ emissions of $S_{11}$, $S_{21}$, $S_{25}$, $S_{31}$, and $S_{32}$ will
peak at 10,700–10,800 Mt; the $S_{12}, S_{13}, S_{22}, S_{23}, S_{34}$ scenarios will all reach about 10,650 Mt of CO$_2$ emissions; and the $S_{14}, S_{24}, S_{35}$ scenarios will peak at 10,500 Mt of CO$_2$ emissions.

Compared to earlier study by Ge et al. (2018), the peak CO$_2$ emissions predicted in this paper are significantly lower, because China’s NDC targets and policies have been effective in reducing carbon emissions during recent years, and China’s actions are now on the track of its carbon peaking pledge. Compared to more recent studies (Cai et al. 2021; Xu et al. 2020), in our study, the projected CO$_2$ peak is higher and the peaking year is later, possibly because we consider the drivers of CO$_2$ emissions comprehensively and include the effects of industrial structure, urbanization, and resident income on CO$_2$ emissions.

**Contribution of driving factors of CO$_2$ emissions during 2020–2060**

We use the LMDI method to decompose the impact of driving factors on CO$_2$ emission reduction and calculate their contributions, comparing and analyzing which factor will play a greater role in the path to achieving carbon neutrality. In this paper, the $S_{21}$ and $S_{35}$ scenarios under the BAU scenario and the $S_{35}$ scenario under the low-carbon (LC) scenario are selected for analysis (Table 10, Fig. 16).

| 2020–2060 | Industrial structure (IS) | Energy intensity (EI) | GDP | Energy structure (ES) | Urbanization (UR) | Population (P) | Household energy (HE) | Total |
|-----------|--------------------------|-----------------------|-----|-----------------------|-------------------|-----------------|----------------------|-------|
| $S_{21}$ (baseline) | $-1697$ | $-6844$ | $8322$ | $-6170$ | $-53$ | $-66$ | $843$ | $-5664$ |
| $S_{35}$ (baseline) | $-2222$ | $-6788$ | $7496$ | $-5622$ | $-74$ | $-63$ | $748$ | $-6525$ |
| $S_{35}$ (low-carbon) | $-1714$ | $-5101$ | $5641$ | $-7655$ | $-72$ | $-45$ | $537$ | $-8410$ |

**Conclusion and policy implications**

**Conclusion**

The introduction of peak carbon emission and carbon neutrality target has guided the direction of China’s low-carbon and green development in the future, but it also means great...
challenges to energy transformation and social development. We calculate energy consumption and CO₂ emissions of various scenarios during 2020–2060 by considering the most important drivers affecting CO₂ emissions and simulating various social-economic policies. The findings of this study can be summarized as follows.

Firstly, under the existing policy, China’s energy consumption will peak at about 6,200 Mtce in 2035. In the BAU scenario, energy consumption will enter a short period of steady fluctuation after 2030 and gradually decline after reaching a peak at 6,200 Mt in 2035, and it is estimated to decrease to 5,400 Mtce in 2060. Encouragingly, with the accelerated process of industrial restructuring and enhanced energy efficiency, energy consumption in the accelerated transition scenario will peak in 2030 at 5,900 Mtce and decline to 4,500 Mtce in 2060.

Secondly, China’s energy-related CO₂ emissions can reach a peak before 2030 with the promotion of new NDC plans. Updated NDC target of increasing non-fossil energy to 25% largely influences the baseline of CO₂ emissions when peaking emissions by 2030 under the current trend. Under the BAU scenario, China’s CO₂ emissions from energy consumption will peak at 11,10 Mt in 2027. With further optimization of energy structure and industrial structure, and continuous reduction in energy intensity, peak CO₂ emissions can be cut to 10,600–10,700 Mt and the peak year can be advanced.

Thirdly, China will not be able to successfully achieve its carbon neutrality target in 2060 even under the updated NDC targets. Achieving carbon neutrality requires reducing CO₂ emissions to a level that can be managed with the projected addition in carbon sink capacity by 2060. According to existing studies (Masson Delmotte et al. 2021; Pan 2021), 800 Mt CO₂ emissions can be offset in 2060 with negative carbon technologies such as CCS and CCUS, while 1,000 Mt CO₂ emissions can be offset with biological carbon sequestration such as afforestation, but energy-related CO₂ emission will reach 4,400 Mt in 2060 in the BAU scenarios, reflecting more than 2,000 Mt of net emissions untactcted. However, our analysis also identifies the possibility of reaching carbon neutrality by 2060 with enhanced policy pathways.

Finally, continuous energy efficiency improvement, rapid industrial restructuring, and energy restructuring are three driving forces of achieving carbon neutrality. We find that the impacts of energy intensity (108.9%), industrial structure (30%), and energy mix (120.8%) on CO₂ emissions are much larger than the impacts of urbanization, resident income, and household energy consumption. A tilt in the industrial pillar from the energy-intensive industries to the strategic emerging industries with low energy consumption will help reduce CO₂ emissions, coupled with the reduction of the secondary industry’s share in GDP, can lead to substantial effect on energy-related CO₂ emission reduction.

Policy implications

To peak CO₂ emissions and achieve carbon neutrality is China’s solemn commitment to building a shared future for mankind, and it will make a significant contribution to global climate governance and sustainable development. However, our study have revealed that the existing policy package is not enough to deliver the carbon neutrality by 2060. Thus, enhanced policy package on economic restructuring, energy restructuring, and energy efficiency improvement is needed.

The first policy implication is to continuously optimize and upgrade the industrial structure and expedite the development of industrial and production modes to conserve resources and protect the environment. It is necessary to promote clean production across the board, promote green agricultural development and its carbon sequestration capacity and efficiency, accelerate the digital transformation of industries, and enhance low-carbon development for service sector. The irrational expansion of energy-intensive and high-emission industries must be curbed and the entry of energy-consumption industries and emission standards need to be more strict. The paper also suggests to vigorously promote low-carbon industries to integrate with emerging technologies deeply.

Secondly, it is suggested to strictly control fossil fuel consumption and significantly improve energy efficiency. It is of vital importance to accelerate the development of the new power system based on non-fossil energy the construction of a low-carbon transportation system, and green transformation in urban and rural development. In terms of new energy production, it is plausible to advance both utility-scale and distributed development modes, and scale up the use of pumped storage and energy storage, which can improve the capacity of the power grid to uptake a high proportion of renewable energy. Improving comprehensive energy utilization, controlling the production capacity of coal-fired power, and expanding the supply and consumption of low-carbon products can contribute to increasing the share of non-fossil energy in primary energy consumption. Pay attention to the energy-saving potential of urban and rural households, and household energy consumption will be reduced by advocating green and low-carbon living patterns. Significantly improving energy efficiency needs to enhance energy conservation in key industries and the energy management system, raise resource input-output efficiency and assign stronger targets and responsibilities for major energy consumers, and accelerate carbon reduction retrofits and upgrades to ensure that energy efficiency will be at the advanced international level by 2060.

Last but not least, achieving the carbon neutrality goal needs to boost technological and institutional innovation, while guarding against risks. It is necessary to improve R&D investments, strengthen research on low-carbon
technologies, overcome the technical difficulties, and promote their application. This paper proposes to continue to enlarge forest stock, consolidate and increase the carbon sink capacity of ecosystems, promote the development of green energy by deepening reform in energy and related fields, and respond appropriately to any economic, financial, and social risks that may arise by low-carbon transformation to ensure that carbon emissions are reduced securely.

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