Is China on the Track of Its Climate Pledge: A Multi-scenario Simulation of China's Energy-Related Co₂ Emissions 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 that explicitly considers China's economic and social development goals in the medium and long term, with analyzing the development trends of various driving factors of CO₂ emissions. Different scenarios for 2020-2060 are projected based on the Kaya identity. Energy consumption will peak at 6200 Mtce in 2035 in the BAU scenario and at 5900 Mtce in 2030 in the accelerated transition scenario. With existing policy, energy-related CO₂ emissions will peak at about 11.1 Gt in 2026-2027, and in the accelerated transition scenario it can be potentially reduced by 300-400 Mt. In the BAU scenario, the net CO₂ emissions will remain around 2000Mt in 2060, after removing 1800Mt CO₂ by CCS/CCUS, indicating that China need enhance its post-2030 policy strength to deliver the carbon neutrality pledge. Steady energy efficiency improvement, radical industrial and energy restructuring are three key driving forces for carbon neutrality.

1. Introduction

Since 2002, the reform and opening-up policy and the booming development of heavy industry have accelerated China's economic growth, while also promoting increased energy consumption (Lin et al., 2016). In 2020, China's total primary energy consumption reached 4980 Mtce, accounting for 26.2% of the world, with an average annual growth rate of 6.17% compared to 2002. However, the CO₂ produced by burning much fossil energy has accelerated the process of global warming, posing a serious threat to global climate security. 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 9899 Mt CO₂ emissions, accounting for 30.7% of global CO₂ emissions. Thus, for global climate governance and sustainable development, China must increase its independent contribution and propose a practical and effective Chinese pathway to address the global climate issues (Yuan et al., 2014b).

The signing of the Paris Agreement has led China to take high attention to the environmental and ecological impact of energy consumption and CO₂ emissions. Since the 11th Five-Year Plan, China has released several energy 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.

In September 2020, China announced that it will strive to reach peak CO₂ emissions by 2030 and work towards carbon neutrality by 2060. To successfully achieve them, China has adopted stronger policies and measures since the 14th Five-Year Plan, which proposed the updated national determined contributions (NDC) target that increases the proportion of non-fossil energy to 25% by 2030 and more than 65% reduction of GDP CO₂ intensity during 2005-2030. Although China's energy conservation and emission reduction efforts have been quite effective over the past decades, even in 2020 China still has nearly 10 Gt energy-related CO₂ emissions, and the inflection point of the environmental Kuznets curve (EKC) has not yet arrived in China. Under the current trend, whether China can achieve its climate pledge of decreasing CO₂ emissions from 10 Gt to zero by 2060, this paper seeks to address these questions from the perspective of China's recently-declared social-economic policies.

The EKC (Grossman and Krueger, 1991) is the main method for analyzing the relationship between CO₂ emissions and economic growth. The EKC shows an approximately inverted "U" curve, that is per capita CO₂ emissions will increase with per capita GDP. However, when economic growth reaches a certain "inflection point", with the further increase of per capita GDP, the per capita CO₂ emissions will decrease. 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. Jaunky (2011) found no EKC inflection point in 36 high-income countries during the period 1980-2005, while he indicated that over time CO₂ emissions would remain stable.

For China, studies have now confirmed the existence of the EKC hypothesis (Ibanez et al., 2019; Tenaw and Beyene, 2021). According to Xu and Song (2010), in China, there is a positive “U” curve between per capita GDP and per capita CO₂ emissions in the western region, 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. Lin and Jiang (2009) found that a simple EKC cannot accurately describe the CO₂ emissions in China. Thus, Xia and Wang (2020) considered the impact of energy consumption intensity and energy structure, and explored the relationship between economic growth, fossil energy, hydropower, industrial development and CO₂ emissions. The results show that EKC considering structural mutation exists in China, and the process of industrialization and economic growth have a significant positive effect on CO₂ emissions.

Although the EKC has been confirmed in some developing countries, Gill et al. (2018) argued that the continued deterioration of the world environment cannot wait for the EKC inflection point if developing countries follow the EKC curve. Developing countries should follow a different path than EKC and be proactive in addressing the environmental issues associated with the growth of CO₂ emissions by releasing policies to promote the use of renewable energy.

EKC reveals a future trend for China's CO₂ emissions that grow slowly to a peak and then gradually decline. Several studies have concluded that the years to peak and the peak values will vary for different scenarios. Without strong climate policies, China's CO₂ emissions will continue to increase to 12.2 Gt in 2050 (Dai et al., 2010). If China's NDC targets are considered, China's CO₂ emissions will reach a peak at around 11.3 Gt in 2030 (Ge et al., 2018). Xu et al. (2020) and Zhou et al. (2021) concluded that CO₂ emission of China will reach a peak at 10.7 Gt in 2030 under the current planning scenario. If the global temperature control targets of 2°C and 1.5°C are considered, China will peak ahead of schedule in 2025 and the CO₂ emission is expected to be further reduced to 10.4 Gt, and China's contribution to global greenhouse gas (GHG) emissions will be higher than its cumulative emission level. Cai et al. (2021) constructed a CO₂ emission pathway for 2020-2060 under China's carbon neutrality target. The study showed that China will reach a peak of 10.6 Gt of CO₂ emissions around 2027, and after reaching the peak, the CO₂ emissions will be 10.5 Gt in 2030 after a plateau period of 5 to 7 years.

In the medium and long term, Zhou et al. (2019) argued CO₂ emissions in 2050 is estimated to be reduced to 42% lower than in 2010 through the large-scale application of CCS technology and the effective implementation of emission reduction policies. Xiao et al. (2021) concluded that China can reduce 6161 Mt of CO₂ emissions by 2060 compared to 2017; and the remaining 2732 Mt of CO₂ emissions can be eliminated through carbon offsetting.

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. Furthermore, different assumptions of scenario settings could lead to various CO₂ emissions of China. However, it is clear that under the current trend, China's carbon emissions will increase slowly to a peak and then gradually decline.

In this paper, we consider the various drivers of CO₂ emissions and various social-economic policies to propose a modeling of energy consumption and CO₂ emissions with consideration of China's updated NDC targets in 2021. The Kaya identity is used to calculate the energy consumption and CO₂ emissions between 2020 and 2060, and the results are further analyzed to determine the feasibility of achieving the peak carbon emissions and carbon neutrality targets in China under the current policy. The paper is organized as follows: Section 2 introduces the research methodology. Section 3 presents the historical trajectory of driving factors and sets assumptions for the scenarios. Section 4 reports the results. Section 5 concludes the paper with policy implications.

2. Methodology

2.1 Kaya identity

In this paper, we use the Kaya identity as the base 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. With the advancement of the urbanization process, the proportion of residential energy consumption in the primary energy would be gradually increasing, we need further model the development of urbanization and differentiate energy consumption for production and daily life. At the same time, it's 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:

$$TEC = GDP \times \frac{Ep}{GDP} + gdp \times \frac{ER}{gdp}$$

1

Where E_p is industry energy consumption and E_R is household energy consumption, gdp indicates GDP per capita.

$$\frac{Ep}{GDP} = \sum SiEi$$

3

The primary energy consumption of 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 .

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

2

The calculation of residential energy consumption we consider from two perspectives, urban and rural energy consumption. We choose urbanization R_U and total population P to express the differences of the urban and rural population. Due to residential consumption, of which energy consumption is an important part, is subject to the status of rural disposable per capita income (I_U) 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 - 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).

$$C = TEC \times \sum (Eief)$$

4

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

2.2 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.

3. Driving Factors Of Energy-related Co Emissions In China

3.1 Population

3.1.1 Population of China during 2000-2020

The total population of China was 1267 million in 2000 and grew to 1412 million in 2020, with a net growth rate of 11.4%. Although China's population showed significant growth from 2000 to 2020, 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, even in 2020, affected by the COVID-19 epidemic, it dropped to an all-time low of 1.45‰ (Fig. 1). The most important factor contributing to the significant 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.

3.1.2 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 in China and inadequate policies to support childbearing, which is reflected in the results of the “universal two-child” policy. Studies to project population of China by domestic and foreign research institutions (Energy Transitions commission, 2020; SIC, 2020) 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 1420-1450 million between 2025 and 2030, and is expected to decrease to 1350-1400 million people 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, 2016), combined with findings of population trend researchs, we expect China's population to gradually decline after peaking at about 1450 million around 2030, which will be 1330 million in 2060 (Fig. 2).

3.2 GDP

3.2.1 GDP growth in China, 2000-2020

China's GDP was 2.23 trillion US\$ in 2000, and by 2020 it has 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 has 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 economic activity, although China is the only economic entity with positive growth worldwide in 2020, its growth rate is well below the level in previous years (Fig. 3). While a declining trend has been shown in China's GDP growth rate, which is still higher than developed countries, and there is still plenty of room for GDP growth in the future.

3.2.2 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 (OECD, 2020; IMF, 2021; Asian Development Bank, 2021) 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 increase 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 of GDP growth in 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; 4% in 2031-2035 and GDP per capita will reach 22000US\$ by 2035, 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 39000US\$, which is 4.8 times the per capita GDP of 8182US\$ in 2019, in line with the development trend in China (Fig. 4).

3.3 Industrial structure

3.3.1 Evolution of China's industrial structure, 2000-2020

We plotted the evolution of China's industrial structure from 2000-2020 (Fig. 5). From the figure we can see that: 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 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 overtaken secondary industry to become the leader of China's economy, and it has maintained a high growth rate trend, with the share of tertiary industry increasing from 39.79% in 2000 to 54.53% by 2020.

3.3.2 Projection of China's industrial structure, 2020-2060

According to World Bank, in the industrial structure of the United States, Britain and other developed countries in 2019, primary industry generally accounted for less than 1%, tertiary industry accounted for 70% or more than 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 have an obvious decline; at the same time, taking into account Chinese national conditions, such a large economic entity to continuously maintain economic development still need 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 the actual situation in China, two development scenarios are provided in Table 1: the baseline is an extension of the existing trend of industrial restructuring considering China's updated NDC targets; the acceleration scenario assumes that China's transition to a service economy will occur at a faster pace than the trend under NDC targets.

Table 1

Projection of industrial structure in China, 2020-2060

Year	Primary industry		Secondary industry		Tertiary industry	
	Baseline	Acceleration	Baseline	Acceleration	Baseline	Acceleration
2020	7.65%		37.82%		54.53%	
2025	6.50%	6.00%	35.80%	35.00%	57.70%	59.00%
2030	5.50%	5.00%	33.80%	32.50%	60.70%	62.50%
2035	5.00%	4.00%	31.30%	30.00%	63.70%	66.00%
2040	4.70%	3.50%	29.00%	27.50%	66.30%	69.00%
2045	4.40%	3.00%	27.00%	25.00%	68.60%	72.00%
2050	4.10%	2.60%	25.50%	22.50%	70.40%	74.90%
2055	3.80%	2.30%	24.00%	20.00%	72.20%	77.70%
2060	3.50%	2.00%	23.00%	18.00%	73.50%	80.00%

3.4 Energy Intensity

3.4.1 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 in 2015 compared to the 2010 level, 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 consumption reduction, and a rapid enhancement in energy efficiency. The data from 2009 to 2018 show that secondary industry, which consumed the most energy during the production process, reduced its share in primary energy consumption year by year (Fig. 6), and the energy intensity of secondary industry has decreased from 1.55 tce/ten thousand RMB to 0.88 tce/ten thousand RMB in the past ten years.

3.4.2 Projection of energy intensity for China, 2019-2060

According to international comparison, China's energy intensity of the economy is still 1.5 times the world average, and the room for decrease is large. 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 the proportion of energy-intensive heavy industry and the rise of high-technology industry will make the energy intensity of second industry continue to decline, but it has limited room for decline. At the same time, 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 baseline scenario is the energy intensity reduction trend that meets updated NDC targets; and 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. The outbreak of the COVID-19 epidemic lead to empty load operations in many industries. By analyzing the data it can be determined that there is no significant decrease in energy intensity in 2020 compared to 2019, so we assume that the energy intensity of each industry in 2020 is the same as in 2019 (Table 2).

Table 2

Projection of energy intensity improvement in China, 2019-2060

Period	Annual decrease rate of PI		Annual decrease rate of SI		Annual decrease rate of TI	
	Baseline	Acceleration	Baseline	Acceleration	Baseline	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%

3.5 Urbanization

3.5.1 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, indicating that China's urbanization process has reached the medium-and-later stage (Fig. 7).

3.5.2 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 development stage, its growth rate will continue to slow down and then stabilize. 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 DESA (2013) predicted that China's urbanization rate will reach 71% in 2030 and 80% in 2050. The 14th FYP also set the development target of reaching a 65% urbanization rate in 2025. According to the above projections and the changes in China's urbanization rate over the past decades, we propose three scenarios in Table 3: the low-speed scenario, the baseline scenario and the high-speed scenario, where the baseline scenario is based on the declared development goals of China.

Table 3

Urbanization rate for China, 2020-2060

Year	Low-speed(%)	Baseline(%)	High-speed(%)
2020	61.40%	61.60%	61.80%
2025	64.40%	65.60%	66.80%
2030	67.40%	69.60%	71.80%
2035	69.40%	72.60%	75.80%
2040	71.40%	75.60%	79.80%
2045	73.40%	77.60%	82.80%
2050	74.40%	79.60%	85.80%
2055	75.40%	81.60%	87.80%
2060	76.40%	82.60%	89.80%

3.6 Resident income

3.6.1 Change of resident income in China, 2013-2020

From 2013 to 2020, the per capita residential income of urban increased 1.66 times from 26467 RMB to 43834 RMB, and the rural resident income increased from 9430 RMB to 17131 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. 8).

3.6.2 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 12535US\$ is considered a high-income level, and per capita GNI of China is 10343.6US\$ 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 five-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 4).

Table 4
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

3.7 Household energy consumption

3.7.1 Change in household energy consumption in China, 2000-2016

Along with economic and income growth, household energy consumption has grown in China, as reflected in data from 2009 to 2016 (Fig. 9): 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 brought by economic growth will increase the household energy consumption, which will soon exceed the level of per capita household energy consumption in urban.

3.7.2 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 (Beijing Municipal Bureau of Statistics, 2020). The urban and rural per capita residential income in Beijing in 2019 is 73849RMB and 28928RMB, and the per capita household energy consumption in the same period is 775.5 kg 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 5).

Table 5

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		1.10	
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

3.8 Energy consumption

3.8.1 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. 10): the share of coal in primary energy consumption decreased from 69.2–56.8%; the share of natural gas increased from 4.0–8.4%; and non-fossil energy increased from 9.4–15.9%.

3.8.2 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, 2020) 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 in primary energy consumption will reach 25% in 2030. The Energy Production and Consumption Revolution Strategy 2016-2030 (National Development and Reform Commission, 2016) 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: the baseline scenario is a reflection of Chinese government's plan, and the 25% NDC target is set as the share of non-fossil energy in the baseline scenario by 2030; 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 (Table 6).

Table 6

Projection of primary energy structure for China, 2020-2060

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

4. Scenario Results

4.1 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 7.

Table 7

The overall description on scenario setting

scenario		S ₁₁	S ₁₂	S ₁₃	S ₁₄	S ₂₁	S ₂₂	S ₂₃	S ₂₄	S ₂₅	S ₃₁	S ₃₂	S ₃₃	S ₃₄	S ₃₅
Industrial structure	Baseline	✓		✓		✓		✓		✓	✓	✓		✓	
	Acceleration		✓		✓		✓		✓				✓		✓
Urbanization	Low speed	✓	✓	✓	✓										
	Baseline					✓	✓	✓	✓	✓					
	High speed										✓	✓	✓	✓	✓
Resident income	Low speed	✓	✓	✓	✓										
	Baseline					✓	✓	✓	✓	✓					
	High speed										✓	✓	✓	✓	✓
Energy intensity	Baseline	✓	✓			✓	✓			✓	✓	✓	✓		
	Acceleration			✓	✓			✓	✓					✓	✓
Household energy	Baseline	✓	✓	✓	✓	✓	✓	✓	✓		✓				
	Acceleration									✓		✓	✓	✓	✓

We set three main scenarios according to urbanization and the growth of residential income, in which S₁₁-S₁₄ are low-speed scenarios, S₂₁-S₂₅ are baseline scenarios, and S₃₁-S₃₅ are accelerated transition scenarios. Within each main scenario, 4-5 sub-scenarios are set based on different development scenarios of industrial structure, energy intensity and household energy consumption.

4.2 Results and discussion

4.2.1 Energy consumption

Based on our scenario assumptions and preceding research methodology, we project the energy consumption in China for 2020-2060 under various scenarios (Fig. 11), 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 (S₁₁), China's energy consumption is expected to peak in 2035 at 6261 Mtce and will reach 5478 Mtce in 2060. In S₁₂, due to accelerating the pace of industrial restructuring, the peak would be reduced by 131 Mtce, and energy consumption will drop to 4927 Mtce in 2060. In S₁₃, compared to the S₁₁ scenario, energy consumption will have a peak decline of 214 Mtce because of strengthening energy efficiency improvement, with the peak appearing five years earlier (in 2030), and energy consumption will be 4987 Mtce in 2060. In the S₁₄ scenario, China's energy consumption will be 5930 Mtce in 2030 and decline to 4502 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 (S₂₁), China's energy consumption is expected to peak at 6248 Mtce in 2035 and will reach 5446 Mtce in 2060, which is slightly smaller than that in S₁₁. Under the S₂₂ scenario, which accelerates the pace of economic restructuring, and the S₂₃ scenario, which increases energy intensity improvement, the peak of China's energy consumption will decrease by 132 Mtce and 208 Mtce, and peak in 2035 and 2030, respectively, by 2060 energy consumption will drop to 4895 Mtce and 4955 Mtce. In S₂₄, peak energy consumption will appear in 2030 at 5923 Mtce, and decline to 4471 Mtce in 2060. The comparison of S₂₁ and S₂₅ reveals the contribution of different household energy consumption: in S₂₅, peak energy consumption will be 42 Mtce less than that in S₂₁ due to lower household energy consumption, and energy consumption in 2060 will drop to 5397 Mtce.

For the accelerated transition scenarios, S_{31} and S_{32} scenarios consider energy consumption with 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 decrease in turn compared with S_{32} , which will be 6061 Mtce in 2035, 6005 Mtce in 2030, and 5888 Mtce in 2030, respectively. In 2060, energy consumption will reach 4809 Mtce, 4870 Mtce and 4385 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 preceding 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 the more remarkable impact on energy consumption. When both industrial structure and energy intensity are in the baseline scenario, energy consumption would peak at around 6200 Mtce in 2035. Energy consumption is expected to peak during 2030-2035 when only one factor of industrial structure and energy intensity is at the baseline scenario, and 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 6100 Mtce in 2035; while only energy intensity is improved in higher speed, energy consumption will peak at about 6000 Mtce in 2030. If both variables develop in acceleration assumption, energy consumption is expected to peak in 2030 at about 5900 Mtce.

4.2.2 CO₂ emissions

By considering the energy consumption and emission factors of each scenario, we calculated CO₂ emissions during 2020-2060 under the baseline scenario and low-carbon scenario of energy structure (Fig. 12), and the details are shown in Appendix A (Table A.2 and Table A.3).

Under the primary energy mix envisioned by China (baseline 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 4400 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 3991 Mt, 3965 Mt and 3895 Mt respectively in 2060. The S_{13} , S_{23} , and S_{34} scenarios have CO₂ emissions of 4040 Mt, 4014 Mt, and 3944 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 3647 Mt, 3621 Mt and 3551 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 2100 Mt in 2060; CO₂ emissions in 2060 under S_{12} , S_{22} , and S_{33} are expected to fall below 2000 Mt, which are 1872 Mt, 1860 Mt, and 1827 Mt, respectively; under S_{13} , S_{23} , and S_{34} scenarios, CO₂ emissions will reach 1895 Mt, 1883 Mt, and 1850 Mt in 2060; in S_{14} , S_{24} and S_{35} , CO₂ emissions will be further reduced, reaching 1711 Mt, 1699 Mt and 1666 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. 13), and the details are shown in Appendix A (Table A.4 and Table A.5).

Under the Baseline scenario, CO₂ emissions from scenarios S_{11} , S_{21} , S_{25} , S_{31} , and S_{32} will peak in 2027 at 11000-11100 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 10900 Mt. CO₂ emissions in S_{13} , S_{23} , and S_{34} will also peak in 2026, with peaks of 10927 Mt, 10922 Mt and 10881 Mt. Under S_{14} , S_{24} , and S_{35} scenarios, CO₂ emissions will peak in 2026 at 10700-10800 Mt.

In the Low-carbon scenario, all scenarios will peak in 2026, and with a slightly reduced peak compared to the baseline scenario. The CO₂ emissions of S₁₁, S₂₁, S₂₅, S₃₁, and S₃₂ will peak at 10700-10800 Mt; the S₁₂, S₁₃, S₂₂, S₂₃, S₃₃, and S₃₄ scenarios will all reach about 10650 Mt of CO₂ emissions; and the S₁₄, S₂₄ and S₃₅ scenarios will peak at 10500 Mt of CO₂ emissions.

4.2.3 Contribution of driving factors of CO₂ emissions during 2020-2060

We use the LMDI method to decompose the impact of driving factors on CO₂ emissions 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 S₂₁ and S₃₅ scenarios under the baseline (BAU) scenario and the S₃₅ scenario under the low-carbon (LC) scenario are selected for analysis (Table 8, Fig. 14).

Table 8

Decomposition results of driving factors of CO₂ emissions in various scenarios (Mt)

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

It can be shown that the contributions of energy mix (ES), industrial structure (IS) and energy intensity (EI) to CO₂ emissions reduction are more obvious. Under the S₂₁ (Baseline) scenario, the contribution rate of ES, IS and EI are 108.9%, 30.0% and 120.8% respectively, while the contribution rate of urbanization and population are only 0.9% and 1.2%. With increasing development level, the energy structure will overtake energy intensity as the most important driver of lower CO₂ emissions. Meanwhile, economic growth will remain the most important driving factor of CO₂ emissions growth, but its pulling effect will diminish as energy mix, industrial structure and energy intensity are at a higher level of development. In the S₂₁ (Baseline), S₃₅ (Baseline) and S₃₅ (Low-carbon) scenarios, the contribution rate of GDP are -146.9%, -114.9% and -67.1%, which indicates that promoting decoupling of CO₂ emissions from economic growth must improve energy efficiency and optimize energy mix and industrial structure.

5. Conclusion And Policy Implications

5.1 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. Ultimately, four findings are obtained in this study as follows.

Firstly, under the existing policy, China's energy consumption will peak at about 6200 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 6200Mt in 2035, and it is estimated to decrease to 5400 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 5900 Mtce and decline to 4500 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 that the share of non-fossil energy in primary energy consumption is 25% in 2030 largely contributes to that CO₂ emissions reach a peak before 2030 under the current trend. Under the BAU scenario, China's CO₂ emissions from energy consumption will peak at 11100 Mt in 2027, and with further optimization of energy structure and industrial structure and continuous reduction of energy intensity, peak CO₂ emissions will drop to 10600-10700 Mt, and the peak year will be advanced.

Thirdly, China will not be able to successfully achieve its carbon neutrality target in 2060 under updated NDC targets. Achievement of carbon neutrality needs to a reduction in CO₂ emissions to below the carbon sink capacity in 2060. According to existing studies (PICC, 2021; Pan, 2021), CO₂ emissions are expected to be dealt with 800 Mt in 2060 using negative carbon technologies such as CCS and CCUS, while CO₂ emissions are expected to be dealt with 1000 Mt through biological carbon sequestration such as afforestation, but energy-related CO₂ emission will reach 4400 Mt in 2060 in the BAU scenarios. There will be more than 2000 Mt of net emissions, which will not achieve the carbon neutrality target in 2060. Through the analysis, we can see that CO₂ emissions of S₁₄, S₂₄, and S₃₅ in the low-carbon scenario are lower than the carbon sink capacity in 2060, and the carbon neutrality target can be successfully achieved.

Finally, continuous energy efficiency improvement, rapid industrial restructuring and energy restructuring are three driving forces of achieving carbon neutrality. Through the analysis, we can find that the impacts of energy intensity, industrial structure and energy mix on CO₂ emissions are much higher than the impacts of urbanization, resident income and household energy consumption, which are 108.9%, 30.0% and 120.8% respectively. 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, its effect on energy-related CO₂ emission reduction will be more obvious.

5.2 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 sustained development. However, existing policy is not enough to deliver it. Thus enhanced policy package on economic restructuring, energy restructuring, and energy efficiency improvement is needed.

Firstly, continuous to optimize and upgrade the industrial structure and expedite the development of industrial and production modes that will 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, and accelerate the digital transformation of industries, while low-carbon development would be enhanced in the service sector. The irrational expansion of energy-intensive and high-emission industries must be curbed, and raise the energy-consumption access and emission standards for them. Vigorously promote low-carbon industries to integrate with emerging technologies deeply.

Secondly, strictly control fossil fuel consumption and significantly improve energy efficiency. Faster moves must be made to develop the new power system based on non-fossil energy, accelerate the construction of a low-carbon transportation system, and promote green transformation in urban and rural development. New energy production needs to advocate both centralized and distributed integration, 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, while accelerating carbon reduction retrofits and upgrades. 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. Continue to enlarge forest stock volume, consolidate and increase the carbon sink capacity of ecosystems. An effective incentive should be created to promote the development of green energy by deepening reform in energy and related fields. Meanwhile, the Chinese government must respond appropriately to any economic, financial, and social risks that may arise by low-carbon transformation and ensure carbon emissions are reduced securely.

Declarations

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Authors' contributions

Hongxin Liu: Formal analysis, Data Curation and Writing – Original Draft; Jian Zhang: Writing-review & editing; Jiahai Yuan: Conceptualization, Methodology, Supervision and Project administration.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Total population and its growth in China, 2000-2020

Figure 2

Projection of population in China, 2021-2060

Figure 3

GDP and its growth in China, 2000-2020

Figure 4

Projection of GDP in China, 2021-2060

Figure 5

Industrial structure in China, 2000-2020

Figure 6

Industry energy consumption in China, 2009-2018

Figure 7

Urbanization in China, 2000-2019

Figure 8

Residential income in China, 2013-2020

Figure 9

Per capita household energy consumption in China, 2000-2016

Figure 10

Primary energy consumption structure in China, 2010-2020

Figure 11

Comparison of various energy consumption scenario results

Figure 12

Comparison of CO₂ emissions under different energy mix scenarios

Figure 13

Comparison of various CO₂ emission scenario results

Figure 14

Contribution of driving factors of CO₂ emissions during 2020-2060 in various scenarios

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