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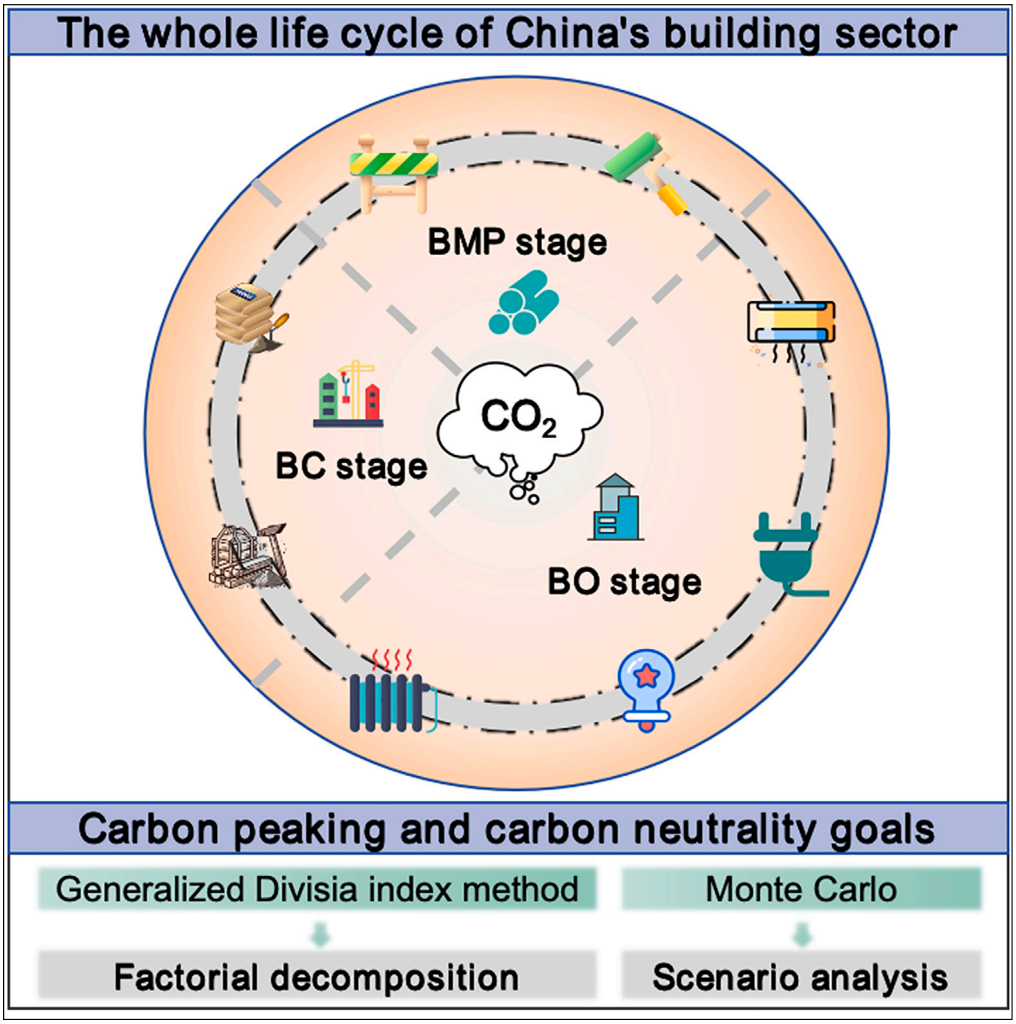

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Highlights

Carbon neutrality pathways of China's building sector at different stages are analyzed

Green innovation output is the dominant factor of CO_2 emissions during the BMP stage

Under four scenarios, carbon emissions peak in 2025, 2030, 2035, and 2040

Only under the TB scenario can China's building sector reach carbon neutrality by 2060

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The road to carbon neutrality in China's building sector

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SUMMARY

The building sector is integral to climate change mitigation in China as well as the globe. By considering the impact of green innovation, we explore the long-term trend of carbon emissions in China's building sector until 2060, encompassing its entire life cycle. Results show that CO_2 emissions of China's building sector will peak at 6.98–7.69 Bt in 2035 and maintain at 1.11 Bt in 2060 under the business-as-usual (BAU) scenario. The "3060 dual carbon goal" will only be achieved under the technological breakthrough (TB) scenario. These findings show that existing or relatively lax policies are insufficient to achieve the "3060" goal for the building sector. China should actively pursue green technological innovation throughout the building sector's life cycle, with a focus on accelerating the green and low-carbon production of key products, such as steel and cement, at the building material production stage.

INTRODUCTION

The temperature rise limit set in the Paris Agreement requires all countries to reach a greenhouse gas peak and achieve carbon neutrality as soon as possible. The realization of China's carbon-neutral goal will significantly impact global climate governance.[1–3] The building sector is one of China's largest sectors in terms of end-use energy consumption and carbon emissions.[4] Its continued rapid growth could jeopardize the Chinese government's commitment to achieving CO_2 emission neutrality by 2060.[5,6] According to the latest research report from the China Association of Building Energy Efficiency (CABEE),[7] the entire life cycle of China's building sector generated 4.07 Bt of CO_2 in 2021, accounting for 38.2% of China's CO_2 emissions generated from energy consumption. Historical data indicate that CO_2 emissions from the building material production (BMP) and the building operation (BO) stages consistently exhibited an upward trend, significantly surpassing those from the building construction (BC) stage (see Figure S1). Therefore, the key to realizing carbon neutrality in the entire life cycle of China's building sector lies in the low-carbon transformation of both the BMP stage and the BO stage.

The main building materials, cement and steel, account for more than 95% of the total emissions in the BMP stage and are pivotal for achieving CO_2 reduction in this stage. CO_2 emissions in the BC stage primarily stem from energy consumption in sub-projects such as civil engineering and installation engineering, with civil engineering and installation engineering accounting for 89% of the total CO_2 emissions in the stage. The high energy consumption in meeting human activity needs (e.g., heating, cooling, lighting, etc.) in the BO stage leads to CO_2 emissions, especially in residential buildings.[8] In addition, differences in winter heating methods, urban and rural building styles, and living characteristics between the northern and southern areas of China, as well as the differences in personnel activities and energy consumption equipment between residential and public buildings, contribute to distinct characteristics in the BO stage (see Figure S1).

With the increasing willingness of the building sector to realize low-carbon transition, domestic and foreign scholars have conducted extensive research on CO_2 emissions in this domain, focusing on the feasibility extrapolation and realization path of China's "3060 dual carbon goal," carbon emission peak projection,[9–13] and CO_2 emission impact factor decomposition.[14–20] Some scholars have also focused on studying the balance between economic benefits and CO_2 emission reduction in the building sector,[21] with a focus on cost-benefit analysis in the building sector,[22] the role of carbon trading and carbon tax policies in promoting energy conservation and emission reduction in the building sector,[23] the potential and economic feasibility of CO_2 emission reduction,[24] and the evaluation of energy efficiency and economic feasibility of energy-saving measures.[25] In addition, regarding the research on carbon neutrality pathways in the building sector, existing literature mainly focuses on the analysis of the BO stages, emphasizing the emission reduction potential of intelligent energy management systems,[26] renewable energy integration,[27] low-carbon technologies and practices,[13] policy impacts and strategies,[28] and energy-saving technology renovations[29] for existing buildings. Via the review, the low-carbon transformation path and driving factors of the building sector have become a key issue of concern at present.

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However, existing studies have predominantly focused on the BO stage,[4,17] analyzing energy use and CO_2 emission trends during the operation of residential and commercial buildings at the national level.[10,30,31] Few studies have comprehensively evaluated the potential long-term CO_2 emission trends of China's building sector at different stages of its life cycle. Moreover, existing studies often have a fixed and limited selection of driving factors for CO_2 emissions, with discussions primarily revolving around the impacts of investment scale, labor productivity, and other factors on CO_2 emissions (see Table S1). Innovation factors, particularly green innovation output, play a crucial role in the industry's low-carbon transformation.[32] Therefore, how to comprehensively evaluate the potential long-term CO_2 emission trends of China's building sector at different stages of its life cycle? How do different climate zones and building types affect CO_2 emissions in the building sector? How to comprehensively understand the potential of green innovation output in achieving CO_2 neutrality goals throughout the entire life cycle of the building sector? These important issues have not been well addressed in previous literature. Solving the aforementioned issues is conducive to a comprehensive analysis of the carbon neutrality path of the building sector and provides reference opinions for the government to formulate CO_2 reduction measures for the building sector from the perspective of life cycle.

The academic community has not reached a unified understanding of the inherent meaning of green innovation output. Overall, there are two main definitions of green innovation output. The first definition equates green innovation output with green technology and green product innovation in the production and operation process.[33] The second definition is more extensive, which considers that green innovation output includes all innovations that can have a favorable impact on the environment, including process innovation, product innovation and institutional innovation, etc., focusing on the measurement of comprehensive effect.[34] The definition of these two methods is mainly related to the measurement of green innovation output indicators. Existing literature mainly uses indicators such as green patent applications,[35] green patent authorizations,[36] and green total factor productivity.[37] We refer to the first definition and focus on green innovation of products and technologies. We quantified the green innovation output of China's building sector at different stages of its life cycle using the number of green invention patents and green utility model patents related to energy consumption in the building sector. It not only reflects the overall green innovation ability of the building sector but also can be specific to the innovation outputs of each stage. Therefore, with reference to previous studies and the characteristics of the building sector, green innovation output refers to innovative achievements in sustainable development, green production, low-carbon operation, and other aspects reflected at different stages of the entire life cycle of the building sector.

There are two paths for the impact of green innovation output on CO_2 emissions in the building sector. On the one hand, if green innovation output is used for green production and low-carbon operations, it can significantly improve the energy efficiency of the building sector, thus reducing building energy intensity.[38,39] Therefore, green innovation output will lead to a reduction in CO_2 emissions. On the other hand, technological progress can lead to a decrease in energy costs, thereby increasing energy demand in the building sector.[40–42] Therefore, green innovation output will lead to an increase in CO_2 emissions. The specific role of green innovation output in reducing CO_2 emissions throughout the entire life cycle of the building sector is an urgent issue that needs to be addressed.

Given the characteristics of China's building sector, we evaluated its development trajectory from different stages of its life cycle up to 2060 through factor decomposition, CO_2 emission trend prediction, and the potential impact of green innovation output on CO_2 emissions. To consider technological innovation, a technological breakthrough scenario was set at different stages of the entire life cycle of China's building sector. More specifically, we focus on assessing the following issues.

1. What green innovations can substantially reduce CO_2 emissions in China's building sector along the entire life cycle? Is there heterogeneity among the impacts of green innovation for different energy end uses and building types during the BO stage?
2. To what extent the green technological breakthroughs and development of renewable energy should be, to achieve carbon neutrality in China's building sector along the entire life cycle by 2060?

In the process, we explore multiple scenarios, including business-as-usual (BAU), high energy demand (HED), green development (GD), and technological breakthrough (TB) scenarios, to evaluate the long-term path of carbon neutrality in China's building sector. Detailed research framework (see Figure S2) and analysis methods are presented in the Method section. Our findings reveal significant differences in the impact of green innovation on CO_2 emissions at different life cycle stages of China's building sector. In particular, different types of green innovation output (electricity, lighting, cooling, and heating) show more pronounced differences across different climate areas and building types at the BO stage. The HED scenario forecasts the highest carbon peak at 7.67–8.96 Bt in 2040, while the TB scenario forecasts the lowest carbon peak at 4.95–5.10 Bt in 2025. While the TB scenario may achieve the "3060 goal" by peaking in 2025 and achieving carbon neutrality by 2060, the other three scenarios (the HED, BAU, and GD scenarios) are unlikely to meet the "3060 goal." More specifically, during the BC stage, both civil engineering and installation engineering can achieve carbon emission peaks in 2030 under the GD scenario, with peak values of 0.09 and 0.02 Bt, respectively. In the BO stage, heating-related CO_2 emissions are projected to peak in 2030, with a growth rate 1.87 times higher than that of 2019, surpassing cooling (1.73), lighting (1.43), and electricity (1.58) emission growth rates.

RESULTS

The driving factors of carbon emissions in China's building sector

In this section, we introduced a generalized Divisia index method (GDIM) to decompose the carbon emissions of China's building sector by stage. We decomposed the CO_2 emissions of cement and steel in the BMP stage, as well as those of civil engineering and installation engineering in the BC stage. In the BO stage, we decomposed the CO_2 emissions of electricity, lighting, heating, and cooling, taking into account the differences between different building types in different climate areas. The results are as follows.

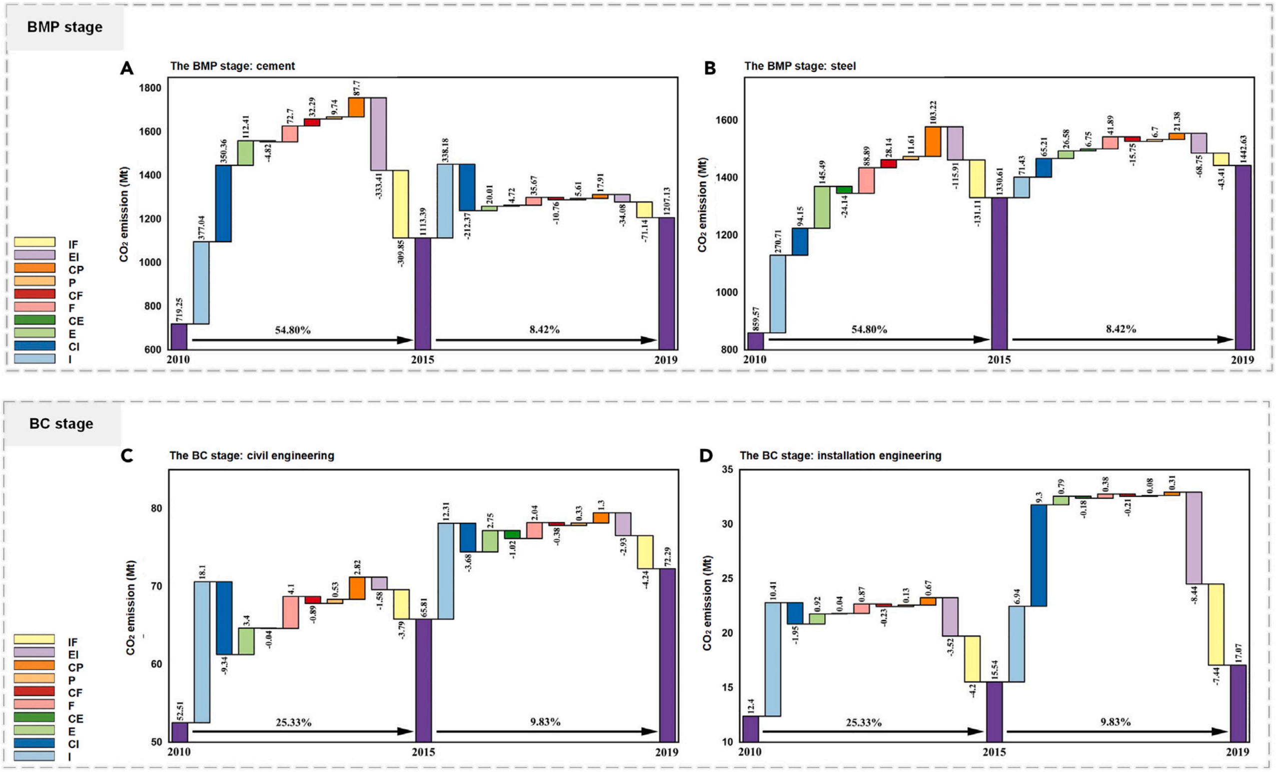

Figure 1. Factor decomposition results for BMP stage and BC stage

(A) The BMP stage: cement.

(B) The BMP stage: steel.

(C) The BC stage: civil engineering.

(D) The BC stage: installation engineering. The period is divided into two sub-stages: 2010–2015 and 2015–2019, following the line of Five-Year plans of China. Cement and steel productions produce more than 95% of the carbon emissions at this stage, so we focus on the effects of the two green innovation outputs of cement and steel, as shown in Figures 1A and 1B. According to Figures 1A and 1B, the CO$_2$ emissions during the BMP stage have increased by 54.8% from 2010 to 2015 and by 8.42% from 2015 to 2019. As the two most important sub-projects, civil engineering and installation engineering account for 89% of the CO$_2$ emissions in the BC stage, and the impact of green innovation outputs in civil engineering and installation engineering on the trend of the CO$_2$ emissions is shown in Figures 1C and 1D. The CO$_2$ emissions during the BC stage also show an increasing trend, with increases of 25.33% and 9.83% in the 12th and 13th Five-Year Plan periods, respectively.

Green innovation output is the dominant factor of CO$_2$ emissions during the BMP stage, especially for steel production. Greening building materials and optimizing the energy mix in the BMP stage are necessary for the "3060 goal" of China's building sector

Figures 1A and 1B highlight the significance of the contributing factors (green innovation output, energy consumption, floor space, population scale, and carbon intensity per capita) driving the growth of CO$_2$ emissions. Overall, the cumulative contribution of green innovation output to cement and steel production is 715.22 and 342.14 Mt CO$_2$. Among them, green innovation output contributed 377.04 Mt and 338.18 Mt CO$_2$ to cement production during China's 12th and 13th Five-Year Plan periods, respectively, with a slight weakening of 10.31%. This indicates that green innovation output has led to a decrease in energy costs by improving energy efficiency, thereby driving more energy consumption and resulting in an increase in CO$_2$ emissions in the building sector. However, it is worth noting that, compared with the 12th Five-Year Plan period, green innovation output in the 13th Five-Year Plan period witnessed a reduction in promotional effect by about 73.61% in steel production. This suggests that research and application of green building materials have led to notable improvements in CO$_2$ productivity and emission efficiency, in particular for cement and steel production. The finding means that green innovation output has great potential and practical effects in reducing CO$_2$ emissions in the high-emission industries. In the future, the focus should also be on reducing the promoting effect of green innovation output and further transforming its role in promoting CO$_2$ emissions into inhibiting CO$_2$ emissions.

Similarly, the contributions of energy consumption also reduced in cement and steel productions by 82.20% and 81.73%, respectively, during the 13th Five-Year Plan period compared with the 12th Five-Year Plan. Ever since the supply-side reform in 2016, environmental policies tightened, resulting in reduced total energy consumption within the building material production stage. Under the supply-side reform, the government strictly controls the installment of new production capacity and implements equivalent and decrement production capacity replacement, resulting in a significant decrease in the total energy consumption of the building material production industry. The positive contributions of floor space, population scale, and carbon intensity per capita on CO_2 emissions also significantly diminished, indicating the weakening of CO_2 emission growth at the BMP stage in the 13th Five-Year Plan period. This was attributed not only to disincentive factors but also to the weakened promotional effects of various contributing factors.

Among the disincentive factors (energy intensity of green innovation output, green innovation output per unit of floor space) driving the decrease of CO_2 emissions, green innovation output per unit of floor space demonstrated the most significant mitigating effects, leading to a reduction of 380.99 and 174.52 Mt of CO_2 emissions in cement and steel productions, respectively, from 2010 to 2019, which is higher than the CO_2 contribution value of energy intensity of green innovation output (cement: 367.49 Mt; steel: 184.66 Mt). The expansion of building area stock typically accompanies urban growth, resulting in a denser innovation network in cities, which drives innovation in green technologies, designs, and building materials to meet the growing market demand and environmental sustainability requirements. Therefore, the increased green innovation output per unit of floor space plays an important role in reducing CO_2 emissions at the BMP stage. The cumulative contribution of energy intensity of green innovation output to CO_2 emission reduction of cement and steel at the BMP stage decreased by 89.78% and 40.68%, respectively, during the 13th Five-Year Plan period. Although national key research and development programs of China, such as the "Green Building and Construction Industrialization," "Green and Livable Village Technology Innovation," and "Solid Waste Resource Utilization," were deployed during the 13th Five-Year Plan period, these projects mostly focused on improving product application performance. Green building material research and development projects based on carbon peak and carbon neutrality goals are limited.

It is worth noting that the carbon intensity of floor space exhibited a promoting effect (cement: 32.29 Mt; steel: 28.14 Mt) during the 12th Five-Year Plan period and a mitigating effect (cement: 10.76 Mt; steel: 15.75 Mt) during the 13th Five-Year Plan period in the CO_2 emissions of cement and steel productions. In the 13th Five-Year Plan for Building Energy Conservation and Green Building Development, the proportion of green building area in newly built urban buildings was targeted to exceed 50%, and the proportion of green building material application was targeted to exceed 40%. It thus promoted the application of green building materials at the BMP stage and reduced the carbon intensity of floor space. On the contrary, the carbon intensity of energy consumption has shifted from a CO_2 emission reduction factor during the 12th Five-Year Plan period (cement: 4.82 Mt; steel: 24.14 Mt) to a CO_2 emission increase factor during the 13th Five-Year Plan period (cement: 4.72 Mt; steel: 6.75 Mt). The result indicates that the clean and low-carbon process of energy structure remains a key measure and a problem that needs to be addressed.

The carbon intensity of green innovation output facilitates the process of achieving a carbon peak at the BC stage. The green innovation output of civil engineering is important for achieving carbon reduction at the BC stage

Figures 1C and 1D show that the green innovation output, energy consumption, floor space, population scale, and carbon intensity per capita remain as contributing factors with positive effects at the BC stage. The green innovation output is the most critical factor contributing to the increase in CO_2 emissions in the BC stage, contributing 30.41 and 17.35 Mt of CO_2 emissions for civil engineering and installation engineering during 2010–2019, respectively, higher than energy consumption (civil: 6.15 Mt; installation: 1.71 Mt), floor space (civil: 6.14 Mt; installation: 1.25 Mt), and population scale (civil: 0.86 Mt; installation: 0.21 Mt). With the rapid urban development and economic construction, the green innovation output exhibited a weakened role in promoting CO_2 emissions in the 13th Five-Year Plan period compared with the 12th Five-Year Plan period, decreasing by 31.99% and 33.34% in the civil engineering and installation engineering, respectively. The promoting effect of energy consumption, floor space, population scale, and carbon intensity per capita shows a weakening effect, in which the floor space is more prominent, with its CO_2 emission contribution reduced by 50.24% and 56.32% in civil engineering and installation engineering, respectively. The expansion of floor space reflects the increase in urban scale and may promote the efficiency of building construction and innovation activities. Therefore, the expansion of floor space can lead to more green innovation needs to a certain extent, further slowing down its promoting effect on CO_2 emissions in the BC stage.

Among the factors contributing to the reduction of CO_2 emissions (carbon intensity of green innovation output, carbon intensity of energy consumption, carbon intensity of floor space, energy intensity of green innovation output, green innovation output per unit of floor space), green innovation output per unit of floor space contributes the most to CO_2 emission reduction at the BC stage, with 8.03 and 11.64 Mt of CO_2 emission reduction cumulatively in civil engineering and installation engineering during 2010–2019, respectively, higher than carbon intensity of energy consumption (civil: 1.06 Mt; installation: 0.14 Mt), carbon intensity of floor space (civil: 1.27 Mt; installation: 0.44 Mt), and energy intensity of green innovation output (civil: 4.51 Mt; installation: 11.96 Mt). This indicates that the application of green construction technology indeed helped to reduce energy consumption in the BC stage to some extent, thereby reducing CO_2 emissions. In addition, China's real estate market is nearing saturation, leading to slower growth in floor space, thus strengthening the effect of green innovation per unit of floor space. The carbon intensity of energy consumption also shows similar effects, with the CO_2 emission reduction contribution value in civil engineering improving by 25.5 times, and the carbon intensity of energy consumption in installation engineering has shifted from a promoting effect (0.04 Mt) during the 12th Five-Year Plan period to an inhibiting effect (0.18 Mt) during the 13th Five-Year Plan period. The carbon intensity of energy consumption shows a significant promoting effect on reducing CO_2 emissions in the BC stage. This suggests that, on the one hand, China's energy structure exhibits a decarbonization adjustment during the 13th Five-Year Plan period; on the other hand, green construction technology reduces the consumption of fossil energy. Therefore, CO_2 emission reduction is achieved.

The carbon intensity of green innovation output is the most critical factor for reducing CO_2 emissions during the BO stage, with varying effects on different types of buildings

Different types of green innovation outputs (electricity, lighting, cooling) show significant differences in different climate areas. Among them, the green innovation output in electricity shows a stronger promoting effect on CO_2 emission growth during the BO stage in

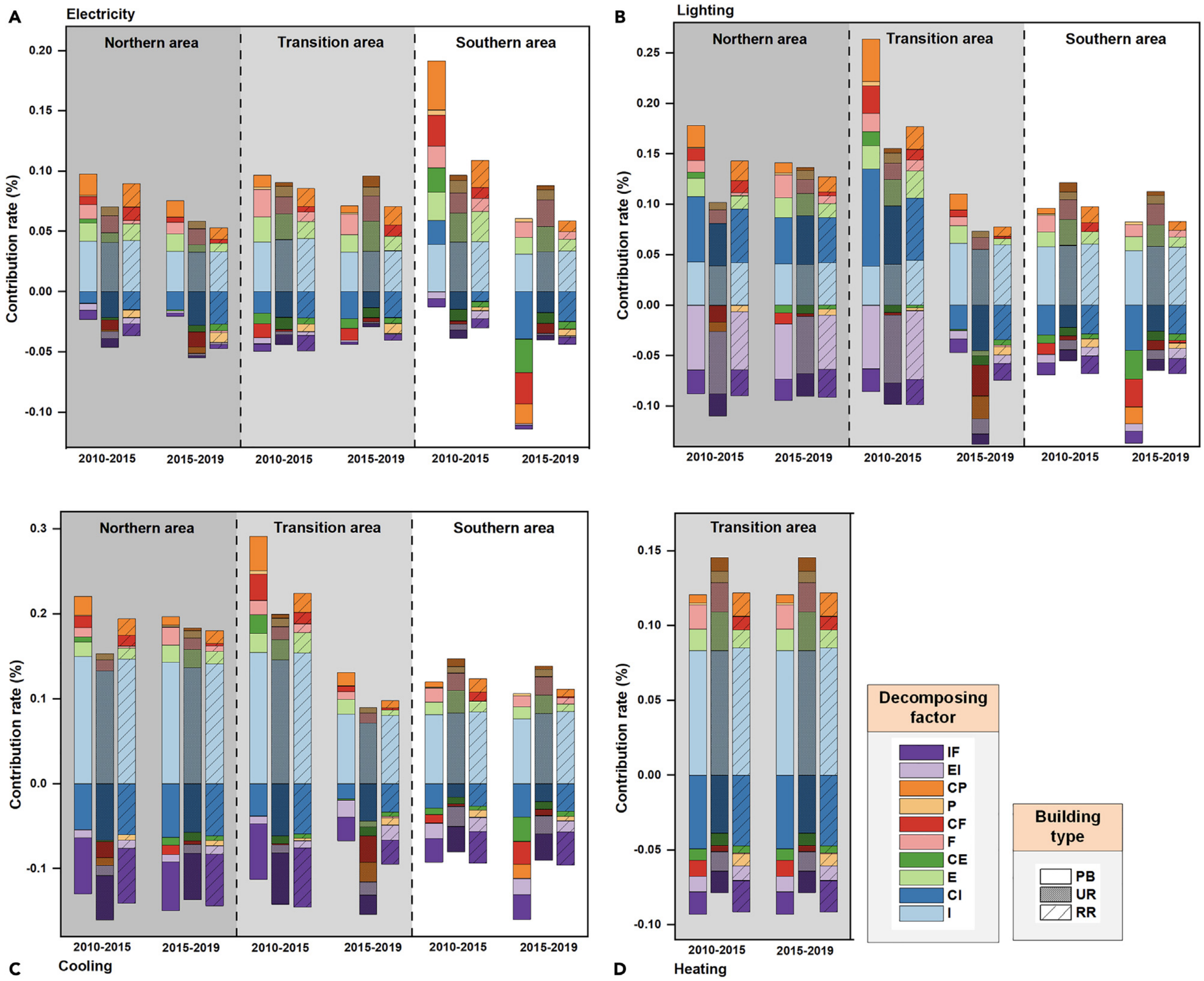

Figure 2. Factor decomposition results for BO stage

(A) Electricity.

(B) Lighting.

(C) Cooling.

(D) Heating. We analyze from three dimensions: different green innovation outputs (electricity, lighting, heating, and cooling), different climate areas (northern, transition, and southern), and different building types (PB, UR, and RR). The main output of green innovation in heating is household decentralized heating equipment, while in the northern area, PB, UR, and RR mainly use centralized heating. In the transition area, distributed heating is the main heating method. In addition, residents living in the southern area do not need heating, so the heating energy consumption can be ignored.[43] Therefore, only the CO_2 emissions generated by decentralized heating in the transition area are considered, as shown in Figure 2C.

the southern area. The green innovation output in lighting shows a relatively low disincentive effect on the CO_2 emissions of rural residential buildings. The green innovation output of refrigeration types shows significant differences between the southern and northern climate areas. Additionally, the green innovation output in cooling exhibits significant differences between the southern and northern climate areas.

As shown in Figure 2A, among the contributing factors (green innovation output, energy consumption, floor space, and carbon intensity per capita), the green innovation output in the area of electricity shows a weakening trend across different climate areas and different building types, suggesting that green innovation output in electricity is more crucial in the BO stage. The carbon intensity of green innovation output, the carbon intensity of energy consumption, the energy intensity of green innovation output, and the green innovation output per unit of floor space maintained a relatively stable effect on reducing CO_2 emissions, which is related to the green innovation of the electric power industry and the adjustment of energy structure. CO_2 emissions in electricity are one of the main sources in the BO stage, and green innovation in electricity plays an important role in reducing CO_2 emissions. During the 13th Five-Year Plan period, the proportion of renewable energy installed capacity in China's power industry has exceeded half of the total installed capacity, and over 60% of the energy consumption increment has been supplied by clean energy. Even if future end-use electrification is not matched by rapid power-sector decarbonization, it will probably reduce emissions in China as well as worldwide.

By analyzing the effect of various driving factors on CO_2 emissions of different building types, we found that population scale has always maintained a disincentive effect in rural residential buildings (RRs), whereas it has promoting effects in public buildings (PBs) and urban residential buildings (URs). This might be caused by the continuous improvement of China's urbanization rate. The urbanization rate of China's registered residence population has increased from 35.93% in 2013 to 44.38% in 2019. As a result, the reduction of rural population size during the 13th Five-Year Plan period contributed 0.63%, 0.65%, and 0.39% of CO_2 emission reduction during the BO stage of RR in the northern, transition, and southern areas, respectively.

By different climate areas, the contribution rates of energy consumption and floor space in the southern area are higher than those in the transition and northern climate areas. The factors reducing CO_2 emissions, such as carbon intensity of energy consumption and green innovation output per unit of floor space, have a slightly higher disincentive impact in the southern area than in the transition and northern climate areas. This might be caused by the differences in electricity demand between the north and south of China. Affected by the high temperatures in summer, the electricity demand for air conditioning in the southern area is higher than that in other areas. In winter, air conditioning and electric furnace heaters are commonly used in the south due to the lack of heating, and the power consumption of these heating facilities is generally high, which can also cause a sharp increase in electricity consumption in the southern area. Therefore, the green innovation output in the electricity sector always has a stronger impact during the operating phase (BO) in the southern buildings.

As shown in Figure 2B, when the green innovation output is patented for lighting, the intensity of the effects of various contributing and disincentive factors in different climate areas did not have significant differences. However, different types of buildings exhibit varying degrees of effect. For example, from 2010 to 2019, the annual contribution rate of green innovation output per unit of floor space to RR was −1.14%, lower than that of PB (−1.52%) and UR (−1.87%), and the energy use for lighting in PB and UR is generally higher than that in RR. Therefore, the green innovation output related to lighting is effective and reduces emissions for buildings in different climate areas, but it has different effects for different building types, with more significant effects in PB and UR.

Figure 2C shows the decomposition results of the influencing factors of green innovation output of cooling patents on CO_2 emissions. The effects of the green innovation output patent relating to cooling CO_2 emissions are very different by climate area. Among areas, the effect in the southern area is relatively strong, with an average annual CO_2 reduction contribution rate (−4.26%) that is higher than in the transition (−3.88%) and northern areas (−3.76%). This is related to the differences in energy consumption usage during the BO stage in different climate areas of China, especially in the southern and northern areas.

Figure 2D shows the effect of the green innovation output of heating on the CO_2 emission of decentralized heating in the transition area. The effects are different by building type, with a cumulative emission reduction effect of −3.93% on UR from 2010 to 2019, higher than that of RR (−3.09%) and PB (−3.00%). In the transition area, the heating demand of UR is relatively high; hence, the green innovation output of heating equipment can lead to stronger CO_2 reduction effects for UR.

The carbon peak and carbon neutrality path of China's building sector

We predict the CO_2 emissions of the building sector at different stages of its life cycle from 2020 to 2060.

Existing climate regulations cannot achieve the goal of China's building sector in reaching its peak emissions before 2030. Only in the TB scenario, China's building sector can achieve carbon neutrality by 2060

For carbon peak, it can be found from Figure 3 that there are significant differences in the amount and time of CO_2 emission peak of China's building sector under different scenarios. Under the HED scenario, without proactive policies to address the growth of demand for building energy services, the CO_2 emissions of China's building sector will continue to increase until 2040, with a peak CO_2 emission of 7.67–8.96 Bt. Under the BAU and GD scenarios, the CO_2 peak times are 2035 (6.98–7.70 Bt) and 2030 (5.30–5.83 Bt), respectively. Under the TB scenario, with green innovation realized, CO_2 peaking can be achieved ahead of schedule in 2025, with emissions peaking at 4.95–5.10 Bt. The results indicate that existing or relatively lax climate policies will not be able to achieve the goal of China's building sector to reach an emission peak by 2030 and subsequently will influence carbon neutrality. The Chinese government should focus on climate change intervention measures in the building sector and, at the same time, strengthen the effectiveness of green innovation and ensure that a carbon peak is achieved by 2030. In addition, green technology innovation in the BMP stage is crucial for achieving a carbon peak. Achieving the breakthrough will assist China in achieving a carbon peak ahead of schedule in 2025.

For carbon neutrality, it can be found from Figure 3 that China's building sector can only reach carbon neutrality as scheduled in the TB scenario. Under the HED scenario, if energy demand is not constrained, China's building sector will still maintain a high CO_2 emission of 4.16 Bt in 2060. Under the BAU and GD scenarios, the CO_2 emissions of China's building sector will decrease to 1.11 and 0.33 Bt, respectively, by 2060, but carbon neutrality still cannot be achieved as scheduled. In contrast, under the TB scenario, with technological innovation realized in green building material production, green construction, green operation, and others to a large extent, China's building sector can enter a period of low CO_2 emissions (0.0005 Bt) in 2049, with subsequent CO_2 emissions continuing to decline and reaching carbon neutrality by 2060. Therefore, to achieve carbon neutrality by 2060, China's building sector needs to continuously realize green innovation and technological innovation while adhering to the path of green development.

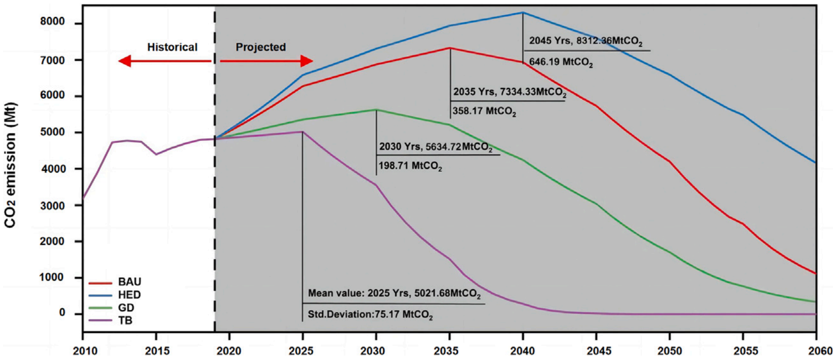

Figure 3. Prediction of CO_2 emission in China's building sector

Based on 2019 as the forecast benchmark year, the forecast period is set at 2060. According to the setting of the change rate of various factor parameters in different scenarios, the CO_2 emissions of China's building sector in the whole life cycle from 2020 to 2060 were predicted, and the evolution trend of the total CO_2 emissions of China's building sector in the whole life cycle under the four scenarios is shown in Figure 3. The CO_2 emissions during the BMP stage come from cement and steel, accounting for 95% of the stage. The CO_2 emissions during the BC stage come from civil engineering and installation engineering, accounting for 89% of the stage.

By stage, the key to achieving a carbon emission peak in China's building sector is the reduction of CO_2 emissions at the BMP stage, and the TB scenario allows for carbon neutrality in 2060 at different stages for the building sector's entire life cycle

According to Figure 4, it can be found that the different stages of China's building sector have the same emission peak time in the four scenarios (BAU, HED, GD, and TB), which are 2035, 2040, 2030, and 2025, respectively. Green technological innovation is important for China's building sector to achieve carbon neutrality. If breakthroughs in green innovation technology can be achieved, carbon neutrality can be achieved as scheduled at all stages for the entire life cycle of China's building sector under the TB scenario.

By stage, the CO_2 emissions during the BMP stage are significantly higher than those during the BC and BO stages, which are related to China's vigorous efforts to renovate old urban residential areas in recent years. On the one hand, the renovation will lead to a high demand for building materials, increasing the CO_2 emissions of the BMP stage. On the other hand, it can improve the energy efficiency of building operations, thereby having a positive impact on carbon reduction in the BO stage. Moreover, if energy consumption is not controlled in the BMP stage, even if CO_2 emissions gradually decrease after reaching the peak in 2045, the CO_2 emissions of cement and steel will still be high by 2060. In the BC stage, both civil engineering and installation engineering can achieve carbon peaks by 2030 under the GD scenario, with peaks of 1.24 and 3.43 Mt, respectively; As for the BO stage, heating CO_2 emissions increase 1.87 times compared with 2019 when they peak by 2030, surpassing cooling (1.73), lighting (1.43), and electricity (1.58). China's transition areas are mostly characterized by decentralized heating and energy use, and the intensity of heating CO_2 emissions is closely related to the low-carbon cleanliness of the heating equipment.

By building type, the CO_2 emission reduction pressure on RR in the southern area is relatively small, and if green and low-carbon emission reduction measures are implemented, carbon peaking can be realized ahead of schedule in 2025

According to Figure 5, during the BO stage, different climate areas and building types were unable to achieve carbon peaking as scheduled under the BAU scenario, with a peak time of 2035, which was later than the 2030 target. Under the GD scenario, carbon peaking can be achieved as scheduled, with RR in the southern climate area achieving carbon peaking ahead of 2030. If breakthroughs in green innovation technology are achieved under the TB scenario, different building types in different climate areas during the BO stage can reach carbon peaking as early as 2025 and enter a period of ultra-low growth in carbon emissions in 2049, ultimately achieving carbon neutrality by 2060 as scheduled. Under the HED scenario, if energy use is not restrained, CO_2 emissions from different building types in different climate areas during the BO stage will continue to maintain a high level of growth in 2060 after reaching the peak in 2045. The CO_2 emissions of UR in the transition and southern areas are 1.32 and 1.03 times higher than the predicted CO_2 emissions in the benchmark period of 2019, respectively.

DISCUSSION

We introduced a GDIM decomposition model to analyze the factors that influence CO_2 emissions at different stages for the entire life cycle of China's building sector. Dynamic scenario analysis was also introduced to predict the peak CO_2 emissions and the peak timing in different stages of China's building sector. We found that the carbon intensity of green innovation output, carbon intensity of energy consumption, energy intensity of green innovation output, and green innovation output per unit of floor space maintain the reduction of CO_2 emissions in China's building sector at different stages. By contrast, the CO_2 emissions of the BO stage in different climate areas and building types are affected by different categories of green innovation outputs. According to the carbon peak prediction results under the aforementioned four scenarios, existing or relatively lax policies cannot help achieve the goal of China's building sector in reaching its emission peak before 2030. In the four scenarios, China's building sector can only achieve carbon neutrality in the TB scenario as scheduled. The key to achieving

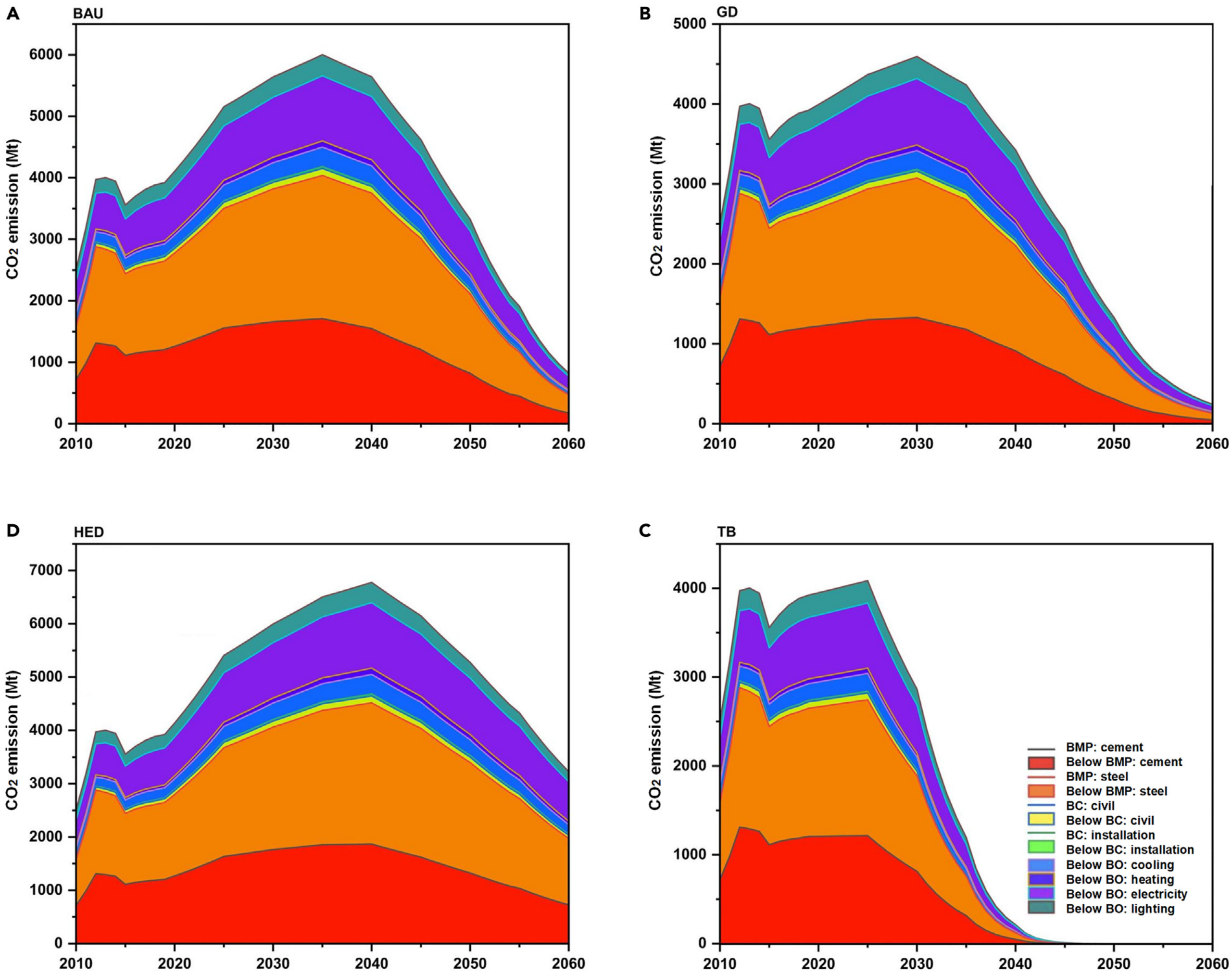

Figure 4. Evolutionary trends of CO2 emissions of China's building sector at different life stages

(A) BAU scenario.

(B) GD scenario.

(C) TB scenario.

(D) HED scenario. Figure 4 shows the evolutionary trends of CO_2 emissions in China's building sector at different stages: the BMP stage (cement and steel), the BC stage (civil engineering and installation engineering), and the BO stage (electricity, lighting, cooling, and heating).

peak carbon in China's building sector lies in the BMP stage, where CO_2 emissions will continue to grow until 2040 if its energy use is not controlled. There are differences in the CO_2 emission trends of different building types in the BO stage, among which RR has the slowest growth trend, with relatively little pressure to reduce CO_2 emissions, which may be related to China's growing urbanization rate.

Based on the aforementioned research, combined with the characteristics and development prospects of China's building sector, we propose low-carbon suggestions to provide a reference for China's building sector to achieve carbon neutrality as scheduled. In the following, we elaborate policy recommendations based on the different stages, taking into account the different climate areas and building types.

(1) China should actively seek green innovation and green low-carbon production in the BMP stage, focusing on key building materials such as steel and cement. The BMP stage is crucial for China's building sector to achieve its dual carbon goals, with CO_2 emissions accounting for 55.4% of the total emissions in the building sector in 2020. The CO_2 emissions from the production of steel and cement account for over 95% of the CO_2 emissions in the BMP stage. According to existing policies, the production of steel and cement still maintains a high CO_2 emission of 0.47 Bt in 2060 under the BAU scenario, showing a significant gap with the carbon neutrality goal. Combined with factor decomposition, the green innovation output per unit of floor space is of great significance for the carbon reduction of cement and steel in the BMP stage, with a cumulative contribution of 0.38 and 0.17 Bt of carbon reduction in the past decade, respectively. Therefore, increasing the green innovation output per unit of floor space in steel and cement will help reduce unit energy consumption and carbon emission intensity levels, thus achieving the dual carbon goals in the BMP stage.

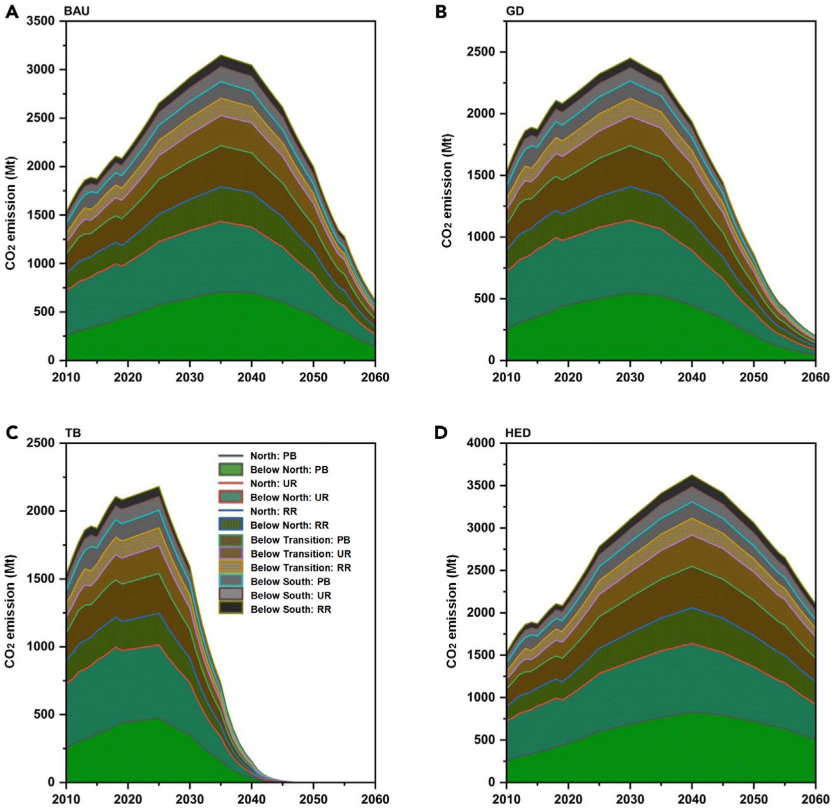

Figure 5. Evolutionary trends of CO2 emissions in different climate zones and building types during the BO stage

(A) BAU scenario.

(B) GD scenario.

(C) TB scenario.

(D) HED scenario.

Figure 5 shows the evolutionary trends of CO_2 emissions of different building types (PB, UR, and RR) in different climate areas (northern area, transition area, and southern area) during the BO stage.

(2) China's building sector should promote green and intensive construction technology during the BO stage to improve the energy efficiency of mechanical equipment. According to the decomposition results, the green innovation output per unit of floor space and the energy intensity of the green innovation output have significant carbon reduction effects on civil engineering (IF: 8.03 Mt; EI: 4.51 Mt) and installation engineering (IF: 11.64 Mt; EI: 11.96 Mt). Therefore, during the BO stage, efficient and low-carbon construction machinery and equipment, such as electric construction machinery and energy-saving generator sets, should be promoted to reduce fuel consumption and CO_2 emissions during the BO stage, which will help to improve the energy efficiency of the BO stage and promote the widespread application of clean energy technologies.

(3) China's building sector should develop differentiated and targeted emission reduction policies and green innovation routes for the BO stage, taking into account regional differences according to local conditions. When the patent of green innovation output is cooling, the contribution rate of green innovation output per unit of floor space to CO_2 emission reduction in the northern and the southern areas in the past ten years is 22.71% and 25.58%, respectively, wherein the effect in the southern area is stronger than that in the northern climate area. Therefore, for the southern area, where the demand for cooling is higher, the application of green energy-saving equipment, such as low-energy air conditioners, should be promoted to realize the CO_2 emission reduction in the BO stage.

(4) Considering the characteristics of different building types, China's building sector should promote efficient and low-carbon building operations and management, especially strengthening the application of green innovative technologies in the BO stage. China should promote the full electrification of new PB, replace gas products with heat pump water heaters and high-efficiency electric stoves, prioritize the consumption of renewable energy power, and take the initiative to participate in demand-side response to electricity. With the continuous increase in urbanization rate, the carbon reduction process of the operation process of UR plays an increasingly important role in achieving the dual carbon goals of China's building sector. It is necessary to improve the energy efficiency level of UR, focusing on the energy-saving renovation of existing UR and the application of green innovative household products in UR, so as to reasonably control its total energy consumption and CO_2 emissions. For RR, strengthening the guidance of policies and

technologies is the key to prevent excessive growth in emissions. Clean heating in RR in the northern area should be promoted to a large extent. The energy-saving renovation of RR should be promoted in the winter, such as clean heating projects in northern areas, to achieve an overall improvement in energy efficiency.

(5) China's building sector should adopt policy measures based on market mechanisms to promote green innovation output applications and transform it into a role in promoting CO_2 emission reduction. Green innovation output has shown a promoting effect at different stages of the entire life cycle of the building sector. Although green innovation output improves energy efficiency in the short term, its higher efficiency drives market demand, thereby increasing overall energy consumption. In addition, there is a certain lag in the promotion and application of green innovation output, which can also lead to the insufficient emission reduction effect in the initial stage. Therefore, China's building sector should develop policy measures based on market mechanisms, such as setting strict energy efficiency standards, controlling the market demand for energy, and providing economic incentives such as subsidies for green innovation output applications to promote energy conservation and carbon reduction.

Limitations of the study

The study has certain limitations, which can be further explored and improved in subsequent research. In the scenario prediction analysis of CO_2 emissions, although the scenario parameters are set with reference to the parameter change rate of China's building sector in recent years, the current social development trend and national policies, which are persuasive to a certain extent, as well as the uncertainty of the evolution of economic variables, are taken into account using the Monte Carlo simulation techniques. However, the effectiveness of policy implementation has a certain degree of uncertainty, and subsequent studies can be combined with Computable General Equilibrium (CGE) models to analyze the differences in the results obtained by different methods. For the exploration of scenarios, we have mainly considered the impact of emission reduction policy measures and related technological innovations in China's building sector CO_2 emissions. However, some studies have shown that the building sector, as one of the three major final energy-consuming sectors, generates a larger proportion of indirect CO_2 emissions than direct CO_2 emissions from power generation. Therefore, the emission reduction actions of other sectors have a significant impact on the development of CO_2 emission reduction strategies in the building sector.[17] For example, what impact will the emission reduction actions of the power sector have on the realization of carbon peaking in the building sector? This may be an interesting direction for future research.

STAR★METHODS

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

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Factorial decomposition in the building sector
  - Data description
  - CO_2 emission prediction
  - Scenarios
  - Analysis of the accuracy of prediction results

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.110664.

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AUTHOR CONTRIBUTIONS

Y.X. was responsible for conceptualization, funding acquisition, methodology, validation, visualization, and writing. Z.Y. handled data curation, formal analysis, software, and writing. X.J. contributed to conceptualization, investigation, and writing. H.W. was involved in conceptualization, investigation, and writing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
CO2 emissions data Energy data Floor space stock data	China Building Energy Consumption and Carbon Emission Database[7] and Annual Report on China Building Energy Efficiency[43]	https://www.cbeed.cn/#/database
Demographic data	State Council of the People's Republic of China	https://www.gov.cn
Patent data	State Intellectual Property Office (SIPO)	https://www.cnipa.gov.cn
GDIM data	This paper	https://doi.org/10.17632/c76g83vnf6.1
Scenario settings data	This paper	https://doi.org/10.17632/c76g83vnf6.1
Software and algorithms		
Code for factorial decomposition	This paper	https://doi.org/10.17632/mnd53d2kb8.1
Code for scenario analysis	This paper	https://doi.org/10.17632/mnd53d2kb8.1

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Yan Xia (xiayan@casipm.ac.cn).

Materials availability

The study did not generate new materials.

Data and code availability

- This paper analyzes existing, publicly available data. These accession numbers for the datasets are listed in the key resources table. The dataset is publicly available. All data has been deposited at Mendeley Data and is publicly available as of the date of publication. DOIs are listed in the key resources table.
- All original code has been deposited at Mendeley Data and is publicly available as of the date of publication. DOIs are listed in the key resources table.
- Any additional information required to reanalyze the data reported in this paper or reproduce the results is available from the lead contact upon request.

METHOD DETAILS

Factorial decomposition in the building sector

According to the International Energy Agency's annual energy outlook, the building sector has a more significant potential for carbon reduction compared with the industrial and transportation sectors, which can reduce carbon reduction costs and improve economic benefits through existing technological means and policies.[30] Identifying the factors influencing CO_2 emissions in China's building sector is of great significance for achieving the dual carbon goals.[3,44] Through factorial decomposition analysis, various driving factors leading to changes in CO_2 emissions can be effectively identified to provide a reference for emission reduction policies.[45,46] The widely accepted decomposition methods based on historical CO_2 emissions include structural decomposition analysis (SDA) and index decomposition analysis (IDA).[47,48] Compared with SDA, IDA has lower data requirements and more flexible decomposition forms.[49] Among the IDA methods, the Log Mean Divisia Index (LMDI) is extensively employed because of its integral theoretic, perfect decomposition, and consistency of aggregation,[3,50] and has been widely used to analyze impact factor decomposition in the environmental field.[51,52] LMDI can decompose the CO_2 emissions of the building sector into various factor variables, such as green innovation output, carbon intensity of green innovation output. However, there are also disadvantages of the LMDI method. Vaninsky (2014) for example pointed out that the existing factorial decomposition methods, including the LMDI, are all based on Kaya identity, which breaks down the target variable into the form of multiplying factors, with formal interdependence among the factors. Its decomposition results also depend on the selection of influencing factors, which makes different factor decomposition forms based on Kaya identity produce contradictory decomposition conclusions. Therefore, a generalized Divisia index method (GDIM) was suggested by Vaninsky,[53] which can overcome the above disadvantages in LMDI decomposition. The GDIM method takes into account multiple absolute and relative factors at the same time and quantifies the actual contributions of different factors to the evolution of CO_2 emissions more accurately.

Green innovation output is an important factor in reducing CO_2 emissions,[54] and the number of green patents has become an indicator for measuring green innovation output.[55,56] Compared with total research and development (R&D) spending, energy patents have a closer connection with environmental performance[57] and can serve as a better proxy to characterize technological progress in the energy sector.[39]

Enterprises, research institutes, and universities are the three main sources of energy patents. The impact of energy patents from different sources on environmental performance varies. Enterprises are on the front line of production, and their technological innovation activities usually aim to maximize profits. Therefore, we only consider the patents developed by enterprises in this paper, as they have higher application value in solving practical environmental problems.

Similarly, energy patents can also be classified based on their intended use. According to China's patent law, there are three types of outputs generated from energy-saving research and development activities: utility model, invention, and design patents. Among them, design patents mainly focus on product design and have little contribution to the production technology field,[58] thus have not been included in the analysis. In addition, considering that patent technology is likely to have an impact on corporate performance during the application process, patent application data will be more stable, reliable, and timely than authorized patents.[59] Based on the above analysis, we employed green invention patents and green utility model patents of listed companies to quantify the green innovation output of China's building sector at different stages of its life cycle. Moreover, the impact of different types of green innovation outputs (electricity, lighting, cooling, heating) on the CO_2 emissions of the BO stage is separated in this paper, taking into account the different end-service demands.

In this context, the GDIM is introduced to map the relationship between the target and factor variables of China's building sector in the following form:

$$C = C_{BMP} + C_{BC} + C_{BO} \quad \text{(Equation 1)}$$

$$C_{BO} = \sum_{i=1}^{3}\sum_{j=1}^{3} C_{ij} = \sum_{i=1}^{3}\sum_{j=1}^{3} \frac{C_{ij}}{I_{ij}} I_{ij} = \sum_{i=1}^{3}\sum_{j=1}^{3} \frac{C_{ij}}{E_{ij}} E_{ij} = \sum_{i=1}^{3}\sum_{j=1}^{3} \frac{C_{ij}}{P_{ij}} P_{ij} = \sum_{i=1}^{3}\sum_{j=1}^{3} \frac{C_{ij}}{F_{ij}} F_{ij} \quad \text{(Equation 2)}$$

$$\frac{E_{ij}}{I_{ij}} = \left(\frac{C_{ij}}{I_{ij}}\right) \Big/ \left(\frac{C_{ij}}{E_{ij}}\right) \quad \text{(Equation 3)}$$

$$\frac{I_{ij}}{F_{ij}} = \left(\frac{C_{ij}}{F_{ij}}\right) \Big/ \left(\frac{C_{ij}}{I_{ij}}\right) \quad \text{(Equation 4)}$$

where the target variable Z = C is the total CO_2 emissions in China's building sector, and C_{BMP}, C_{BC}, and C_{BO} are the CO_2 emissions in the BMP, BC, and BO stages, respectively. i is the ith climate area of China (i = 1, northern area; i = 2, transition area; i = 3, southern area) and j is the j-th building type (j = 1, PB; j = 2, UR; j = 3, RR).

For the sake of easier readability, the kth driver leading to CO_2 changes is denoted by X_k (k = 1, 2, …, 10), and their specific meanings are illustrated in Table S2. X_1, X_3, X_5, and X_7 are aggregate indicators, X_1 = I is green innovation output; X_3 = E is energy consumption; X_5 = F is floor space; and X_7 = P is population scale. X_2, X_4, X_6, and X_8 are the corresponding carbon intensities. X_2 = CI = C/I denotes the carbon intensity of green innovation output, X_4 = CE = C/E denotes the carbon intensity of energy consumption, X_6 = CF = C/F denotes the carbon intensity of floor space, and X_8 = CP = C/P denotes the carbon intensity per capita. Two indicators, X_9 and X_{10}, are also included in the basic model to increase its explanatory power. X_9 = EI = E/I denotes the energy intensity of green innovation output, and X_{10} = IF = I/F denotes green innovation output per unit of floor space.

Thus, Equations 1, 2, and 3 can be converted as follows:

$$Z = f(X) = f(X_1, \cdots X_{10}) = X_1 X_2 = I \cdot CI \quad \text{(Equation 5)}$$

$$\Phi_1 : I \cdot CI - E \cdot CE = 0 \quad \text{(Equation 6)}$$

$$\Phi_2 : I \cdot CI - P \cdot CF = 0 \quad \text{(Equation 7)}$$

$$\Phi_3 : I \cdot CI - F \cdot CP = 0 \quad \text{(Equation 8)}$$

$$\Phi_4 : E - I \cdot EI = 0 \quad \text{(Equation 9)}$$

$$\Phi_5 : I - F \cdot IF = 0 \quad \text{(Equation 10)}$$

where the resulting indicator C in Equation 5 is a function of the factorial indicators that are interconnected by the Equations 6, 7, 8, 9, and 10 named matrix-valued function. A Jacobi matrix $\Phi(x)$ composed of the relevant factors can be constructed from Equations 5, 6, 7, 8, 9, and 10:

$$\Phi_x = \begin{pmatrix} CI & I & -CE & -E & 0 & 0 & 0 & 0 & 0 & 0 \\ CI & I & 0 & 0 & -CF & -F & 0 & 0 & 0 & 0 \\ CI & I & 0 & 0 & 0 & 0 & -CP & -P & 0 & 0 \\ -EI & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -I & 0 \\ 1 & 0 & 0 & 0 & -IF & 0 & 0 & 0 & 0 & -F \end{pmatrix}^T \qquad \text{(Equation 11)}$$

Based on the GDIM principle, the amount of change in CO_2 emissions ΔC can be decomposed by summing the contributions of the following factors:

$$\Delta C[X|\Phi] = \int_L \nabla C^T \left(I - \Phi_X \Phi_X^+\right) d_X \qquad \text{(Equation 12)}$$

where L denotes the time span, $\nabla C = (CI \quad I \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0)$ denotes the unit matrix, and "+" denotes the generalized inverse matrix; if the columns in the Jacobi matrix are linearly uncorrelated, then $\Phi_X^+ = (\Phi_X^T \Phi_X)^{-1} \Phi_X^T$. Ultimately, changes in CO_2 emissions can be decomposed into the sum of 10 effects: ΔC_I, ΔC_E, ΔC_F, ΔC_P, ΔC_{CI}, ΔC_{CE}, ΔC_{CF}, ΔC_{CP}, ΔC_{EI}, and ΔC_{IF}.

Data description

Based on the maximum availability and timeliness of data, we collected inter-provincial historical data in China from 2010 to 2019, excluding Tibet, Hong Kong, Macao, and Taiwan, China. Among them, the data on the permanent urban and rural populations by province is obtained from the statistical yearbooks of each province of China. The data on CO_2 emissions, energy consumption, and floor space stock of different building types (PB, UR, and RR) by province is obtained from the China Building Energy Consumption and Carbon Emission Database[7] and the research report on building energy efficiency published by the Building Energy Efficiency Research Center of Tsinghua University.[43] In addition, climatic conditions influenced the cooling and heating energy consumption of buildings. Huge climatic differences across China result in different space heating and cooling needs. To fully consider the characteristics of energy utilization in Chinese buildings, China was divided into three areas with reference to existing studies: northern, transition, and southern areas.[11,16,60,61] We followed this line to divide the climate areas, please refer to Table S3 for more details.

Patent data is obtained from the State Intellectual Property Office (SIPO). Based on the international patent classification (IPC), we screened green patents of listed companies through the World Intellectual Property Organization (WIPO) Green Patent List. Patent data were classified based on IPC categories to characterize the effect of green innovation output in each category on CO_2 emissions at different stages for the entire life cycle of China's building sector. The specific classification is shown in Table S4.

CO_2 emission prediction

The analysis of the historical evolutionary trend of CO_2 emissions can help establish the impact of different factors on CO_2 emissions in the past. As shown in Table S1, the Long-term Energy Alternatives Planning (LEAP) system and the Demand-Resource-Energy Analysis Model (DREAM) are often applied to CO_2 emission forecasts.[9–11] In addition, some scholars have tried to combine factor decomposition and scenario analysis to explore CO_2 emissions in China.[62] Among them, scenario analysis based on Kaya identity can clearly describe the future trajectory and peak of CO_2 emissions through time series.[63]

However, Kaya's identity requires a specific setting of each factor, which faces uncertainty problems in the long term. The Monte Carlo simulation is a computational method based on probabilistic and statistical theories, where an approximate solution to the problem can be obtained through statistical simulation or random sampling. Therefore, some scholars have employed the Monte Carlo method to deal with uncertainty problems in the scenario analysis based on Kaya identity, to better forecast the long-term CO_2 emission range.[64] In this paper, based on factor decomposition, we also used the Monte Carlo simulation to conduct a dynamic scenario analysis on the forecasts of CO_2 emissions in China's building sector.

More specifically, according to the results of the factor decomposition of CO_2 emissions, floor space is an important factor for the growth of CO_2 emissions in different stages for the entire life cycle of China's building sector (BMP, BC, and BO stages). Green innovation output per unit of floor space, energy intensity of green innovation output, and carbon intensity of energy consumption are the most important factors leading to the decrease of CO_2 emissions in China's building sector. Therefore, the following equations were constructed for further scenario analysis:

$$C = F \times \frac{C}{F} = F \times \frac{I}{F} \times \frac{E}{I} \times \frac{C}{E} \qquad \text{(Equation 13)}$$

Combining the basic methods of the factor decomposition model described above, four possible CO_2 emission scenarios were set, and the future changes in CO_2 emissions from China's building sector were forecasted by taking 2019 as the base year. The changes in CO_2 emissions at different stages of China's building sector in year t+1 is expressed as the following equation:

$$C_{t+1} = F_{t+1} \times IF_{t+1} \times EI_{t+1} \times CE_{t+1} = F_{t+1} \times (1+\alpha) \times IF_{t+1} \times (1+\beta) \times EI_{t+1} \times (1+\varepsilon) \times CE_{t+1} \times (1+\eta) \qquad \text{(Equation 14)}$$

where the rate of change of floor space, green innovation output per unit of floor space, energy intensity of green innovation output, and carbon intensity of energy consumption are α, β, ε, and η, respectively. The rate of change of CO_2 emissions is expressed as:

$$\omega = (1+\alpha)\times(1+\beta)\times(1+\varepsilon)\times(1+\eta) \quad \text{(Equation 15)}$$

Future CO_2 emissions can be derived from the predicted values of these four factors. The evolution of CO_2 emissions from China's building sector is closely related to the evolutionary trends of floor space, green innovation output per unit of floor space, energy intensity of green innovation output, and carbon intensity of energy consumption. Among them, the energy intensity of green innovation output reflects the energy efficiency level of green innovation output in the building sector, and the higher the value, the lower the resource utilization efficiency. The change in CO_2 emissions can be calculated by Equation 15, and the long-term CO_2 emissions of the building sector can then be forecasted.

The potential change rate of various factors in the building sector is the benchmark variable in Monte Carlo simulation. According to the basic principle of the Monte Carlo simulation, the accepted benchmark variable needs to be given a value range rather than a specific single value. Therefore, based on the possible value range of each variable and fully considering uncertainty, a more reasonable "distributed" simulation of its future evolution trend can be carried out. We refer to the triangular distribution for the random selection of variables.[64]

Scenarios

Most energy-environment-economy models use scenario analysis methods to make *a priori* assumptions about future trends at present. Considering the uncertainties in energy demand, technological innovation, and other factors that affect CO_2 emissions, we constructed four scenarios for the future development of China's building sector based on the past evolutionary trend of each factor, the effectiveness of the implementation of the existing policies, and the potential space for emission reduction: the BAU, HED, GD, and TB scenarios.

The BAU scenario is based on an "extrapolation" of past trends in China's building sector and takes into account possible parameter changes with reference to targets set by relevant Chinese authorities related to the green transition. The HED scenario is based on a scenario in which the building sector fails to develop in line with the green sustainability targets after 2019. The GD scenario is based on China's ecological civilization concept of sustainable development, where the government has strengthened its interventions on climate change, leading to the further optimization of the energy structure and improvement of energy-saving technologies. The TB scenario examines the increase in energy-saving and emission-reduction green innovation input to a greater extent and the resulting increase in energy and building construction technologies. The TB scenario highlights to a greater extent the increase in the scale of investment in energy-saving and emission-reduction green innovations, as well as the thinking on whether breakthroughs in energy and construction technologies can realize the CO_2 emission reduction goals of China's building sector.

In the process, to comprehensively reflect the inertia evolution trend and potential possibilities of various factors as much as possible, we fully consider the cyclical adjustment characteristics, such as China's five-year development plan, to set the potential changes of factors related to China's building sector in the future. Based on the above basic logic and practical laws, the median of the potential change rates of various factors in the BAU scenario from 2020 to 2060 is taken from the relevant data of China's building sector from 2010 to 2019. It should be noted that although the CO_2 emissions of China's building sector in 2020–2022 have already occurred, it is not yet possible to estimate their specific data accurately due to availability constraints. The forecast results are also compared and analyzed with the relevant data in the Research Report on Building Energy Consumption and Carbon Emissions in China published by the CABEE.[7]

In addition, considering the effectiveness and uncertainty of policy implementation, the minimum and maximum values of the potential rate of change are adjusted downward and upward by 0.2 percentage points from the median value, respectively.[65] We take the change rate of various factors in 2019 as the initial data for the BAU, HED, GD, and TB scenarios so that the four scenarios are at the same level in 2019. Combined with the growth trend of historical data, the population and urbanization rate data are expected to project the growth rates of China's resident, urban, and rural populations. With the acceleration of urbanization and population growth, China's building stock will continue to grow, but the growth rate will gradually slow down and tend to stabilize.[25,66] With reference to the Ministry of Housing and Urban-Rural Development and the Tsinghua Center for Energy Research in Buildings, the trend of stock changes in floor space is projected based on the target values of floor space per capita for different building types at the national level. In China's 14th Five-Year Plan and 2035 Vision Goal Outline, the average annual growth rate of R&D investment in the whole society is over 7%, and the number of high-value invention patents per 10,000 people will reach 12 by 2025. The input-output elasticity of innovation funds in China is 0.465, which means that for every 1% increase in R&D investment in China, patent output increases by 0.465%,[67] according to which the rate of change of green innovation output in China's building sector can be deduced. Energy consumption mainly depends on the energy consumption structure. In 2019 and 2022, the proportion of non-fossil fuels in China's total energy consumption reached about 15.13% and 17.3%, respectively. In addition, according to the planning requirements, the proportion of non-fossil fuels in primary energy consumption will reach about 25% by 2030, over half by 2050, and over 80% by 2060. China's 14th Five-Year Plan and 2035 Vision Goal Outline states that energy consumption per unit of GDP will decrease by 13.5% compared with 2020, and CO_2 emissions per unit of GDP will decrease by more than 65% compared with 2005 by 2030. The change rate of energy carbon intensity refers to Zhang et al.,[68] which detailed how CO_2 emission factors are planned based on energy structure and planning policies and provided the expected change rate of CO_2 emission intensity in different scenarios.

Analysis of the accuracy of prediction results

The year 2019 is taken as the base year, with the forecast period set to 2060. Based on the settings of the rate parameters of each factor under different scenarios, the CO_2 emissions for the entire life cycle of China's building sector from 2020 to 2050 are forecasted, and the forecast results are also compared with existing authoritative measurement reports and previous studies to verify their accuracy. We employed the data in the year 2020 to explore the accuracy of our forecast. As mentioned before, based on the availability of data, 2020 was also included in the forecast period for the trend analysis. The forecast showed that under the BAU scenario, the CO_2 emissions of the BMP, BC, and BO stages in 2020 were 2.78 Bt (total CO_2 emissions from steel and cement, accounting for about 95%), 0.09 Bt (total CO_2 emissions from civil and installation engineering, accounting for about 89%) and 2.17 Bt (PB: 0.88 Bt; UR: 0.86 Bt; RR: 0.43 Bt) respectively. The research report from CABEE shows that the CO_2 emissions for the different stages in China's building sector in 2020 were 2.82 Bt, 0.10 Bt and 2.16 Bt (PB: 0.90 Bt; UR: 0.83 Bt; RR: 0.43 Bt) respectively. The difference in forecasts is reasonable.

In addition, the national CO_2 emission forecast for the BO stage of China's building sector is a study conducted in recent years. To analyze the accuracy of the prediction results, we summarize the results of the existing literature on China's national-level building operation emission prediction, as shown in Table S5. Our estimates of the peak emissions of PB and UR under the BAU scenario are between the values of the three studies. The peak times of UR and PB are in line with the time of their peak emissions, while only RR reaches the peak a little bit later, with a higher peak of emissions. The reliability and rationality of the prediction results of the paper are verified.