Original Research

Towards carbon neutrality: A study on China's long-term low-carbon transition pathways and strategies

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ABSTRACT

As the world's biggest carbon dioxide (CO_2) emitter and the largest developing country, China faces daunting challenges to peak its emissions before 2030 and achieve carbon neutrality within 40 years. This study fully considered the carbon-neutrality goal and the temperature rise constraints required by the Paris Agreement, by developing six long-term development scenarios, and conducting a quantitative evaluation on the carbon emissions pathways, energy transformation, technology, policy and investment demand for each scenario. This study combined both bottom-up and top-down methodologies, including simulations and analyses of energy consumption of end-use and power sectors (bottom-up), as well as scenario analysis, investment demand and technology evaluation at the macro level (top-down). This study demonstrates that achieving carbon neutrality before 2060 translates to significant efforts and overwhelming challenges for China. To comply with the target, a high rate of an average annual reduction of CO_2 emissions by 9.3% from 2030 to 2050 is a necessity, which requires a huge investment demand. For example, in the 1.5 °C scenario, an investment in energy infrastructure alone equivalent to 2.6% of that year's GDP will be necessary. The technological pathway towards carbon neutrality will rely highly on both conventional emission reduction technologies and breakthrough technologies. China needs to balance a long-term development strategy of lower greenhouse gas emissions that meets both the Paris Agreement and the long-term goals for domestic economic and social development, with a phased implementation for both its five-year and long-term plans.

1. Introduction

The Paris Agreement urges all parties to submit the updated Nationally Determined Contributions (NDCs) and the Long-Term Low Greenhouse Gas (GHG) Emission Development Strategies (LTS) of mid-century. In September 2020, the Chinese government also put forward the goal of "striving to be carbon neutral before 2060". Prior to 15 October 2021, 66 countries across the world have communicated a net-zero target, which together represent over 56.5% of the global emissions [1]. The Intergovernmental Panel on Climate Change) (IPCC) conceptualized carbon neutrality as "Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period" [2]. As the world's largest CO_2 emitter, China's long-term strategy of low-carbon transition and implementation pathways towards carbon neutrality would exert

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significant influences on whether the Paris Agreement's long-term temperature goal will be successful.

Inconsistent with China's 2060 carbon neutrality target, most of the existing studies on low-carbon transition in China have only taken the global 2 °C and 1.5 °C temperature goal as the pre-conditions, with limited research on analyzing the multiple-target-multiple-alternative-futures scenarios (i.e., China's 2060 carbon neutrality target, global 2 °C and 1.5 °C temperature goal, transition pathway) [3–10]. Moreover, newly published studies on China's transition pathway towards carbon neutrality are focus on the energy and power sectors, without covering the full range of GHG emissions and sectors, and considering China's existing long-term socio-economic strategies as a combined objective [11–14]. Transformation pathways have been another focus of recent studies of comparative analysis on multiple models (Energy Foundation, 2020 ; ; Duan et al., 2021). Although the transition cost is one of the most significant issues for policy makers, relevant research is still scant.

Based on the guiding ideology of simultaneously realizing both the goal of China's socialist modernization in the new era and the global temperature control targets under the Paris Agreement, our research focused on the Long-Term Low GHG Emission Development Strategies consistent with the Paris Agreement, by taking China's concrete conditions and characteristics of the development stages into account. In addition, under the guidance of building a moderately prosperous society and achieving deep decarbonization, this paper conducted policy simulations and analyzed the emission reduction pathways, technology requirements and investment demands. In addition, our research provides technical support to the Chinese government on formulating relevant domestic and international strategies and policies, meanwhile giving a wide range of other developing countries a reference.

The remainder of this paper is organized as follows: Section 2 describes the methods and scenario setting. Section 3 elaborates on carbon emissions pathways, GHG emission structures, primary energy structures, and electrification rates in end-use sectors. Section 4 presents discussions on additional efforts and energy infrastructure investments in achieving the 1.5 °C target. Section 5 outlines the conclusions of the paper and provides several policy implications and recommendations.

2. Methods and scenario setting

2.1. Project research methods

This study combined both bottom-up and top-down methodologies to depict and simulate China's overall low-carbon transition pathways based on the characteristics of the two development stages. Currently, the Chinese government has formulated the 2035 economic and strategic social development goals, with a very determined development path from 2020 to 2035. Therefore, by adopting the "top-down" methodology, we can estimate the energy consumption and carbon emissions in key years based on the predictable economic scale by 2035, historical data, and expert's anticipation of the target year's carbon intensity reduction objective, and the speed and intensity of energy structure optimization.

For the stage of 2035–2050, based on the "bottom-up" methodology, the total amount of electricity demand, energy consumption and direct carbon emissions were calculated by using the specific model of end-use sectors, which covers industrial, building, transport, plus the agricultural and forestry sectors and the systematic losses. Next, by taking the end-use electricity as an input of the power sector, the total energy consumption and structure of the power sector were analyzed. Lastly, through the synthetization of the data from various sectors, the total energy consumption and

carbon emissions with a "bottom-up" perspective were also calculated.

Based on the results put forward by the "bottom-up" sectoral models, we took into account the economic inertia and growth expectations with a "top-down" perspective, experts' judgment and the existing relevant research results. Accordingly, the development situation and characteristics of various sectors in a balanced state were concluded by connecting and iterating the total energy demand and carbon emissions (Fig. 1).

The specific calculation process is as follows:

At the macro level, under the given GDP growth rate and potential optimization of energy structure, the total energy consumption and total CO_2 emissions of the whole economy are predicted at the recent declining rate of carbon intensity. At the macro level, the balance of total energy consumption meets in Equation (1):

$$1 - \frac{\frac{E_{t+T} \times \sum_i e_{i,t+T} \times \alpha_i}{GDP_{t+T}}}{\frac{E_t \times \sum_i e_{i,t} \times \alpha_i}{GDP_t}} = \lambda \qquad (1)$$

In Equation (1), E stands for total energy consumption, e stands for energy structure, GDP stands for Gross Domestic Product, i stands for the consumption of different energy types (coal, oil, natural gas, and non-fossil energy), t and $t + T$ respectively stand for different years, α stands for emission factor, and λ stands for the declining rate of carbon intensity.

At the sectoral level, sectors such as industrial, building, transport and electric power are subject to bottom-up sectoral modeling, which needs to meet the balance between power consumption and power production at the economic level as a whole:

$$\sum_{j=1,2,3,4} Ele\_c_j = Ele\_p_{j=4} \qquad (2)$$

In Equation (2), Ele_c stands for power consumption; Ele_p stands for power production; j stands for terminal sector; $1, 2, 3$ and 4 stands for industrial, building, transport and power respectively, and the power consumption on the production side of the power sector mainly includes auxiliary power and line loss.

In addition, the energy structure of the whole economy should also be consistent with the energy structure after the summation of bottom-up energy consumption of all sectors, that is, the balance of energy structure:

$$E_{t,i} = E_t \times e_i = \sum_{j=1,2,3,4} E_{t,j,i} \qquad (3)$$

In Equation (3), E stands for the total energy consumption, e stands for energy structure, t stands for the year, i stands for energy type (coal, oil, natural gas and non-fossil energy), j stands for the terminal sector, $1, 2, 3$ and 4 stands for industrial, building, transport and electric power, respectively.

The three kinds of balance mentioned above are satisfied in each scenario by using the flexible connection approach that continuously iterates the top-down model and the bottom-up model. Published literature for the description of sectoral modeling and related research results are outlined in Refs. [4,15–21].

2.2. Scenario setting

China is still a developing economy. The 19th National Congress of the Communist Party of China held in 2017 identified the "two-stage development goal of building China into a great modern socialist country by the middle of this century (2035/2050)" as China's overall national strategy by 2050. In this study, the
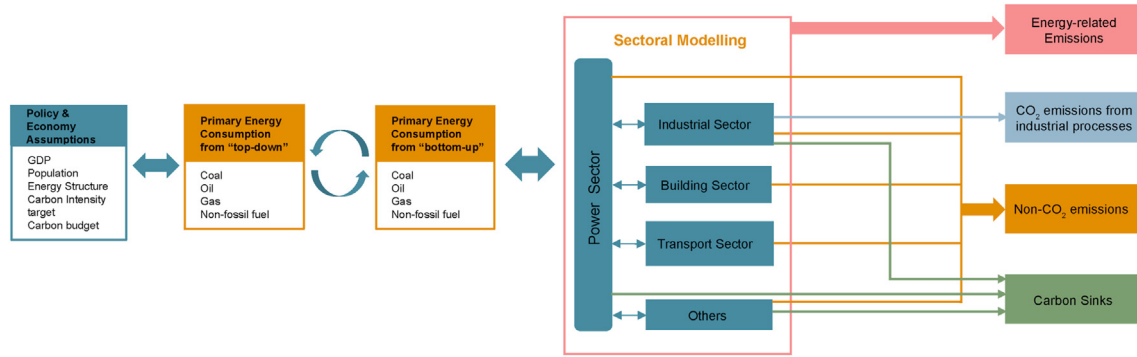
Fig. 1. Research framework and methodologies.

combination of China's domestic climate change strategy and two-step strategic deployment of China's socialist modernization is fully considered (2035/2050). In addition, China's long-term low-carbon transition pathway is divided into two stages, by taking the inertia of economic development, the temperature rise control target of the Paris Agreement and China's "2060 carbon neutral" goal into account. The first phase, from 2020 to 2035, will focus on implementing and strengthening the NDCs of emission reduction in line with the social and economic development goals of "basically realizing the strategy of socialist modernization and building a beautiful China". The second stage, from 2035 to 2050, will achieve the pathway of deep decarbonization of energy and economy, which is not only consistent with the goal of holding global average temperature increase to "*well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*", but realizing the goal of fully building a great modern socialist country by 2050.

- NDC scenario: Implementing and continuing the NDC targets, action plans and related policies submitted by China in 2015. The major policy goals include peaking carbon emissions around 2030 and a 20% share of renewable energy in primary energy consumption by 2030; the continuation of the reduction efforts of emission intensity from 2030 as it is before 2030.
- ENDC scenario: Enhancing energy conservation, improving energy efficiency and optimizing energy structure before 2030, continuously increasing the reduction efforts of emission intensity from 2030 as it is before 2030.
- 2 °C scenario: Achieving an emissions reduction scenario consistent with the goal of limiting the global temperature rise to 2 °C by 2050, assuming that the transition can be achieved immediately from 2020 and that per capita CO_2 emissions will not exceed about 1.5t by 2050, which is actually an "ideal" scenario without considering the development inertia of China's economy.
- 1.5 °C scenario: Achieving net-zero CO_2 emissions by 2050 and deep emissions reduction in other greenhouse gases is also an "ideal" scenario without considering the development inertia of China's economy.
- 2 °C target-oriented scenario (the 2 °C path): This scenario takes into account the inertia of China's economic development and the two-stage goal of socialist modernization, setting an ENDC pathway before 2030, accelerating the transition from 2030, and limiting the per capita CO_2 emissions level to around 1.5t/person by 2050.
- 1.5 °C target-oriented scenario (the 1.5 °C path): This scenario takes into account the inertia of China's economic development and the two-stage goal of socialist modernization, setting an

ENDC pathway before 2030, accelerating the transition from 2030, limiting the per capita CO_2 emissions level to around 1t/person and achieving net zero carbon emissions by 2050.

3. Results

3.1. Carbon emissions pathways

The carbon emission trajectories of both the NDC and the ENDC scenarios are still far behind the global temperature goal of the Paris Agreement. Under the NDC scenario, the growth of energy-related CO_2 emissions would slow down from the year 2025 and carbon emissions would peak around 10.9 billion tons before 2030. Under the ENDC scenario, CO_2 emissions would reach a plateau by 2025 and peak around 10.5 billion tons before 2030. Significant emissions reduction would be needed earlier under the 2 °C scenario and 1.5 °C scenario, bringing forward the peak year to 2025 and 2020, respectively, with the peak value correspondingly reduced to 10.1 and 9.2 billion tons (Fig. 2), energy-related CO_2 emissions would fall accordingly to 2.92 and 1.47 billion tons by 2050. If considering industrial process emissions, carbon capture and storage (CCS) and agroforestry carbon sink, net CO_2 emissions would reach about 2 billion tons by 2050 under the 2 °C scenario. Correspondingly, under the 1.5 °C scenario, CCS and agroforestry carbon sink, net zero CO_2 emissions would be basically achieved by 2050.

Because of the inertia of China's current economic and social development, it is difficult to shift quickly to the emissions reduction pathway under the 2 °C and 1.5 °C scenarios over the short term. One feasible solution could be to build on the ENDC scenario
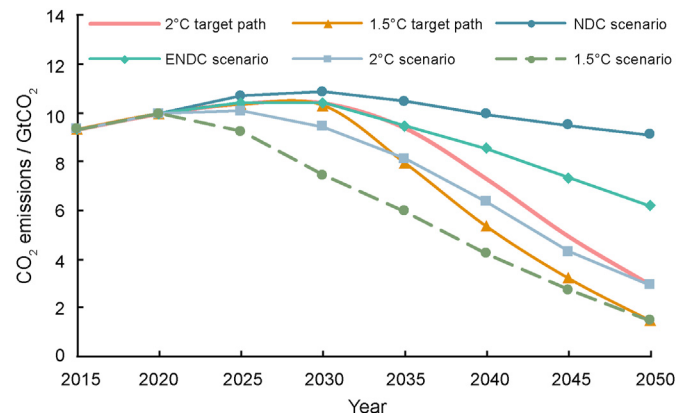

Fig. 2. Comparison of CO_2 emission reduction pathways in different scenarios.

by 2030 and strive to achieve deeper emission reduction later than those of the ENDC scenario. For example, from 2030 the low-carbon energy structure and improved energy efficiency will accelerate the transition to the emission reduction path under both the 2 °C and 1.5 °C scenarios. Under the 2 °C target-oriented scenario, the average annual reduction rate of CO_2 emissions would need to reach 6.1% during the period of 2030−2050, while under the 1.5 °C target-oriented scenario it is expected to be 9.3%.

3.2. GHG emission structure

Both the 2 °C and 1.5 °C target-oriented scenarios need to consider the deep reduction of all GHG emissions, CCS and bio-energy with carbon capture and storage (BECCS), and the increase of agroforestry carbon sink potential. Compared to 2020, under the 2 °C target-oriented scenario, it would lead to an 80% reduction in net CO_2 emissions, a 30% reduction in non-CO_2 emissions and a 70% reduction in total GHG emissions by 2050. The annual increased carbon sink potential in agriculture, forestry and land use could reach 700 million tons, and CO_2 emissions stored with CCS and BECCS could reach 510 million tons. Reductions of non-CO_2 GHG emissions would be more important in the future. In 2050, non-CO_2 GHG emissions would account for 34% which is much higher than its current value of 16%.

According to the 1.5 °C oriented net-zero scenario, the decarbonization process in all sectors would need to be further accelerated after 2030, especially in the industrial and power sectors. By 2050, with the annual contribution of 780 million tons of increased carbon sinks from agriculture, forestry and land use, plus 880 million tons of storage with CCS and BECCS, net CO_2 emissions would need to be reduced to about 60 million tons to achieve net-zero CO_2 emissions. At that time, reducing non-CO_2 emissions would still lack cost-effective technical support. Therefore only a 50% reduction in emissions could be achieved compared to the 2020 levels, which totals approximately 1.27 billion tons CO_2 equivalent in 2050. The total net GHGs would be about 90% lower than that of the year 2020, equaling 1.33 billion tons, which would lay the foundation for achieving net-zero GHG emissions before 2060 (Fig. 3).

3.3. Primary energy structure

China has been heavily reliant on fossil fuels, which accounted for 84% of the country's total primary energy consumption in 2020. Coal was the primary fossil fuel used (about 57.5% of China's energy mix), followed by oil (18%) and natural gas (8.7%). Under the 2 °C target-oriented scenario, China's primary energy consumption enters a plateau before peaking around 2035. It then falls about 13% from 2030 to 2050. Coal as a share of primary energy use drops

from 45% in 2030 to less than 10% in 2050. The share of non-fossil fuels, by contrast, increases significantly, from 25% in 2030 to 70% in 2050. To achieve the 1.5 °C target, China needs to further decarbonize its energy system while limiting energy demand increases. In the 1.5 °C target-oriented scenario, China's energy consumption peaks five years earlier in around 2030 and then falls by 16.4% by 2050. The move towards 1.5 °C also requires China to accelerate the shift away from fossil fuels after 2030. As shown in Fig. 4, by 2050, coal's share in energy consumption falls below 5%, while the share of non-fossil fuel grows to 85%. Both scenarios see a decarbonized energy system dominated by non-fossil fuels and a substantial reduction in energy demand driven by energy conservation, energy efficiency improvement, household energy consumption patterns change and other actions targeting lowering carbon footprints.

3.4. Electrification rates in end-use sectors

To enable a low-carbon transition, China needs to promote the substitution of electricity for fossil fuels to increase the share of electricity consumed in end-use sectors, at the same time, reducing total energy demand. In 2020, China's final energy consumption was still dominated by fossil fuels, with electricity accounting for only 25%. The industrial sector was the largest energy consumer, accounting for 60% of total final energy consumption, followed by building (21%), transport (14%) and other sectors (5%). Under the 2 °C target-oriented scenario, electricity's share in final energy consumption exceeds 30% by 2030, and the share of primary energy used for electricity generation increases from the current 45% to over 50%. By 2050, electricity makes up approximately 55.6% of the final energy consumption, and the remainder is met by direct use of fossil fuels (35.1%) and zero-carbon fuels (9.3%) such as hydrogen and biomass. The 1.5 °C target-oriented scenario sees higher electrification rates and lower energy consumption in end-use sectors (see Fig. 5). For example, the transport sector requires significant increases in the electrification rate of all modes of transport, but mainly in the electrification of passenger cars and inland vessels. By 2050, the total final energy consumption drops by 16.4% from the 2030 level, and the share of electricity consumption in industrial, building and transport sectors reaches 69.5%, 77.4% and 57.1%, respectively.

3.5. Transformation in the power sector

End-use electrification and green hydrogen production are expected to accelerate China's electricity demand growth over the next 30 years. Compared to 2020, China's electricity demand by 2050 increases by 80% under the 2 °C target-oriented scenario and by 95% under the 1.5 °C target-oriented scenario. Transforming the power sector with a cleaner electricity supply is among the key
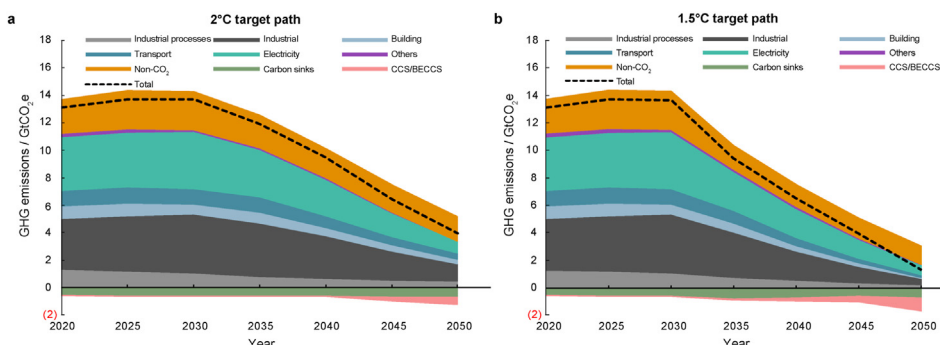

Fig. 3. Greenhouse gases emissions under the 2 °C and the 1.5 °C target-oriented scenarios.
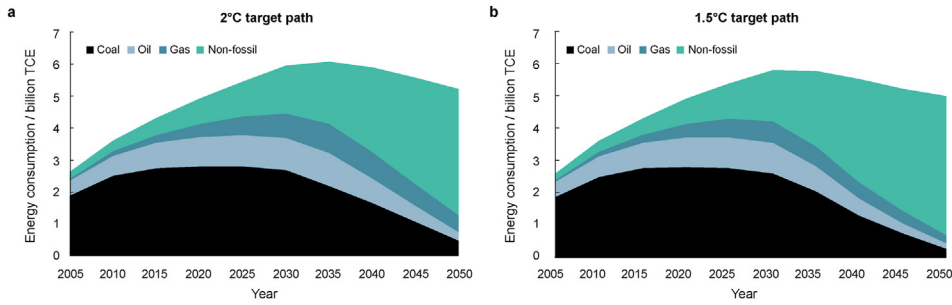
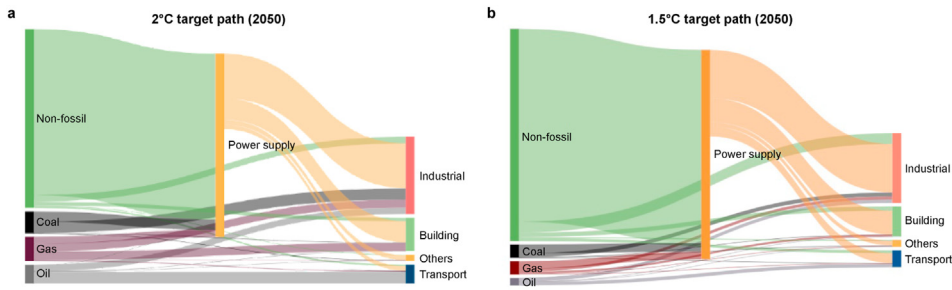**Fig. 4.** Primary energy consumption by fuel under the 2 °C and the 1.5 °C target-oriented scenarios.

Fig. 5. Final energy consumption by fuel type and sector under the 2 °C and the 1.5 °C target-oriented scenarios.

measures for achieving deep decarbonization. As shown in Fig. 6, in both scenarios, by 2050, non-fossil power generation makes up more than 93% of the installed capacity and more than 90% of the electricity supply. Renewables play a critical role in driving the transformation, contributing 60% of the total output. In addition, the development of CCS and BECCS technologies provides flexibility to keep coal and natural gas in China's future power mix. Under the 2 °C target-oriented scenario, the installed capacity of CCS-equipped coal plants reaches 68 GW in 2050 with 320 Mt CO_2 captured annually, while the installed capacity of BECCS reaches 32 GW with 190 Mt CO_2 captured. Under the 1.5 °C target-oriented scenario, the installed capacity of CCS-equipped coal plants increases to 149 GW in 2050 with 600 Mt CO_2 captured annually, while the installed capacity of BECCS increases to 48 GW with 280 Mt CO_2 captured.

4. Discussion

4.1. Achieving 1.5 °C target needs extensive mitigation efforts

The study finds that, moving from 2 °C pathway to 1.5 °C pathway requires all sectors to intensify efforts to achieve net zero energy-related CO_2 emissions by 2050. These efforts include

ramping up emission reductions in power and end-use sectors, implementing CCS/BECCS at field scale, and deploying non-CO_2 emissions reduction technologies in advance (Fig. 7). Under the 1.5 °C target-oriented scenario, the net CO_2 emissions in 2050 are about 2200 Mt lower than the 2 °C target-oriented scenario. The results also indicate that, to meet the 1.5 °C target, China needs to sharply cut GHGs from the industrial sector, maximize emission reductions in building and transport sectors, and offset the remaining CO_2 emissions with CCS and BECCS technologies. Technology innovations may provide opportunities to further bring down non-CO_2 GHG emissions. However, reducing non-CO_2 emissions may still be a critical challenge for China to go completely net zero in the last mile. Our analysis shows that, under the 1.5 °C scenario, China's non-CO_2 emissions total 1.33 Gt CO_2 equivalent in 2050.

4.2. Reaching carbon neutrality requires huge energy infrastructure investment

The low carbon transition requires significant investments for building new energy and power supply systems, improving end-use energy efficiency, constructing alternative energy infrastructure, and upgrading existing facilities. Our analysis finds that, in all
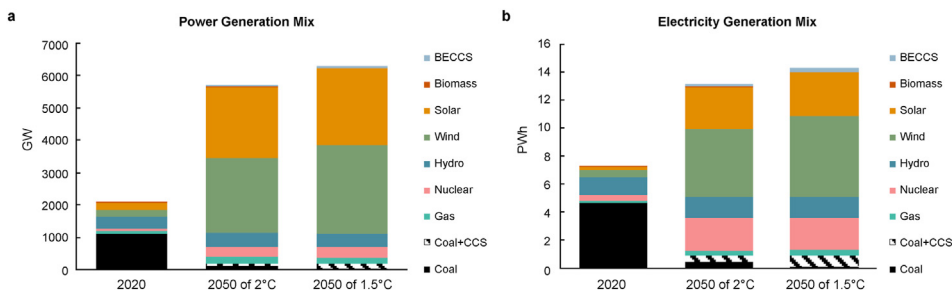

Fig. 6. Mix of energy sources for electricity generation and installed capacity under the 2 °C and the 1.5 °C target-oriented scenarios.
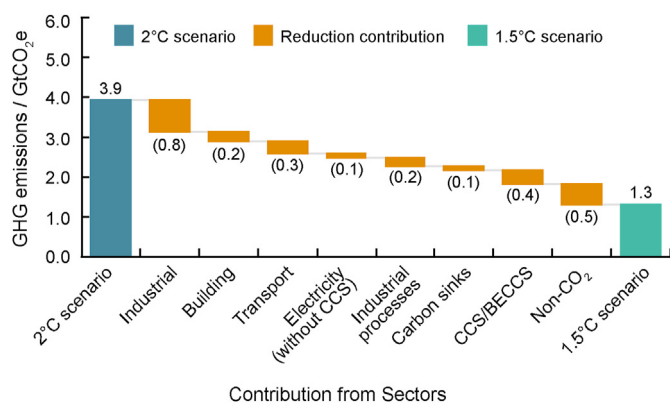
Fig. 7. Contribution of sectors to the emission reduction for shifting away from the 2 °C—1.5 °C pathways.
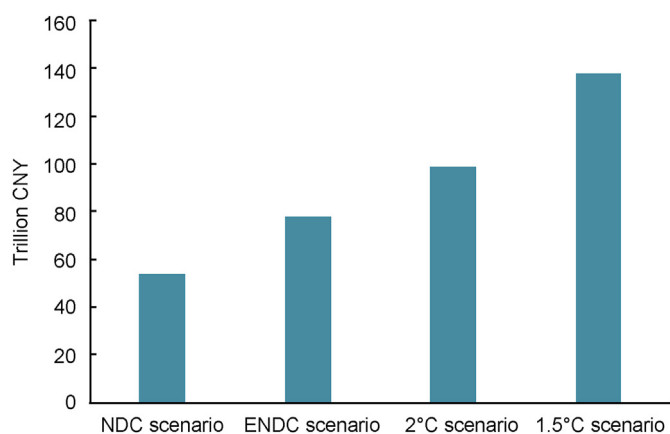

Fig. 8. Cumulative investments needed for energy infrastructure during 2020—2050.

policy scenarios that consider temperature goals set by the Paris Agreement, investment in the energy sector will soar. As shown in Fig. 8, cumulative investments in the energy infrastructure during 2020—2050 are projected to be CNY 53.7 trillion (at constant 2015 prices) under the NDC scenario. This figure increases by more than 50% under the ENDC scenario, 90% (CNY 99.1 trillion) under the 2 °C scenario, and 160% (CNY 137.7 trillion) under the 1.5 °C scenario. The annual average investments required are CNY 1.8 trillion under the NDC scenario, CNY 2.6 trillion under the ENDC scenario, CNY 3.3 trillion under the 2 °C scenario, and CNY 4.6 trillion under the 1.5 °C scenario. Globally, the world's annual energy investment needs are around 2.5% (1.6—3.4%) of GDP for achieving the 2 °C goal and 2.8% (1.8—3.9%) for achieving the 1.5 °C goal. Looking to the future, China expects to have a much higher demand for energy investment than other major economies [22].

5. Conclusions and policy implications

Reaching carbon neutrality before 2060 will be a challenging yet achievable goal for China. Our analysis finds that, following the 1.5 °C pathway, energy-related CO_2 emissions need to reach a plateau as soon as possible; net zero CO_2 emissions will be basically achieved by 2050 before 2060. For net zero emissions to be

achieved before 2060, the average annual reduction of CO_2 emissions is required to be around 0.5 billion tons from 2030 to 2050. Non-CO_2 greenhouse gas emissions would need to peak at around 2.5 billion tCO_2e by 2030, and then fall rapidly to 1.3 billion tons of tCO_2e by 2050 after reaching the peak, which corresponds to a reduction of 48% relative to the level of 2020s.

Most importantly, China needs to further decarbonize its energy mix and limit the total energy demand surge. Under the 1.5 °C target-oriented scenario, China's final energy demand in 2050 is 40% lower compared to the NDC scenario, and 13% lower than that under the 2 °C target-oriented scenario. The proportion of non-fossil fuels in primary energy reaches 86.2% in 2050, nearly 50% higher than that under the NDC scenario and about 13% higher than that under the 2 °C target-oriented scenario. Transitioning to carbon neutrality also requires huge energy infrastructure investments. Under the 1.5 °C scenario, the total amount of energy infrastructure investment needs during the period of 2020—2050 are CNY 137.7 trillion, translating to CNY 4.6 trillion each year.

The above results offer several important policy implications. First, China's technological pathway towards carbon neutrality will be highly reliant on energy conservation and energy efficiency improvements, and establishing non-fossil energy supply systems, electrifying end-use sectors, mitigating non-CO_2 emissions, enhancing agroforestry carbon sinks, and reducing energy demands significantly through changing consumption patterns. Second, in addition to conventional emission reduction technologies, specific attention need to be paid to the areas that are difficult to achieve deep emission reductions, and the guidance of low-carbon consumption patterns in the whole society as well. In this context, a comprehensive assessment and earlier deployment of strategic technologies are needed.

Lastly, China needs to incorporate climate change into its medium and long-term overall development goals and strategies in the new era of socialist modernization, and to make it a priority by formulating a long-term development strategy of low GHG emissions that meets both the Paris Agreement and their own long-term goals for domestic economic and social development. Accordingly, a domestic long-term climate strategy towards carbon neutrality with a phased implementation in both its Five-year Plans and the long-term plan is also needed.

Declaration of competing interest

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

Acknowledgements

Appendix

Table 1
GDP, Energy consumption and CO_2 emissions in the NDC scenario.

		2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Annual GDP growth rate (%)			11.3	7.9	6.5	5.5	5.0	4.5	4.0	3.5	3.0
GDP index		1.0	1.7	2.5	3.4	4.5	5.7	7.1	8.7	10.3	11.9
Energy consumption (billion TCE)		2.6	3.6	4.3	4.9	5.5	6.1	6.1	6.1	6.2	6.2
Energy mix	Coal (%)	72.4	69.2	64.0	57.4	52.7	47.6	44.5	40.9	37.7	34.9
	Oil (%)	17.8	17.4	18.1	18.0	18.2	18.4	17.6	16.5	15.6	14.8
	Natural gas (%)	2.4	4.0	5.9	8.7	10.1	11.6	12.2	12.9	13.5	14.0
	Non-fossil fuels (%)	7.4	9.4	12.0	15.9	19.0	22.4	25.7	29.8	33.2	36.3
CO_2 emissions per unit of energy consumption (kg CO_2/kgce)		2.3	2.3	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.5
Annual decline of CO_2 emissions per unit of energy consumption (%)			0.6	0.8	0.9	1.0	1.5	1.0	1.3	1.2	1.1
CO_2 emissions (GtCO_2)		6.1	8.1	9.3	10.2	10.8	11.1	10.6	10.0	9.5	9.1
Annual decline of energy consumption per unit of GDP (%)			6.0	2.8	1.9	1.1	0.5	−0.9	−1.1	−1.0	−0.9
Annual decline of CO_2 emissions per unit of GDP (%)			4.7	4.7	4.3	4.2	4.3	5.1	4.9	4.4	3.8
Decline from the 2005 level (%)			21.5	38.5	50.6	60.2	68.0	75.4	80.9	84.7	87.4

Table 2
GDP, Energy consumption and CO_2 emissions in the ENDC scenario

		2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Annual GDP growth rate (%)			11.3	7.9	6.5	5.5	5.0	4.5	4.0	3.5	3.0
GDP index		1.0	1.7	2.5	3.4	4.5	5.7	7.1	8.7	10.3	11.9
Energy consumption (billion TCE)		2.6	3.6	4.3	4.9	5.5	6.0	6.0	6.0	5.8	5.6
Energy mix	Coal (%)	72.4	69.2	64.0	57.4	51.9	46.0	40.4	35.2	30.1	25.3
	Oil (%)	17.8	17.4	18.1	18.0	17.4	16.7	15.3	13.7	12.6	11.3
	Natural gas (%)	2.4	4.0	5.9	8.7	10.8	13.1	12.7	12.4	12.2	11.9
	Non-fossil fuels (%)	7.4	9.4	12.0	15.9	19.9	24.3	31.6	38.6	45.1	51.5
CO_2 emissions per unit of energy consumption (kg CO_2/kgce)		2.3	2.3	2.2	2.1	1.9	1.8	1.6	1.4	1.3	1.1
Annual decline of CO_2 emissions per unit of energy consumption (%)			0.6	0.8	0.9	1.6	1.4	2.2	2.3	2.4	2.7
CO_2 emissions (GtCO_2)		6.1	8.1	9.3	10.2	10.6	10.6	9.6	8.5	7.3	6.2
Annual decline of energy consumption per unit of GDP (%)			6.0	2.8	1.9	0.7	0.1	−2.1	−2.2	−3.0	−3.3
Annual decline of CO_2 emissions per unit of GDP (%)			4.7	4.7	4.3	4.6	4.7	6.3	6.0	6.3	6.1
Decline from the 2005 level (%)			21.5	38.5	50.6	61.0	69.2	77.8	83.7	88.3	91.4

Table 3
GDP, Energy consumption and CO_2 emissions in the 2 °C scenario

		2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Annual GDP growth rate (%)			11.3	7.9	6.5	5.5	5.0	4.5	4.0	3.5	3.0
GDP index		1.0	1.7	2.5	3.4	4.5	5.7	7.1	8.7	10.3	11.9
Energy consumption (billion TCE)		2.6	3.6	4.3	4.9	5.4	5.6	5.6	5.5	5.3	5.2
Energy mix	Coal (%)	72.4	69.2	64.0	57.4	51.0	43.2	37.1	28.2	16.6	9.1
	Oil (%)	17.8	17.4	18.1	18.0	16.9	15.5	13.4	11.4	9.4	7.7
	Natural gas (%)	2.4	4.0	5.9	8.7	10.5	12.6	11.9	11.2	10.6	10.0
	Non-fossil fuels (%)	7.4	9.4	12.0	15.9	21.6	28.6	37.6	49.2	63.4	73.2
CO2 emissions per unit of energy consumption (kg CO2/kgce)		2.3	2.3	2.2	2.1	1.9	1.7	1.5	1.2	0.8	0.6
Annual decline of CO2 emissions per unit of energy consumption (%)			0.6	0.8	0.9	2.0	2.2	2.8	4.3	7.1	6.9
CO2 emissions (GtCO2)		6.1	8.1	9.3	10.2	10.1	9.4	8.1	6.4	4.3	2.9
Annual decline of energy consumption per unit of GDP (%)			6.0	2.8	1.9	−0.3	−1.4	−3.0	−4.7	−7.5	−7.4
Annual decline of CO2 emissions per unit of GDP (%)			4.7	4.7	4.3	5.5	6.1	7.2	8.4	10.7	10.1
Decline from the 2005 level (%)			21.5	38.5	50.6	62.8	72.8	81.2	87.9	93.1	96.0

Table 4
GDP, Energy consumption and CO_2 emissions in the 1.5 °C scenario

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Annual GDP growth rate (%)		11.3	7.9	6.5	5.5	5.0	4.5	4.0	3.5	3.0
GDP index	1.0	1.7	2.5	3.4	4.5	5.7	7.1	8.7	10.3	11.9
Energy consumption (billion TCE)	2.6	3.6	4.3	4.9	5.3	5.3	5.2	5.1	5.1	5.0
Energy mix Coal (%)	72.4	69.2	64.0	57.4	46.8	35.4	28.2	19.5	12.0	5.4
Oil (%)	17.8	17.4	18.1	18.0	15.7	13.2	10.8	7.8	5.3	3.0
Natural gas (%)	2.4	4.0	5.9	8.7	10.6	12.6	10.9	8.9	7.1	5.5
Non-fossil fuels (%)	7.4	9.4	12.0	15.9	26.9	38.7	50.1	63.8	75.7	86.1
CO_2 emissions per unit of energy consumption (kg CO_2/kgce)	2.3	2.3	2.2	2.1	1.7	1.4	1.1	0.8	0.5	0.3
Annual decline of CO_2 emissions per unit of energy consumption (%)		0.6	0.8	0.9	3.5	4.0	4.1	6.5	8.0	11.5
CO_2 emissions (GtCO_2)	6.1	8.1	9.3	10.2	9.3	7.4	6.0	4.2	2.7	1.5
Annual decline of energy consumption per unit of GDP (%)		6.0	2.8	1.9	−2.0	−4.3	−4.4	−6.7	−8.2	−11.7
Annual decline of CO_2 emissions per unit of GDP (%)		4.7	4.7	4.3	7.1	8.9	8.5	10.3	11.3	14.3
Decline from the 2005 level (%)		21.5	38.5	50.6	65.8	78.5	86.2	92.0	95.6	98.0

Table 5
GDP, Energy consumption and CO_2 emissions in the 2 °C target-oriented scenario

Item (Unit)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Annual GDP growth rate (%)		11.3	7.9	5.9	5.3	4.8	4.4	4	3.6	3.2
GDP index	1	1.7	2.5	3.3	4.3	5.5	6.8	8.2	9.8	11.5
Energy consumption (billion TCE)	2.6	3.6	4.3	4.9	5.5	6.0	6.1	5.9	5.6	5.2
Energy mix Coal (%)	72.4	69.2	64.0	57.0	51.0	45.0	36.0	28.0	19.0	9.1
Oil (%)	17.8	17.4	18.1	18.5	18.0	17.0	17.0	13.0	9.0	7.7
Natural gas (%)	2.4	4.0	5.9	8.5	11.0	13.0	15.0	14.0	12.0	10.0
Non-fossil fuels (%)	7.4	9.4	12.0	16.0	20.0	25.0	32.0	45.0	60.0	73.2
CO_2 emissions per unit of energy consumption (kg CO_2/kgce)	2.3	2.3	2.2	2.0	1.9	1.8	1.6	1.2	0.9	0.6
Annual decline of CO_2 emissions per unit of energy consumption (%)		0.6	0.8	1.3	1.3	1.6	2.5	4.4	6.5	8.6
CO_2 emissions (GtCO_2)	6.1	8.1	9.4	10.0	10.5	10.5	9.4	7.3	4.9	2.9
Annual decline of energy consumption per unit of GDP (%)		4.2	3.8	3.1	3.0	3.0	4.0	4.4	4.5	4.4
Annual decline of CO_2 emissions per unit of GDP (%)		4.7	4.6	4.3	4.2	4.6	6.3	8.6	10.7	12.7
Decline from the 2005 level (%)		21.5	38.0	50.3	60.0	68.3	77.1	85.4	91.7	95.8

Table 6
GDP, Energy consumption and CO_2 emissions in the 1.5 °C target-oriented scenario

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Annual GDP growth rate (%)		11.3	7.9	5.9	5.3	4.8	4.4	4.0	3.6	3.2
GDP index	1	1.7	2.5	3.3	4.3	5.4	6.8	8.2	9.8	11.5
Energy consumption (billion TCE)	2.6	3.6	4.3	5.0	5.6	6.2	6.1	5.9	5.9	5.6
Energy mix Coal (%)	72.4	69.2	64.0	56.1	50.5	44.0	33.4	21.7	11.8	7.1
Oil (%)	17.8	17.4	18.1	17.7	16.8	15.7	11.3	7.4	5.0	2.7
Natural gas (%)	2.4	4.0	5.9	8.3	10.1	11.1	9.1	7.4	5.5	3.3
Non-fossil fuels (%)	7.4	9.4	12.0	17.9	22.7	29.1	46.3	63.5	77.7	86.9
CO_2 emissions per unit of energy consumption (kg CO_2/kgce)	2.3	2.3	2.2	2.1	1.9	1.7	1.3	0.8	0.5	0.3
Annual decline of CO_2 emissions per unit of energy consumption (%)		0.6	0.8	0.9	1.4	1.9	5.0	6.6	8.0	8.4
CO_2 emissions (GtCO_2)	6.1	8.1	9.3	10.2	10.4	10.4	7.7	5	3	1.7
Annual decline of energy consumption per unit of GDP (%)		6.0	2.8	1.9	2.8	2.4	4.2	4.0	3.4	3.5
Annual decline of CO_2 emissions per unit of GDP (%)		4.7	4.7	4.3	4.1	4.1	8.2	9.3	10.0	10.4
Decline from the 2005 level (%)		21.5	38.5	50.6	60.3	68.4	81.3	90	95	97.6

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