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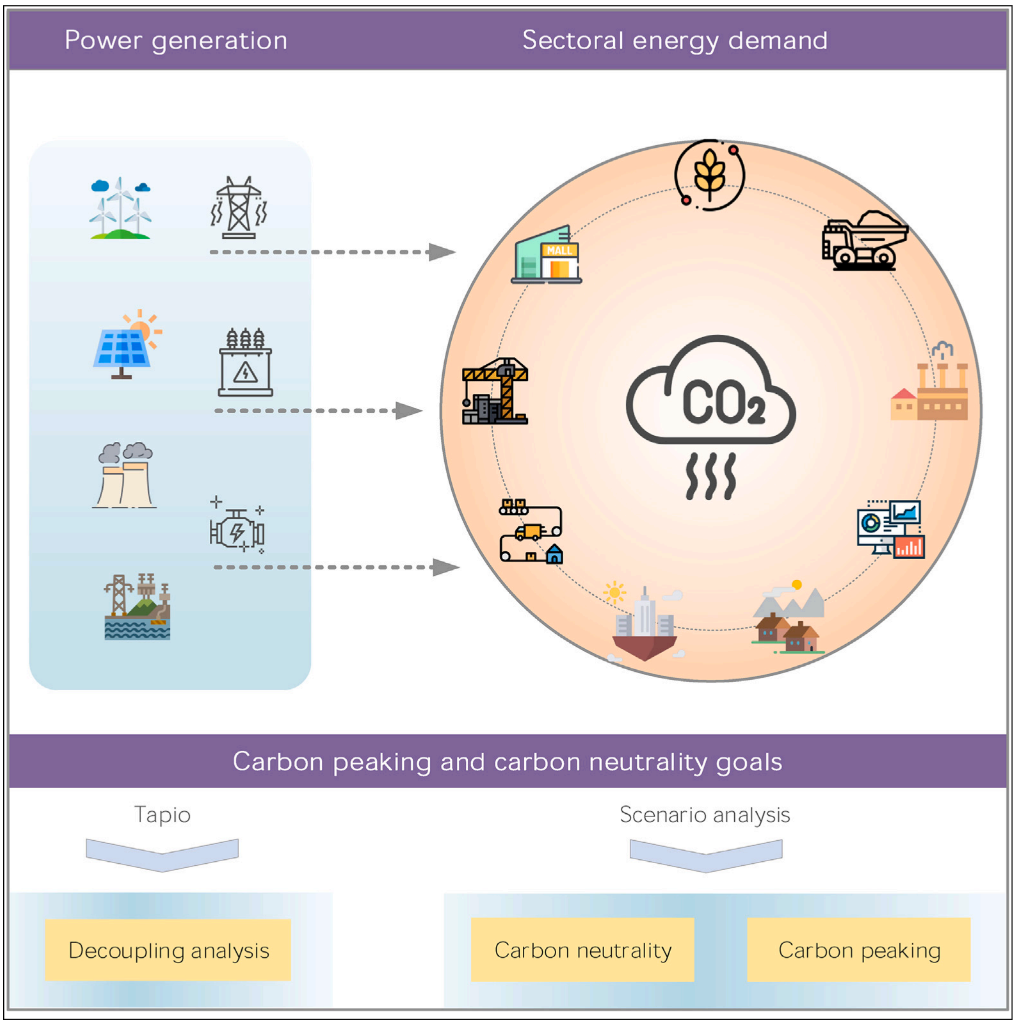
Multi-scenario reduction pathways and decoupling analysis of China's sectoral carbon emissions



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Highlights

Sectoral energy consumption and carbon emission pathways in China are analyzed

Under three scenarios, China's carbon emissions peak in 2030, 2026, and 2025

Strong decoupling of economic growth and CO_2 lags one year behind the peak reached

In 2050, wind and PV will account for around 50% of electricity generation

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Multi-scenario reduction pathways and decoupling analysis of China's sectoral carbon emissions

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SUMMARY

To achieve its goal of carbon emissions peak and neutrality, China requires synergistic efforts across all sectors. In this study, three scenarios—baseline, policy, and green low-carbon—were developed to explore the pathways for China's emissions reduction across sectors from 2020 to 2060, and the timing of decoupling economic growth from CO_2. The results showed that, under these scenarios, China's carbon emissions peak in 2030, 2026, and 2025, with strong decoupling time, lagged one year behind peak attainment. The agriculture, forestry, livestock, and fishing (AFH) and mining and quarrying (MQ) sectors would be the first to achieve a carbon peak. Under all three scenarios, all of the other sectors—with the exception of electricity, gas, and water production and supply (EGW)—will achieve a carbon peak by 2030. Therefore, policymakers should set carbon peak goals based on sector characteristics and ensure energy security in the process of achieving carbon neutrality.

INTRODUCTION

The climate change caused by the consumption of fossil fuels has become one of the most important issues of concern in the world given rapid economic development.[1–5] In the Emissions Gap Report 2020, the United Nations Environment Program pointed out that global greenhouse gas emissions reached 59.1 billion tons of carbon dioxide equivalent in 2019.[6–8] Unless global greenhouse gas concentrations fall by 7.6% per year from 2020 to 2030, the Paris Agreement's goal of holding global temperature increases in this century to 1.5°C will not be achieved.[9,10] To mitigate climate change as quickly as possible, 110 countries have proposed or committed to carbon neutrality targets by 2050 in various forms, such as legislation, legal proposals, and policy documents.[11–13]

China, with its vast territory, complex natural conditions, and fragile ecological environment, is one of the countries that would be significantly affected by the adverse effects of climate change,[14,15] so it has always attached great importance to the issue.[16,17] China signed the Kyoto Protocol in May 1998 and the Paris Agreement in April 2016, and it has formulated and implemented a series of proactive policies and actions to reduce emissions in conjunction with its national economic and social strategies.[18,19] In September 2020, China officially proposed the goal of achieving its carbon peak by 2030 and carbon neutrality by 2060 at the 75th session of the United Nations General Assembly.[20,21] Further, the Chinese State Council, the Energy Bureau, and other relevant departments have issued a number of guidance documents on emissions reduction. At the regional level, some provinces and municipalities have included "dual carbon" goals in their government work reports.

China's energy structure remains dominated by fossil fuels, however, and the factors influencing carbon emissions are complex and variable, involving multiple subjects, levels and industries.[22,23] China's carbon neutrality target therefore requires a concerted adjustment across multiple sectors.[24] Currently, China has developed carbon reduction documents for the power generation sector or key energy-consuming industries; however, other sectors are only mentioned in government documents. In this context, it is necessary to better understand the sectoral characteristics of total energy consumption and carbon emissions, so as to develop reasonable pathways for China's carbon reduction.[25,26] Current studies either analyze only the timing of carbon peaks and reduction pathways for countries as a whole or for specific sectors. Different models and data sources make it difficult to make meaningful comparisons across sectors.[27,28] From the perspective of sustainable economic and social development, carbon neutrality also means that economic development will change from a high-carbon development model to a low-carbon green development model. Therefore, the relationship between economic growth and carbon emissions needs to be further considered.[29] Decoupling index can be used to examine the relationship between economic growth and carbon emissions, to find out whether economic development comes at the cost of environmental pollution.[21,22,30] There has been some research that has used decoupling analysis to discuss the decoupling time of economic growth and carbon emissions in China; however, there are still relatively few studies that have comprehensively compared the decoupling status of different sectors in the country.

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Table 1. Selected related studies

	Model	Region	Time period	Main findings	Reference
Carbon emissions and carbon neutrality	Kaya	Mexico	2015–2050	Gradual transition scenarios reach 501 Mt carbon emissions in 2050.	De La Peña et al.[2]
	EKC	China	2018–2060	China could reach a carbon peak in 2027, 2026, and 2025, and then achieve the zero-carbon emission goal in 2050, 2044, and 2040, respectively.	Xu et al.[7]
	STIRPAT	China	2015–2045	Results show that China may reach peak emissions in the period 2028–2040.	Fang et al.[11]
Carbon emissions reduction and Scenario analysis	Monte Carlo simulation	Chongqing	2000–2050	Urban residential buildings will probably hit the emissions peak in 2042.	Huo et al.[46]
	Fast learning network	Guangdong	2020–2060	In Guangdong Province, the peak of carbon emissions can be achieved by 2030.	Ren and Long[44]
	Nonlinear autoregressive network with exogenous input	China	2016–2050	The peak of China's carbon emissions will occur in 2029, 2031, or 2035 under different scenarios.	Xu et al.[41]
Sectoral carbon emissions reduction	LEAP	Building sector	2018–2030	The carbon emissions of Shenzhen's building sector could be capped by 2022–2025 and decreased by more than 60% by 2030.	Jiang et al.[47]
	STIRPAT	Household sector	2015–2040	The household sector in China is most likely to reach its carbon emissions peak between 2025 and 2030.	Zhao et al.[48]
	G-LEAP	Cement industry	2000–2060	Improving energy efficiency and alternative low-carbon fuels would contribute 9%–12% and 17%–22% of the cumulative emissions reduction.	Tan et al.[38]

In general, existing studies use top-down, bottom-up, or integrated models to conduct research on carbon emissions forecasting by region and industry.[31] Top-down models are mainly used to forecast by economic indicators and energy systems, with computable general equilibrium models (CGE) and integrated assessment model (IAM) being the most commonly used top-down models.[32–35] For example, Zhang et al. used a dynamic CGE to compare the carbon emissions of nuclear power under three scenarios.[35] Bottom-up models focus on energy consumption and production patterns for supply and demand forecasting and environmental impact analysis, including the long-term energy alternative planning system model (LEAP).[36–38] Liu et al., for example, classified the 2 + 26 cities according to their industrial structure and energy intensity and built a LEAP city model to analyze the gaps and pathways to carbon neutrality for different city types under different scenarios.[39] Similarly, Cai et al. explored the ways to achieve the dual carbon goals in Bengbu under four scenarios using a LEAP model.[40] These studies provide insights for regional or industrial energy transformation plans, but the results lack comparability.[9]

Previous research also has used methods such as the STIRPAT model and machine learning to forecast carbon emissions.[41,42] The STIRPAT model first decomposes the factors influencing carbon emissions and then combines scenario analysis to forecast regional emissions.[43] Yu et al., for example, evaluated the drivers of household CO_2 emissions in China using the STIRPAT model.[43–45] These studies, however, have not yet fully explored the carbon reduction pathways of different sectors. This study summarizes some of the recent related studies in Table 1.

In summary, the CGE model does not allow for a detailed representation of the impact of technological progress on energy consumption, while the IAM has a more complex model structure and more stringent data requirements. Some predictive models also have stringent data requirements and are difficult to train with improved accuracy.[7,32] The LEAP model has the characteristic of low initial data requirement, and it includes embedded tools to create different data structures for each region. It allows a quick and direct comparison of energy consumption and carbon emissions in different sectors.[17,49] Further explanations about the advantages and disadvantages of different models are given in Table S1 in the supplemental information.

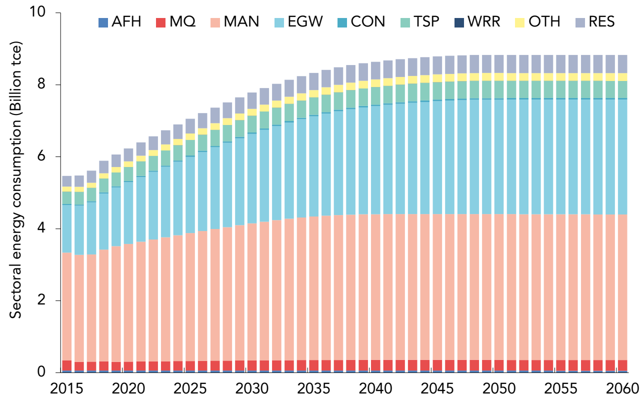

Figure 1. Sectoral energy consumption under the policy scenario

Production sectors include agriculture, forestry, livestock, and fishing (AFH); mining and quarrying (MQ); manufacturing (MAN); electricity, gas, and water production and supply (EGW); construction (CON); transport, storage, and postage (TSP); wholesale and retail trade and hotels and restaurants (WRR); and other (OTH). The household sector (RES) includes both urban and rural residents.

This study makes three potential contributions. First, it analyzes sectoral energy consumption and carbon emissions trends in China and compares the timing of carbon peaking of different sectors under different scenarios. These findings can help policymakers to clarify the current situation of carbon emissions and the potential of carbon reductions of different sectors. In addition, this study predicts the future power generation structure in China under different scenarios, to determine the carbon emissions reduction pathways from the energy supply perspective. This can support developing sectoral carbon emissions reduction strategies considering the power generation structure. Finally, we compare the decoupling times of economic growth and carbon emissions of different sectors using Tapio decoupling analysis. It can support policymakers improve emission reduction programs for different sectors based on the decoupling status of economic growth and carbon emissions.

RESULTS

China's sectoral energy consumption

Energy consumption of different sectors in the same scenario

Figure 1 illustrates the changes in China's ultimate energy consumption for each sector under the policy scenario. The results of the baseline scenario and green low-carbon scenario are presented in Figures S1 and S2 of the supplemental information.

As shown in Figure 1, China's energy consumption follows an increasing trend during the study period under the policy scenario, but there are differences among the sectors. In 2019, China's energy consumption totaled 4.86 billion tons of standard coal, an increase of 3.3% over the previous year. China's total energy consumption grows faster, followed by a slight slowdown from 2020 to 2060. Under the policy scenario that integrates improved energy efficiency and reduction of energy intensity, the manufacturing (MAN) and electricity, gas, and water (EGW) sectors still have the highest energy consumption. By 2030, energy consumption in MAN sector will reach 3,808 million tons and 4,053 million tons by 2050. The energy consumption of the household sector remains basically stable. By 2050, the energy consumption of urban residents will reach 356.4 million tons and 147.7 million tons for rural residents. This suggests that energy consumption in China varies considerably across sectors, so analyzing the characteristics of energy consumption in different sectors is necessary. Figure 2 shows the consumption of different energy types in China.

As shown in Figure 2, in 2019, the consumption of coal, crude oil, natural gas, and electricity increased by 1%, 6.8%, 8.6%, and 4.5%, respectively. Electricity consumption accounted for 23.4% of total energy consumption. By 2040, the share of electricity consumption will exceed 50%, making it the highest proportion in total energy consumption. By 2060, the shares of coal, crude oil, natural gas, and non-fossil energy will be 7.9%, 4.6%, 3.4%, and 82%, respectively, in the policy scenario, compared to 11%, 7%, 3.9%, and 74.7%, respectively, in the baseline scenario. Coal consumption will fall to 695 million tons of standard coal, mainly for emergencies. From 2020 to 2060, natural gas consumption shows an increasing trend, which then stabilizes and finally decreases. Due to the uncertainty of wind and solar power, sufficient natural gas can ensure a safe energy supply. Natural gas, with its clean and low-carbon characteristics, will be an important bridge in the transition of China's energy structure from fossil energy to clean energy.

Comparison of energy consumption in the different scenarios

China's total energy consumption under the three scenarios is shown in Figure 3.

As can be seen in Figure 3, China's total energy consumption shows a trend of growth followed by stability over the period 2020–2060. Under the three different scenarios, China's fossil energy consumption will peak in 2030, 2027, or 2026 with peaks of 5.7 billion tons, 5.3 billion tons, or 5 billion tons, respectively. China's total fossil energy consumption peaks the earliest under the green low-carbon scenario, and the

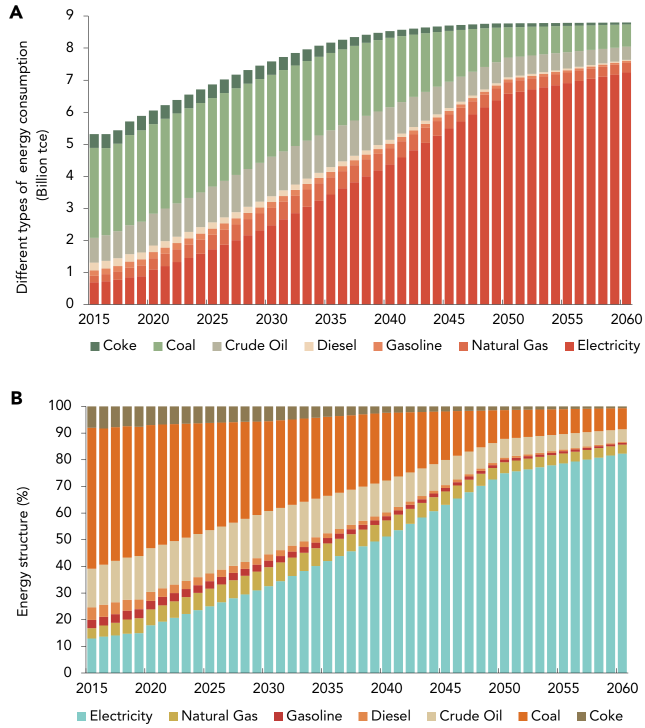

Figure 2. China's energy consumption under the policy scenario

(A) Energy consumption profile in China under the policy scenario.

(B) China's energy structure under the policy scenario.

overall energy consumption is lower; by 2060, total energy consumption will reach 8.1 billion tons under the green low-carbon scenario. Changes in the energy structure of selected sectors are shown in Figure 4.

Figure 4 illustrates the changes in China's energy structure from 2020 to 2060 for several key sectors. The main energy types consumed by the MAN sector are electricity, natural gas, crude oil, coal, and coke; from 2020 to 2060, electricity consumption grows very rapidly, and coal consumption declines quickly; these changes are more pronounced in the decade after peak carbon. However, the consumption of natural gas remains almost unchanged, which suggests that MAN has to ensure energy security while gradually increasing the share of electricity consumption. From 2020 to 2040, the EGW sector retains a high share of coal consumption, but the use of electricity follows an increasing trend. This is associated with a significant increase in the proportion of wind and photovoltaic power generation on the energy supply side. In addition, electrification is increasing in the transport,storage, and postage (TSP) and urban household sectors. The use of energy sources such as diesel, gasoline, and natural gas is slowly decreasing.

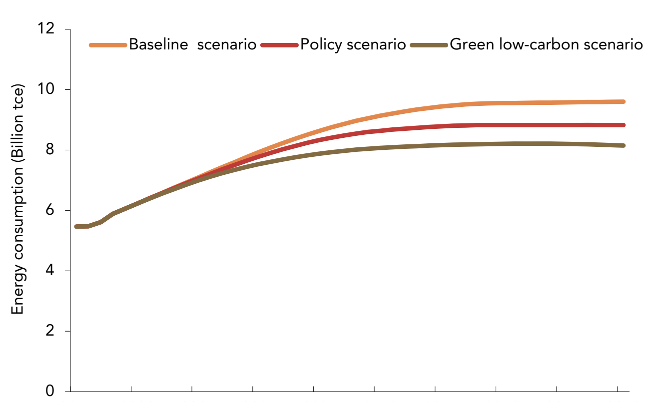

Figure 3. Comparison of China's total energy consumption under the three scenarios, 2015–2060.

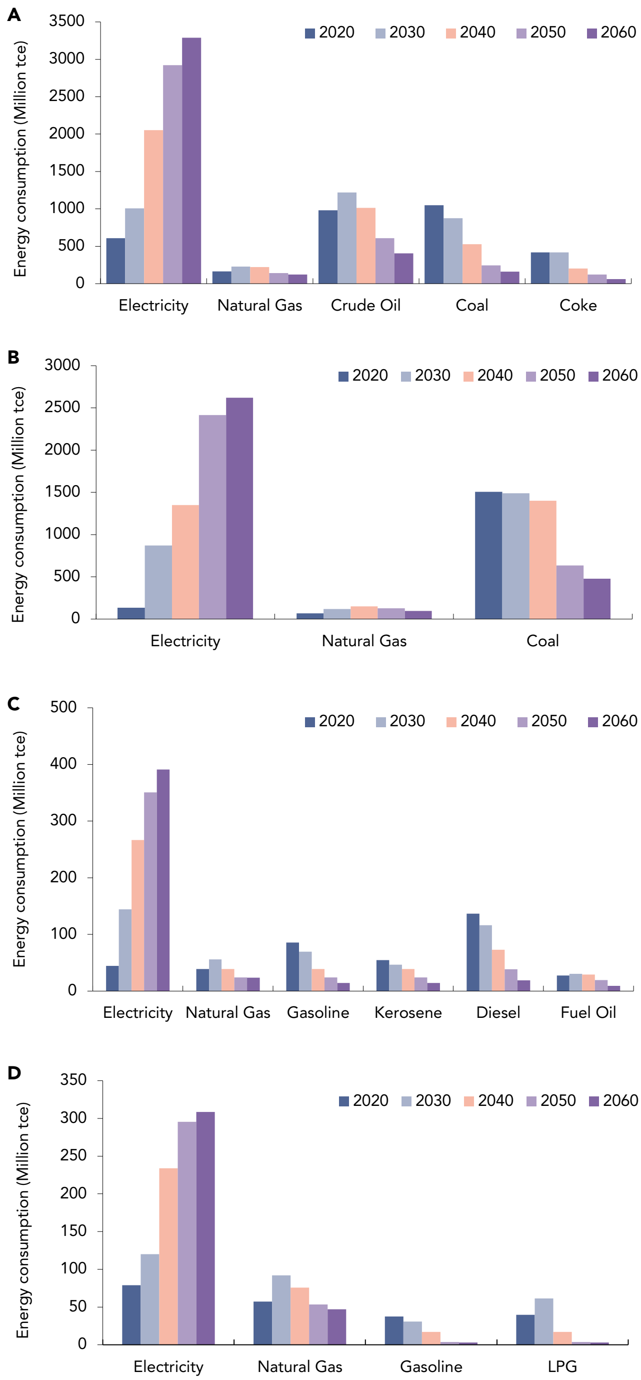

Figure 4. Changes in the energy structure of selected sectors, 2020–2060

(A) Changes in the energy structure of the MAN sector.

(B) Changes in the energy structure of the EGW sector.

(C) Changes in the energy structure of the TSP sector.

(D) Changes in the energy structure of the urban household sector.

Time to peak carbon emissions and total carbon emissions in different sectors

There are differences in the timing of China's peak carbon emissions and the total amount of carbon emissions under the different scenarios. Figure 5 illustrates China's carbon emissions from energy consumption under the different scenarios.

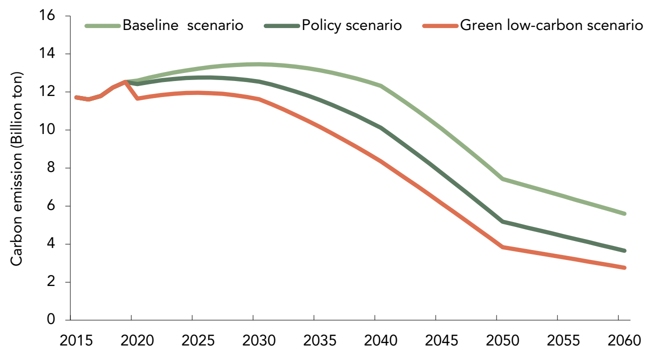

Figure 5. Carbon emissions from energy consumption under the three scenarios, 2015–2060.

As can be seen in Figure 5, China's carbon emissions follow a path of slow growth to a peak, which is then followed by a continuous decline under all three scenarios. Under the three scenarios, China's carbon emissions will peak in 2030, 2026, and 2025 with consumptions of 13.5 billion tons, 12.8 billion tons, and 12 billion tons, respectively. By 2050, the total carbon emissions under the three scenarios will be 7.4 billion tons, 5.2 billion tons, and 3.8 billion tons, respectively. China's carbon emissions will reach 2.8 billion under the green low-carbon scenario in 2060. This suggests that, in the process of achieving carbon neutrality, China should not only consider the reduction of carbon emissions from the perspective of energy consumption, but also from the point of view of carbon sinks and carbon capture to further reduce carbon emissions.

Different sectors have different modes of production, which lead to large differences in the type and total quantity of energy consumption. It is necessary to further analyze the carbon reduction potential of the different sectors. To clarify the current situation and future trend of carbon emissions in China from a sectoral perspective, the time to peak carbon emissions and total carbon emissions for different production sectors under the different scenarios is calculated. The specific results are shown in Figure 6.

Figure 6 illustrates the carbon emissions of different sectors in China under the three scenarios, which can be divided into two categories according to sectoral emissions. The first category includes the sectors that have already reached their peak carbon emissions before forecast year, such as the AFH, MQ, and CON sectors. The other category includes sectors that will reach their peak carbon emissions within the forecast year, including the MAN, TSP, WRR, OTH, and RES sectors. It is thus necessary to set carbon reduction targets based on the characteristics of sectoral production and energy consumption, as well as to gradually promote climate change action in key sectors. Figure 7 illustrates the further analysis of the trends in carbon emissions and the energy structure of the different production sectors under the policy scenario.

As can be seen in Figure 7, the MAN sector has the highest carbon emissions, followed by the EGW sector. Energy structure is one of the key reasons for differences in carbon emissions among sectors. The MAN sector is the pillar industry of China's national economy and the leading sector of economic growth. All of the material products needed for survival and development come from the MAN sector industry. It also includes, however, many high energy consuming processes and procedures. This energy structure is relatively difficult to change, which makes it the sector with the greatest carbon emissions.[50] For the WRR sector, total energy consumption is relatively low and the highest percentage energy consumption is sourced from electricity, which makes it one of the sectors with lowest carbon emissions.

China's power generation structure

Under the call for energy conservation and emissions reduction, the zero-carbon energy source of solar and wind power are gradually becoming the primary options for energy supply. With the change in the energy structure, a sustainable power supply is the guarantee for normal production and livelihood. With reference to the historical installed capacity of different power generation modes and the relevant policies on wind and photovoltaic power generation, this study also forecasts the total amount of power generation under the different scenarios. Figure 8 illustrates the total amount of power generation in China under the three scenarios.

As shown in Figure 8, China's total power generation follows a trend of rapid growth followed by steady growth. It is closely related to the country's strategic development approach of significantly increasing the installed capacity of wind and solar power generation and gradually adjusting the structure of energy consumption. Under the green low-carbon scenario, China's power generation in 2030 will be 10.6 trillion kWh, an increase of 56% compared to 2019. Total power generation would reach 18 trillion kWh in 2060 under the green low-carbon scenario and 15 trillion kWh in the baseline scenario. It is also necessary to analyze the changes in the proportion of power generation from clean energy sources. Coal, hydro, wind, photovoltaic, and nuclear power are the main modes of power generation in China. Under the policy scenario, wind and photovoltaic power generation will account for around 50% of total power generation in 2050, followed by hydro and nuclear power generation, with a share of approximately 25%. Biomass power generation methods are further developed, with a 5% share in 2050. Similarly, the proportion of power generated from renewable sources continues to increase between 2050 and 2060, reaching 60% by 2060.

Decoupling of carbon emissions and economic growth

After the peak of carbon emissions, the government or related organizations will take measures to reduce emissions automatically, pursuing low resource consumption in exchange for the same or even more rapid economic growth. Figure 9 illustrates the status of the decoupling of economic development and carbon emissions under three scenarios.

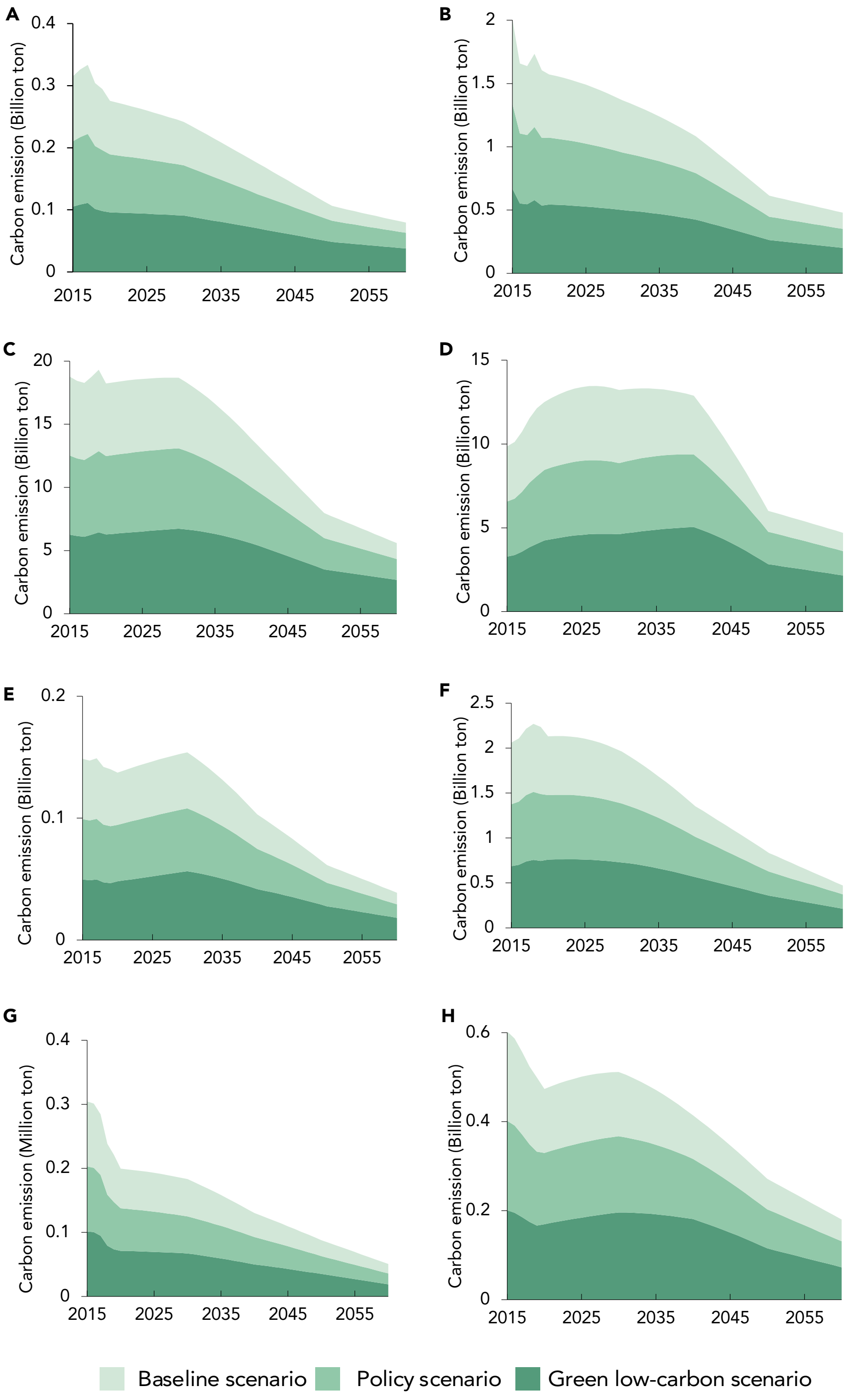

Figure 6. Carbon emissions from different production sectors under the three scenarios

(A) Carbon emissions from the AFH sector under the three scenarios.
(B) Carbon emissions from the MQ sector under the three scenarios.
(C) Carbon emissions from the MAN sector under the three scenarios.
(D) Carbon emissions from the EGW sector under the three scenarios.
(E) Carbon emissions from the CON sector under the three scenarios.
(F) Carbon emissions from the TSP sector under the three scenarios.
(G) Carbon emissions from the WRR sector under the three scenarios.
(H) Carbon emissions from the OTH sector under the three scenarios.

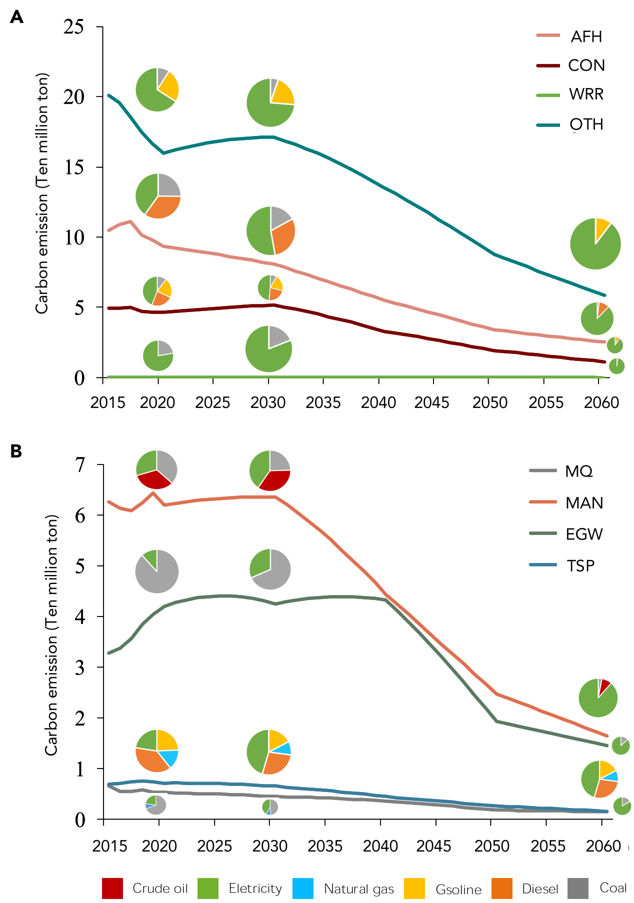

Figure 7. Carbon emissions in different sectors under the policy scenario
(A) Carbon emissions in AFH, CON, WRR, OTH sectors under the policy scenario.
(B) Carbon emissions in MQ, MAN, EGW, TSP sectors under the policy scenario.

Under all three scenarios, China's economic growth and carbon emissions show a strong decoupling in 2031, 2027, and 2026, respectively. It is worth noting that there is a significant increase in the Tapio decoupling index from 2050 to 2060, because by this period, China's carbon emissions reduction has moved to a lower and more stable level, but the Chinese economy is still growing. Although the value of the Tapio index has risen, it is still below zero, which means that China's economic growth and carbon emissions remain decoupled. To gain a more precise perspective on the extent of decoupling in China, the decoupling status of carbon emissions and economic growth in the production sector is analyzed, and the decoupling status for each sector is shown in Figure 10.

As can be seen in Figure 10, under the policy scenario, the AFH sector is decoupled first in 2018, with MAN, CON, and WRR sectors steadily decoupling over the period 2030–2031. The decoupling of the EGW sector lags behind, with a strong decoupling of economic growth and carbon emissions only achieved in 2037. Under the green low-carbon scenario, strong decoupling has been achieved in all productive sectors in China by 2031, that is, economic growth no longer comes at the expense of the environment. China's economic development can thus reach a more ideal state, which will be conducive to achieving carbon neutrality as soon as possible.

Uncertainty analysis

Four additional scenarios have been added to the existing ones to illustrate the reliability of the results. Scenarios a1 and a2 consider changes in the energy structure. Under scenarios a1, the energy structure transforms slower than the policy scenario, while under scenario a2 the energy structure transformation accelerates. Scenarios b1 and b2 consider the change in energy intensity. Figure 11 illustrates the trends in carbon emissions under the different scenarios.

As shown in Figure 11, the reduction in energy intensity contributes to the reduction of carbon emissions. Under scenarios a1 and b1, China's carbon emissions will peak in 2027 at 12.9 billion tons and 13 billion tons, respectively, lagging one year behind the policy scenario. Although China's carbon emissions peak appears earlier in the a2 and b2 scenarios compared to the policy scenario, the magnitude of change in the peak of carbon emissions is smaller, which also indicates the reliability and stability of the results. In summary, China's carbon emissions

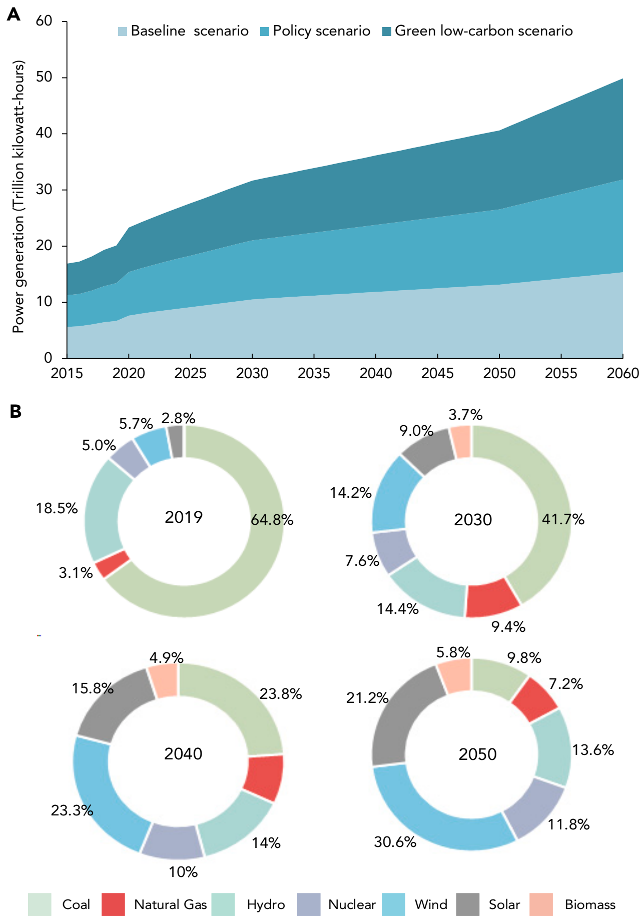

Figure 8. China's total power generation and the proportion of different power generation modes

(A) Total power generation in China under the three scenarios.

(B) Power generation structure in China in 2019, 2030, 2040, and 2050 under the policy scenario.

are most likely to peak between 2025 and 2030. Optimization of the energy structure and reduction of energy intensity can contribute to more rapid achievement of the carbon neutrality target.

In conclusion, looking at the type of energy consumption, coal consumption will peak by 2024 at the latest, while natural gas will peak around 2032 and then stabilize. China's carbon emissions are most likely to peak between 2024 and 2030 under the different scenarios, with a strong decoupling time lagging one year behind the peak. Looking at the subsectors, the AFH and MQ sectors are the first to achieve a carbon peak and economic decoupling. Under all three scenarios, all of the other sectors (with the exception of the EGW sector) will achieve their carbon peak by 2030. The proportion of power generation from clean energy sources will also increase significantly from 2020 to 2060.

DISCUSSION

Under the three proposed scenarios, China's energy consumption follows a trend of rapid growth followed by stable growth from 2020 to 2060. By energy consumption type, the change trend of different energy sources is quite different. The peaks for coal consumption under the three scenarios are 2024, 2022, and 2022, with peaks of 2.85 billion tons, 2.8 billion tons, and 2.72 billion tons, respectively. Thereafter, coal consumption accounts for increasingly smaller proportion of total energy consumption. By 2050, the consumption of coal under the three

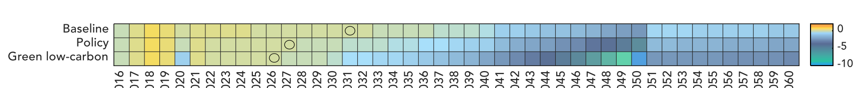

Figure 9. Decoupling status of economic development and carbon emissions in China under the three scenarios

The circle denotes the time at which the sector achieves a strong decoupling of economic growth and carbon emissions.

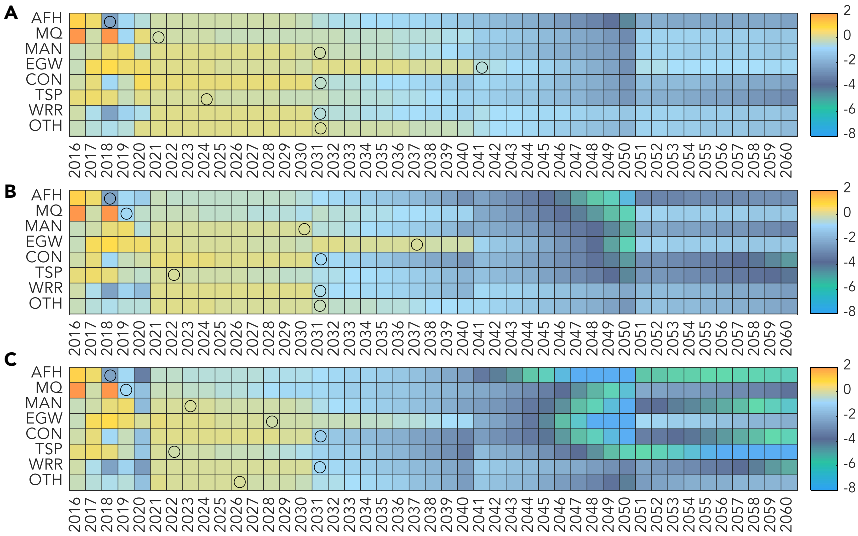

Figure 10. Decoupling status of different sectors under different scenarios

The circle denotes the time at which the sector achieves a strong decoupling of economic growth and carbon emissions.

(A) Sector decoupling status under the baseline scenario.

(B) Sector decoupling status under the policy scenario.

(C) Sector decoupling status under the green low-carbon scenario.

scenarios will be 1.41 billion tons, 0.95 billion tons, and 0.66 million tons. Natural gas is an important guarantee for the transformation of China's energy structure, and under the three scenarios, the country's natural gas consumption follows a growing trend that peaks around 2038, followed by a slight decline.

China's carbon emissions will peak in 2030, 2026, and 2025 under three scenarios with peaks of 13.5 billion tons, 12.8 billion tons, and 12 billion tons, respectively. Except for EGW sector, all of the other sectors will be able to achieve a carbon peak gradually by 2030 under three scenarios. Collaborative carbon reduction across sectors could also accelerate the achievement of carbon peak and carbon neutrality goal. The timing of the peak in all of the sectors is further advanced in the policy scenario compared to the baseline scenario, which suggests that China's initiatives will have a positive effect. Similarly, China's carbon emissions are more optimistic in the green low-carbon scenario due to a significant improvement in the energy structure. From a power generation perspective, the share of wind and photovoltaic power is gradually increasing, becoming pillars of the power supply and laying the foundation for accelerated electrification on the energy consumption side. Achieving China's carbon neutrality goal will require synergy between energy supply and demand.

Economic growth and energy consumption are closely related. Under the three scenarios, China's economic growth is decoupled from carbon emissions in 2031, 2027, and 2026, respectively. However, there are some differences among production sectors in the timing of this decoupling. Under the policy scenario, the AFH sector takes the lead in decoupling economic growth from carbon emissions in 2018, with the CON, WRR, and OTH sectors achieving decoupling in 2031. The last sector to achieve decoupling is the EGW sector, with weak decoupling in 2026 and strong decoupling in 2037.

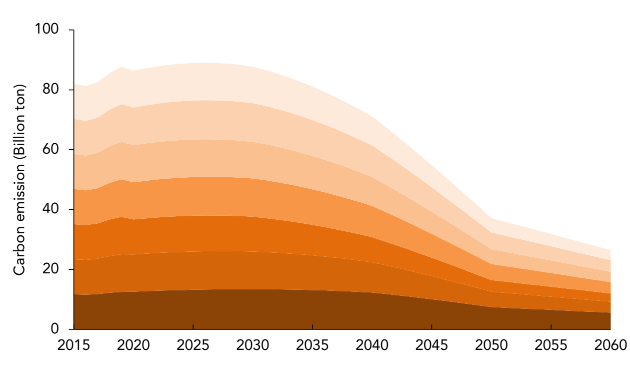

Figure 11. Carbon emissions from energy consumption under the different scenarios, 2015–2060.

The achievement of carbon neutrality requires a comprehensive and systematic analysis of technology, economics, and society.[51] Carbon emissions projections provide different pathways for energy consumption among sectors in China, and can also serve as a reference for policymakers to formulate carbon reduction plans.[44,52,53] Based on the findings of this study, we make recommendations targeting both energy consumption and power generation.

From the energy consumption side, policymakers should determine the carbon emissions calculations for each sector according to their energy consumption structure and sectoral production characteristics. This involves accurately accounting for the energy consumption of each production process in different production sectors and formulating carbon reduction measures from key stages. Policymakers should also develop implementation plans for carbon peaking and carbon reduction in the EGW, MAN, CON, TSP, AFH, and rural sectors. Sectors with relatively easy energy structure transitions to peak carbon emissions should be prioritized. There should also be greater reliance on green and low-carbon technology innovation to continuously improve the efficiency of energy use and optimize the structure of energy consumption in all sectors. This will ensure that each sector can accomplish its carbon emissions reduction goal.

As the largest energy consumer and carbon emitter, China's demand for energy will continue to grow. To ensure security in the consumption of energy, China needs to prioritize non-fossil energy sources and vigorously develop and utilize such sources in its energy development. According to the natural characteristics of the region, the installed capacity for wind power and photovoltaics should be increased, especially in the western region. The construction of a new power system based on clean energy should be accelerated, and energy storage technologies should be developed to further ensure the security of the country's energy utilization under extreme weather conditions.

Policymakers also need to clarify which measures are beneficial in the long term and which are not sustainable. For example, building clean power generation facilities is beneficial in the long term, but closing down coal-fired power plants and energy-intensive, low-productivity enterprises will only work in the short term. China's emissions reduction path should also be adjusted according to different stages of development.

LIMITATIONS OF THE STUDY

There are several aspects of this study that could be further developed in future research. First, this study examines China as a whole and does not consider the variability among provinces. Different regions have different key industries due to differences in resource endowments, so the energy consumption reduction initiatives for the same industry in different provinces can vary greatly, and more detailed data are needed for further research. Second, this study uniformly selects the annual output value as the activity level, and although it facilitates cross-sectional comparisons among sectors, other characteristics among sectors are not highlighted. In the future, we will conduct further research from a provincial perspective, based on the production methods and characteristics of each industry.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- RESOURCES AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHODS DETAILS
  - Long-term energy alternative planning system
  - Calculation of energy consumption and emissions
  - Calculation of the tapio decoupling index
  - Scenario settings

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.108404.

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AUTHOR CONTRIBUTIONS

K.Z. and J.Y. designed the study, and performed data analysis. J.Y. prepared the writing-original manuscript. K.Z., H.Y., and T.D. contributed to writing and revising the manuscript. K.Z. and T.D. supervised the study.

DECLARATION OF INTERESTS

The authors filed patent applications CN202211422862.4 for urban carbon emission forecasting. There are no other conflicts of interest to declare.

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REFERENCES

1. Cui, L.-B., Fan, Y., Zhu, L., and Bi, Q.-H. (2014). How will the emissions trading scheme save cost for achieving China's 2020 carbon intensity reduction target? Appl. Energy *136*, 1043–1052. https://doi.org/10.1016/j.apenergy.2014.05.021.
2. De La Peña, L., Guo, R., Cao, X., Ni, X., and Zhang, W. (2022). Accelerating the energy transition to achieve carbon neutrality. Resour. Conserv. Recycl. *177*, 105957S. https://doi.org/10.1016/j.resconrec.2021.105957.
3. Iqbal, S., Bilal, A.R., Nurunnabi, M., Iqbal, W., Alfakhri, Y., and Iqbal, N. (2021). It is time to control the worst: testing COVID-19 outbreak, energy consumption and CO(2) emission. Environ. Sci. Pollut. Res. Int. *28*, 19008–19020. https://doi.org/10.1007/s11356-020-11462-z.
4. Barecka, M.H., Ager, J.W., and Lapkin, A.A. (2021). Carbon neutral manufacturing via on-site CO(2) recycling. iScience *24*, 102514. https://doi.org/10.1016/j.isci.2021.102514.
5. Wheeler, V.M., Kim, J., Daligault, T., Rosales, B.A., Engtrakul, C., Tenent, R.C., and Wheeler, L.M. (2022). Photovoltaic windows cut energy use and CO2 emissions by 40% in highly glazed buildings. One Earth *5*, 1271–1285. https://doi.org/10.1016/j.oneear.2022.10.014.
6. Ortega-Ruiz, G., Mena-Nieto, A., Golpe, A., and García-Ramos, J. (2022). CO2 emissions and causal relationships in the six largest world emitters. Renew. Sustain. Energy Rev. *162*, 112435. https://doi.org/10.1016/j.rser.2022.112435.
7. Xu, G., Dong, H., Xu, Z., and Bhattarai, N. (2022). China can reach carbon neutrality before 2050 by improving economic development quality. Energy *243*, 123087. https://doi.org/10.1016/j.energy.2021.123087.
8. Barron, A.R., Domeshek, M., Metz, L.E., Draucker, L.C., and Strong, A.L. (2021). Carbon neutrality should not be the end goal: Lessons for institutional climate action from U.S. higher education. One Earth *4*, 1248–1258. https://doi.org/10.1016/j.oneear.2021.08.014.
9. Obura, D.O., DeClerck, F., Verburg, P.H., Gupta, J., Abrams, J.F., Bai, X., Bunn, S., Ebi, K.L., Gifford, L., Gordon, C., et al. (2023). Achieving a nature- and people-positive future. One Earth *6*, 105–117. https://doi.org/10.1016/j.oneear.2022.11.013.
10. Cox, B., Innis, S., Kunz, N.C., and Steen, J. (2022). The mining industry as a net beneficiary of a global tax on carbon emissions. Commun. Earth Environ. *3*, 17. https://doi.org/10.1038/s43247-022-00346-4.
11. Fang, K., Tang, Y., Zhang, Q., Song, J., Wen, Q., Sun, H., Ji, C., and Xu, A. (2019). Will China peak its energy-related carbon emissions by 2030? Lessons from 30 Chinese provinces. Appl. Energy *255*, 113852. https://doi.org/10.1016/j.apenergy.2019.113852.
12. Hussain, M., Lin, Y., and Wang, Y. (2023). Measures to achieve carbon neutrality: What is the role of energy structure, infrastructure, and financial inclusion. J. Environ. Manage. *325*, 116457. https://doi.org/10.1016/j.jenvman.2022.116457.
13. Chen, W., Sun, X., Liu, L., Liu, X., Zhang, R., Zhang, S., Xue, J., Sun, Q., Wang, M., Li, X., et al. (2022). Carbon neutrality of China's passenger car sector requires coordinated short-term behavioral changes and long-term technological solutions. One Earth *5*, 875–891. https://doi.org/10.1016/j.oneear.2022.07.005.
14. Chen, X., and Lin, B. (2021). Towards carbon neutrality by implementing carbon emissions trading scheme: Policy evaluation in China. Energy Pol. *157*, 112510. https://doi.org/10.1016/j.enpol.2021.112510.
15. Zheng, J., Mi, Z., Coffman, D., Shan, Y., Guan, D., and Wang, S. (2019). The Slowdown in China's Carbon Emissions Growth in the New Phase of Economic Development. One Earth *1*, 240–253. https://doi.org/10.1016/j.oneear.2019.10.007.
16. Chen, W., and Yan, S. (2022). The decoupling relationship between CO2 emissions and economic growth in the Chinese mining industry under the context of carbon neutrality. J. Clean. Prod. *379*, 134692. https://doi.org/10.1016/j.jclepro.2022.134692.
17. Zhang, L., Wu, P., Niu, M., Zheng, Y., Wang, J., Dong, G., Zhang, Z., Xie, Z., Du, M., Jiang, H., et al. (2022). A systematic assessment of city-level climate change mitigation and air quality improvement in China. Sci. Total Environ. *839*, 156274. https://doi.org/10.1016/j.scitotenv.2022.156274.
18. Dong, K.-Y., Sun, R.-J., Li, H., and Jiang, H.-D. (2017). A review of China's energy consumption structure and outlook based on a long-range energy alternatives modeling tool. Pet. Sci. *14*, 214–227. https://doi.org/10.1007/s12182-016-0136-z.
19. Wang, K., Wang, Z., Xian, Y., Shi, X., Yu, J., Feng, K., Hubacek, K., and Wei, Y.M. (2023). Optimizing the rolling out plan of China's carbon market. iScience *26*, 105823. https://doi.org/10.1016/j.isci.2022.105823.
20. Zhang, Z., Hu, G., Mu, X., and Kong, L. (2022). From low carbon to carbon neutrality: A bibliometric analysis of the status, evolution and development trend. J. Environ. Manage. *322*, 116087. https://doi.org/10.1016/j.jenvman.2022.116087.
21. Mi, Z., Zheng, J., Green, F., Guan, D., Meng, J., Feng, K., Liang, X., and Wang, S. (2021). Decoupling without outsourcing? How China's consumption-based CO(2) emissions have plateaued. iScience *24*, 103130. https://doi.org/10.1016/j.isci.2021.103130.
22. Hao, J., Gao, F., Fang, X., Nong, X., Zhang, Y., and Hong, F. (2022). Multi-factor decomposition and multi-scenario prediction decoupling analysis of China's carbon emission under dual carbon goal. Sci. Total Environ. *841*, 156788. https://doi.org/10.1016/j.scitotenv.2022.156788.
23. Tang, L., Ruan, J., Bo, X., Mi, Z., Wang, S., Dong, G., and Davis, S.J. (2022). Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO2 in China's cement sector. One Earth *5*, 892–906. https://doi.org/10.1016/j.oneear.2022.07.003.
24. Hang, Y., Wang, Q., Zhou, D., and Zhang, L. (2019). Factors influencing the progress in decoupling economic growth from carbon dioxide emissions in China's manufacturing industry. Resour. Conserv. Recycl. *146*, 77–88. https://doi.org/10.1016/j.resconrec.2019.03.034.
25. Zeng, S., Su, B., Zhang, M., Gao, Y., Liu, J., Luo, S., and Tao, Q. (2021). Analysis and forecast of China's energy consumption structure. Energy Pol. *159*, 112630. https://doi.org/10.1016/j.enpol.2021.112630.
26. Yang, X., Nielsen, C.P., Song, S., and McElroy, M.B. (2022). Breaking the hard-to-abate bottleneck in China's path to carbon neutrality with clean hydrogen. Nat. Energy *7*, 955–965. https://doi.org/10.1038/s41560-022-01114-6.
27. Cai, B., Cui, C., Zhang, D., Cao, L., Wu, P., Pang, L., Zhang, J., and Dai, C. (2019). China city-level greenhouse gas emissions inventory in 2015 and uncertainty analysis. Appl. Energy *253*, 113579. https://doi.org/10.1016/j.apenergy.2019.113579.
28. Kassem, N., Galantino, C.R., Tester, J.W., Anderson, C.L., and Moore, M.C. (2021). Moving toward a framework for electricity and heat equivalence in energy systems analysis. iScience *24*, 103123. https://doi.org/10.1016/j.isci.2021.103123.
29. Fang, G., Gao, Z., and Sun, C. (2023). How the new energy industry contributes to carbon reduction?—Evidence from China. J. Environ. Manage. *329*, 117066. https://doi.org/10.1016/j.jenvman.2022.117066.
30. Yang, F., Shi, L., and Gao, L. (2023). Probing CO2 emission in Chengdu based on STRIPAT model and Tapio decoupling. Sust. Cities Soc. *89*, 104309. https://doi.org/10.1016/j.scs.2022.104309.
31. Zhou, X., Niu, A., and Lin, C. (2023). Optimizing carbon emission forecast for modelling China's 2030 provincial carbon emission quota allocation. J. Environ. Manage. *325*, 116523. https://doi.org/10.1016/j.jenvman.2022.116523.

32. Dong, B., Ma, X., Wang, N., and Wei, W. (2020). Impacts of exchange rate volatility and international oil price shock on China's regional economy: A dynamic CGE analysis. Energy Econ. *86*, 103762. https://doi.org/10.1016/j.eneco.2017.09.014.
33. Jiang, H.-D., Liu, L.-J., Dong, K., and Fu, Y.-W. (2022a). How will sectoral coverage in the carbon trading system affect the total oil consumption in China? A CGE-based analysis. Energy Econ. *110*, 105996. https://doi.org/10.1016/j.eneco.2022.105996.
34. Wajsman, N. (1995). The use of computable general equilibrium models in evaluating environmental policy. J. Environ. Manage. *44*, 127–143. https://doi.org/10.1006/jema.1995.0035.
35. Zhang, T., Ma, Y., and Li, A. (2021). Scenario analysis and assessment of China's nuclear power policy based on the paris agreement: A dynamic cge model. Energy *228*, 120541. https://doi.org/10.1016/j.energy.2021.120541.
36. El-Sayed, A.H.A., Khalil, A., and Yehia, M. (2023). Modeling alternative scenarios for Egypt 2050 energy mix based on LEAP analysis. Energy *266*, 126615. https://doi.org/10.1016/j.energy.2023.126615.
37. Lin, J., Kang, J., Khanna, N., Shi, L., Zhao, X., and Liao, J. (2018). Scenario analysis of urban GHG peak and mitigation co-benefits: A case study of Xiamen City, China. J. Clean. Prod. *171*, 972–983. https://doi.org/10.1016/j.jclepro.2017.10.040.
38. Tan, C., Yu, X., and Guan, Y. (2022). A technology-driven pathway to net-zero carbon emissions for China's Guangdong industry. Appl. Energy *325*, 119804. https://doi.org/10.1016/j.apenergy.2022.119804.
39. Liu, Y., Chen, S., Jiang, K., and Kaghembega, W.S.-H. (2022). The gaps and pathways to carbon neutrality for different type cities in China. Energy *244*, 122596. https://doi.org/10.1016/j.energy.2021.122596.
40. Cai, L., Luo, J., Wang, M., Guo, J., Duan, J., Li, J., Li, S., Liu, L., and Ren, D. (2023). Pathways for municipalities to achieve carbon emission peak and carbon neutrality: A study based on the LEAP model. Energy *262*, 125435. https://doi.org/10.1016/j.energy.2022.125435.
41. Xu, G., Schwarz, P., and Yang, H. (2019). Determining China's CO2 emissions peak with a dynamic nonlinear artificial neural network approach and scenario analysis. Energy Pol. *128*, 752–762. https://doi.org/10.1016/j.enpol.2019.01.058.
42. Su, K., and Lee, C.-M. (2020). When will China achieve its carbon emission peak? A scenario analysis based on optimal control and the STIRPAT model. Ecol. Indic. *112*, 106138. https://doi.org/10.1016/j.ecolind.2020.106138.
43. Yu, S., Zhang, Q., Hao, J.L., Ma, W., Sun, Y., Wang, X., and Song, Y. (2023). Development of an extended STIRPAT model to assess the driving factors of household carbon dioxide emissions in China. J. Environ. Manage. *325*, 116502. https://doi.org/10.1016/j.jenvman.2022.116502.
44. Ren, F., and Long, D. (2021). Carbon emission forecasting and scenario analysis in Guangdong Province based on optimized Fast Learning Network. J. Clean. Prod. *317*, 128408. https://doi.org/10.1016/j.jclepro.2021.128408.
45. Dong, J., and Li, C. (2022). Scenario prediction and decoupling analysis of carbon emission in Jiangsu Province, China. Technol. Forecast. Soc. Change *185*, 122074. https://doi.org/10.1016/j.techfore.2022.122074.
46. Huo, T., Xu, L., Feng, W., Cai, W., and Liu, B. (2021). Dynamic scenario simulations of carbon emission peak in China's city-scale urban residential building sector through 2050. Energy Pol. *159*, 112612. https://doi.org/10.1016/j.enpol.2021.112612.
47. Jiang, J.-J., Ye, B., Zeng, Z.-Z., Liu, J.-G., and Yang, X. (2022b). Potential and roadmap of CO2 emission reduction in urban buildings: Case study of Shenzhen. Adv. Clim. Chang. Res. *13*, 587–599. https://doi.org/10.1016/j.accre.2022.06.006.
48. Zhao, L., Zhao, T., and Yuan, R. (2022). Scenario simulations for the peak of provincial household CO(2) emissions in China based on the STIRPAT model. Sci. Total Environ. *809*, 151098. https://doi.org/10.1016/j.scitotenv.2021.151098.
49. Li, X., Yao, X., Guo, Z., and Li, J. (2020). Employing the CGE model to analyze the impact of carbon tax revenue recycling schemes on employment in coal resource-based areas: Evidence from Shanxi. Sci. Total Environ. *720*, 137192. https://doi.org/10.1016/j.scitotenv.2020.137192.
50. Lin, B., and Teng, Y. (2022). Decoupling of economic and carbon emission linkages: Evidence from manufacturing industry chains. J. Environ. Manage. *322*, 116081. https://doi.org/10.1016/j.jenvman.2022.116081.
51. Liu, Z., Deng, Z., He, G., Wang, H., Zhang, X., Lin, J., Qi, Y., and Liang, X. (2021). Challenges and opportunities for carbon neutrality in China. Nat. Rev. Earth Environ. *3*, 141–155. https://doi.org/10.1038/s43017-021-00244-x.
52. Türe, Y., and Türe, C. (2020). An assessment of using Aluminum and Magnesium on CO2 emission in European passenger cars. J. Clean. Prod. *247*, 119120. https://doi.org/10.1016/j.jclepro.2019.119120.
53. Wang, Z.-X., and Ye, D.-J. (2017). Forecasting Chinese carbon emissions from fossil energy consumption using non-linear grey multivariable models. J. Clean. Prod. *142*, 600–612. https://doi.org/10.1016/j.jclepro.2016.08.067.
54. Li, B., Han, S., Li, J., Wang, Y., Wang, Y., and Wang, Y. (2020). Feasibility assessment of the carbon emissions peak in China's construction industry: factor decomposition and peak forecast. Sci. Total Environ. *706*, 135716. https://doi.org/10.1016/j.scitotenv.2019.135716.
55. Peng, B., Du, H., Ma, S., Fan, Y., and Broadstock, D.C. (2015). Urban passenger transport energy saving and emission reduction potential: a case study for Tianjin, China. Energy Conv. Manag. *102*, 4–16. https://doi.org/10.1016/j.enconman.2015.01.017.
56. Liu, L., Wang, K., Wang, S., Zhang, R., and Tang, X. (2018). Assessing energy consumption, CO2 and pollutant emissions and health benefits from China's transport sector through 2050. Energy Pol. *116*, 382–396. https://doi.org/10.1016/j.enpol.2018.02.019.
57. Wang, P., Huang, R., Zhang, S., and Liu, X. (2023). Pathways of carbon emissions reduction under the water-energy constraint: A case study of Beijing in China. Energy Pol. *173*, 113343. https://doi.org/10.1016/j.enpol.2022.113343.
58. Tapio, P. (2005). Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transp. Policy *12*, 137–151. https://doi.org/10.1016/j.tranpol.2005.01.001.
59. National Development and Reform Commission, the 14th Five Renewable Energy Development Plan. https://www.ndrc.gov.cn/xwdt/tzgg/202206/t20220601_1326720.html?code=&state=123.
60. State Council of the People's Republic of China. Outline of the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Vision 2035. http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.
61. State Council of the People's Republic of China, the National Population Development Plan (2016-2030). http://www.gov.cn/zhengce/content/2017-01/25/content_5163309.htm.
62. STate Council of the People's Republic of China. Carbon Peaking Action Program by 2030. http://www.gov.cn/zhengce/content/2021-10/26/content_5644984.htm.
63. State Council of the People's Republic of China. The 14th Five-Year Plan for a Modern Energy System. http://www.gov.cn/zhengce/zhengceku/2022-03/23/content_5680759.htm.
64. State Council of the People's Republic of China. Comprehensive Work Plan for Energy Conservation and Emission Reduction in the 14th Five-Year Plan. http://www.gov.cn/zhengce/content/2022-01/24/content_5670202.htm.
65. State Council of the People's Republic of China. World and China Energy Outlook 2050. http://www.gov.cn/xinwen/2017-08/19/content_5218826.htm.
66. National Development and Reform Commission. Energy Production and Consumption Revolution Strategy 2016-2030. https://www.ndrc.gov.cn/xxgk/zcfb/tz/201704/t20170425_962953.html.
67. State Council of the People's Republic of China. The 13th Five-Year Plan for Electricity Development (2016-2020). http://www.gov.cn/xinwen/2016-11/07/content_5129638.htm.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Demographic data	State Council of the People's Republic of China	https://www.gov.cn/
Energy data	National Energy Administration	http://www.nea.gov.cn/
Scenario settings data	This paper (supplemental information)	Tables S3 and S4
Software and algorithms		
LEAP	Stockholm Environment Institute	https://leap.sei.org/

RESOURCES AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Kaile Zhou (zhoukaile@hfut.edu.cn).

Materials availability

The study did not generate new materials.

Data and code availability

The sources of the datasets supporting the current study are presented in the methods details Section ''scenario settings'' and the supplemental information Section. Relevant data and codes can be available on request from the lead contact. Any additional information required to reanalyze the data reported in this paper or reproduce the results is available from the lead contact upon request.

METHODS DETAILS

Long-term energy alternative planning system

The LEAP model is based on long-term scenario analysis and is a software tool for analyzing energy policy, mitigating climate change, and planning for air pollution reduction.[40,54] The LEAP model includes technology and environmental databases that describe information about the characteristics, costs, and environmental impacts of energy technologies.[55,56] It contains modules for the key assumptions, requirements, transformation, and resources.[39] The key assumptions module focuses on the setting of macro variables, and the demand module considers the energy demand of each sector.[30] The transformation module is primarily used to simulate the processing of and conversion process for various energy sources. The resource module accounts for the primary and secondary energy sources demanded by the energy system.[57] The research framework for this study is presented in Figure S3 in the supplemental information.

Calculation of energy consumption and emissions

Calculation of energy consumption

For the production sector, this study used the annual output value as the activity level of the sector, and the energy consumption per unit of added value as the energy intensity.

$$E_i = AC_i \times EI_i \quad \text{(Equation 1)}$$

$$EI_i = GDP \div \sum_{j=1}^{n} E_{ij} \quad \text{(Equation 2)}$$

where E_i denotes the total energy consumption of production sector i. AC_i and EI_i denote the activity level and energy intensity of production sector i, respectively. GDP_i denotes the value added of industry in production sector i in a given year.

The household sector is divided into rural residents and urban residents and the total energy consumption is calculated based on per capita energy consumption.

$$E_c = P_u \times A_u + P_r \times A_r \quad \text{(Equation 3)}$$

where E_c represents the total energy consumption in the household sector. P and A denote population and energy consumption per capita, respectively.

Calculation of carbon emissions

$$CE = \sum_{i=1}^{m} \sum_{j=1}^{n} E_{ij}F_j \qquad \text{(Equation 4)}$$

where CE indicates the total carbon emissions. E_{ij} denotes the consumption of j types of energy in sector i. F_j represents the carbon emissions factor of j energy.

Calculation of the tapio decoupling index

The decoupling index can be used to examine the relationship between economic growth and carbon emissions to further determine whether economic growth occurs at the expense of the environment.[30,58] The Tapio decoupling index can more accurately reflect the relationship between economic growth and carbon emissions in different sectors.[30,58] Therefore, the Tapio decoupling index is used here to measure the relationship between China's economic growth and energy consumption under the different proposed scenarios from 2015 to 2060.

$$\varepsilon = \frac{\Delta CO_2 / CO_2}{\Delta GDP / GDP} \qquad \text{(Equation 5)}$$

where ε is the decoupling index. $\Delta CO_2/CO_2$ is the rate of change in carbon emissions. $\Delta GDP/GDP$ is the rate of change in gross domestic product. Depending on the value of ε, there are eight Tapio carbon decoupling elasticity indices and types. Table S2 in the supplemental information provides a detailed explanation of the decoupling index.

Scenario settings

Scenario analysis is primarily used to predict the characteristics of changes in the system in different directions under the influence of multiple uncertainties.[37,45] The scenario analysis method can be used to fully consider trends in the development of certain indicators in different policy contexts to further assess whether a certain policy can achieve the expected goals.[35] Based on existing research, this study sets as indicators in the energy consumption module population, urbanization rate, economic growth rate, energy structure, and energy intensity, which directly or indirectly affect energy consumption and carbon emissions. The values of each indicator under the different scenarios are set with reference to existing policy documents and the relevant literature. The settings of the key parameters for the three scenarios are shown in Tables S3 and S4 of the supplemental information.

Baseline scenario

The indicators in the baseline scenario are set according to the existing trends and existing policies, while any future intervention policies are not used. Considering that the characteristics of energy consumption and economic growth in the new normal period differ significantly from those in the old normal period, the model parameters in this scenario are set based on the characteristics of energy consumption and the pattern of economic development in the new normal period.

Policy scenario

The policy scenario is based on the existing development model, considering the national economic and environmental objectives, and setting the key indicators in the model according to various policies and documents issued by the government. Policies and documents include the 14th Five-Year Renewable Energy Development Plan,[59] Outline of the 14th Five-Year Plan for National Economic and Social Development and Vision 2035 of the People's Republic of China,[60] The National Population Development Plan (2016–2030),[61] Carbon Peaking Action Program by 2030,[62] The 14th Five-Year Plan for a Modern Energy System,[63] the Comprehensive Work Plan for Energy Conservation and Emission Reduction in the 14th Five-Year Plan,[64] the World and China Energy Outlook 2050,[65] the Energy Production and Consumption Revolution Strategy 2016–2030,[66] and the 13th Five-Year Plan for Electricity Development, among others.[67] For example, in the State Council's Action Plan for Carbon Peaking by 2030, it is clearly stated that, by 2030, the proportion of non-fossil energy consumption will reach about 25%, and carbon dioxide emissions per unit of GDP will drop by more than 65% compared to 2005 to achieve the goal of carbon peaking by 2030 successfully. The State Council's National Population Development Plan (2016–2030) states that the inertia of China's total population growth will diminish and reach a peak around 2030, with the total population forecast to reach about 1.45 billion in 2030. Table S5 in the supplemental information lists the policies related to the setting of key parameters in the policy scenario. These policies include development objectives and specific policy measures on population, energy supply and energy consumption. The setting of parameter values is based on the targets in the policies in certain years.

Green low-carbon scenario

The green low-carbon scenario is based on a policy scenario that considers the new characteristics of China's energy consumption and economic growth and optimizes existing policies. Under this scenario, a modern energy system that is safe, efficient, clean, and low carbon is rapidly reshaped, a low-carbon economy is fully implemented. And the adaptability and flexibility of the energy supply to changes in energy demand and services are greatly enhanced. The industrial structure of the production sector has been optimized, energy-saving and emission-reduction technologies are widely used, the proportion of clean energy use has been further increased, and the level of industrial electrification has been significantly enhanced. The green low-carbon concept is applied throughout the whole process of transportation infrastructure planning, construction, operation, and maintenance to reduce energy consumption and carbon emissions throughout its life cycle. The proportion of residents' green travel has increased. In the power generation module, the installed capacity and power generation capacity of clean energy through photovoltaic, wind energy, and biomass have increased significantly and become the primary mode of power generation.