Resources, Conservation & Recycling 188 (2023) 106679

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Modeling carbon emission trend in China's building sector to year 2060

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ARTICLE INFO

Keywords:
Building sector
Carbon peak
Carbon neutrality
Carbon emission mitigation
Scenario simulation
Building stock turnover model

ABSTRACT

Mitigating carbon emissions of China's building sector can significantly contribute toward realizing China's climate goals of achieving carbon peak and carbon neutrality. To understand the carbon emission trend and tap the potential of emission mitigation, this study developed an innovative carbon emissions simulation model that considers climate area, building type and end-use service, and quantifies technique renovation by building metabolism. The results of this study represent China's building sector need to adopt stronger strategies to realize the carbon peak goal. To further conduct deep decarbonization and achieve carbon neutrality, the collective efforts of overall society will lead to the achievement of 64.51% carbon emission mitigation in 2060, decarbonization of electricity generation (47.85%), building stock regulation (M9: 14.24%, 0.14 $BtCO_2$), and residential green behavior guidance (M10: 13.68%, 0.13 $BtCO_2$) contribute the top three carbon abatement. Moreover, our results indicate that carbon capture, utilization, and storage techniques must be employed to realize the "last mile" of China building neutrality. Overall, this study provided a valuable reference and emission quantification tool for setting specific carbon emission mitigation goals.

1. Introduction

As the world's largest carbon emission country, the carbon emission mitigation actions of China play an important role in mitigating the global climate change (Liu et al., 2015). Therefore, the Chinese government has announced its aggressive carbon emission goals of achieving carbon peak in 2030 (UNFCCC, 2015) and carbon neutrality in 2060 (Zhao et al., 2022). As one of the three major final energy consumption and carbon emission sectors in China (Ma et al., 2020), the building sector produced 2.11 billion tons of CO_2 ($BtCO_2$) in 2018, accounting for 21.90% of China's energy-related carbon emission (CABEE, 2020). Compared with the developed countries, the per capita building area and building end-use service demand are still low in China. According to the data of International Energy Agency (IEA, 2021b), the per capita building energy intensity in China is only 21%, 72%, and 23% of that in the US, Japan, and the UK, respectively. Therefore, in future, with an increase in residents' income and development of tertiary industry, the energy consumption of China's building sector will continuously face a strong increasing trend in its carbon emissions (Ramaswami et al., 2016), which will severely hinder the realization of China's carbon peak and neutrality goals (Ma et al., 2019; Zhang et al., 2022a).

It is worth noting that, compared with the industry and transportation sectors, the building sector has more obvious carbon emission mitigation potential, and it may achieve cost savings and economic benefits through existing technologies and policies (IEA, 2020a; LNBL, 2016; McKinsey, 2013). The study of Lawrence Berkely National Laboratory (LNBL, 2016) reported that the building sector can achieve 74% carbon emissions by 2050. In practice, to limit the direct and indirect carbon emissions of the building sector of China, its multi government departments have published a series of severe policies such as the *standard of building energy conservation and renewable energy utilization* published by the Ministry of Housing and Urban-Rural Development (MOHURD, 2021), the *plan of winter clean heating in northern area (2017–2021)* published by the National Energy Administration (NEA, 2017), and the *plan of carbon peak and carbon neutrality of electricity* published by the State Grid (Grid, 2021). Considering the huge carbon emissions and obvious emission mitigation potential of China's building sector, it is necessary to formulate rational carbon emission trends and determine key emission mitigation strategies for achieving its carbon peak and carbon neutrality goals (Guo et al., 2021; Ma et al., 2020). Therefore, in this study, we aimed to address the following three key issues.

- **What is the future carbon emission trend of China's building sector?**

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https://doi.org/10.1016/j.resconrec.2022.106679
Received 8 April 2022; Received in revised form 5 September 2022; Accepted 19 September 2022
Available online 24 September 2022

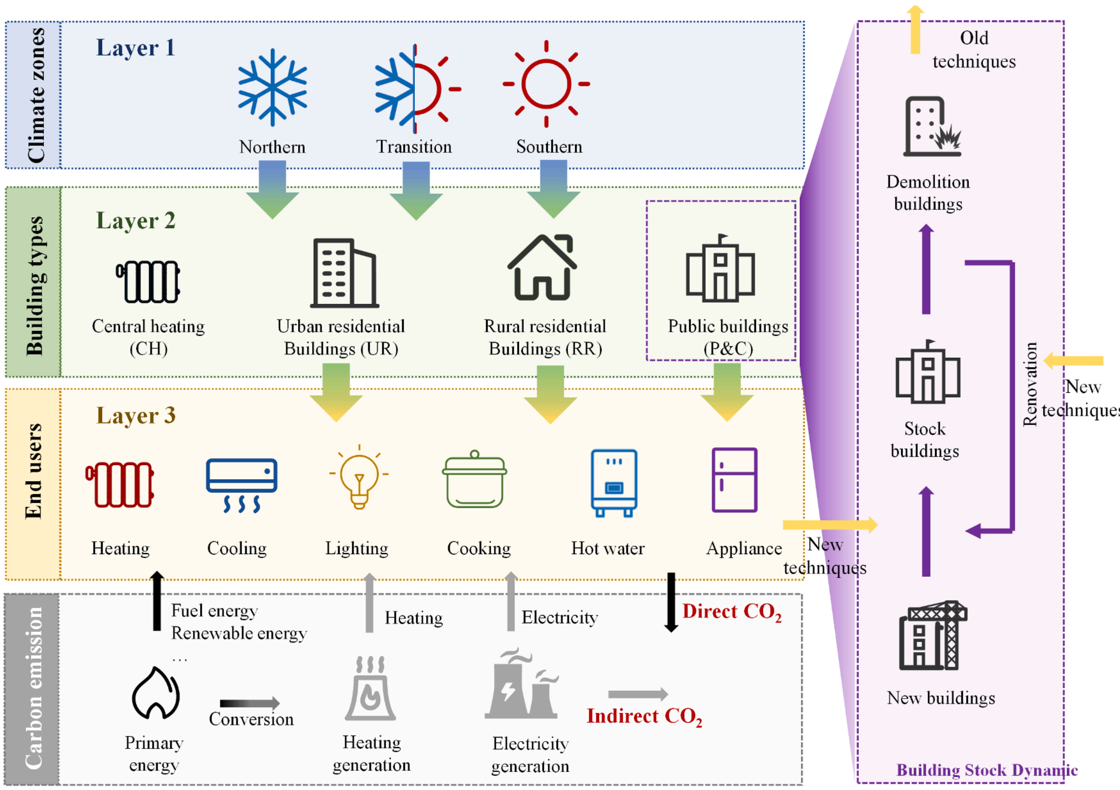

Fig. 1. Framework of China's building carbon emission model.

- **What are the main driving factors of the future carbon emission trend of China's building sector?**
- **What would be the main emission mitigation strategies for China's building sector?**

To solve the above issues, based on the characteristics of China's building sector, we first developed a multi-layer (climate areas, building types, and end-use services) dynamic carbon emission quantization model that covers most of the emission mitigation strategies derived from the present practical policies. Subsequently, to respond to issue 1, four combined scenarios (base scenario, single building sector scenario, collective effort of multi sectors scenario, collective of over society scenario) were developed to forecast the future carbon emissions. Finally, the logarithmic mean Divisia index (LMDI) decomposition method was adopted to identify the main driving factors for the future carbon emission trend and to quantify the emission mitigation contribution of each strategy at the national and building type levels, as responses to issues 2 and 3, respectively.

The most significant contribution of this study is the multi-layer dynamic emission quantization model. To investigate energy consumption emission trends, existing studies have established different models. Xu and Wang (2020) employed the a "stochastic impacts by regression on population, affluence, and technology" (STIRPAT) model to established the energy consumption outlook of China's building sector in 2100. However, this model doesn't integrate the building characteristics. To address this gap, Tan et al. (2018) and Guo et al. (2021) developed models that consider the four building types: urban residential buildings, rural residential buildings, public and commercial buildings and central heating. The model developed by Delmastro et al. (2015) considered the impact of climate and merged five of China's climate zones into three: northern (cold and severe cold region), transition (hot summer and cold winter region), and southern areas (hot summer and warm winter as well as moderate regions). The model developed by Yang et al. (2017) followed a bottom-up framework and integrated six end-services demands (heating, cooling, lighting, cooking, hot water, and other appliances). Furthermore, the model developed by Ma et al. (2020) considered the uncertainty of parameters and established the distribution of carbon peak time and value of China' commercial and public buildings. However, these models have some limitations. 1) Generally, the models directly set the future building area target and technique-related parameters separately, ignoring the relationship between techniques renovation and metabolism (Yang et al., 2022); for example, the renovation of building envelop technique occurs during building energy renovation or constructing the new buildings. Owing to such limitations, these models do not match with practical policies and provide limited guidance on the formulation of policies. For example, carbon peak action in the building sector required the new building to adopt a building energy efficiency standard, rather than implement a certain percentage reduction in average energy consumption unit area of overall building sector. To solve this problem, this study employed a building stock turnover model was employed to represent the techniques renovation. 2) To formulate reasonable decarbonization pathway, existing studies have attempted to set scenarios based on single or a combination of policies (Huo et al., 2021; Li et al., 2021; Tan et al., 2018). However, most policies are concentrated in building sector, such as optimizing building design, building energy renovation, and improving end-use service equipment energy efficiency (Huo et al., 2021; Li et al., 2021; Tan et al., 2018). In practice, the building sector is one of top three final energy consumption sectors, its indirect carbon emissions derived from electricity and heating generation account for a larger proportion than direct carbon emissions. Therefore, emission mitigation action of other sectors has an obvious impact on formulating emission mitigation strategies for the building sector, such as building electrification and decarbonization of electricity generation. In the study, the model parameters covered the emission mitigation strategies within the building sector as well as in other sectors (heating and electricity generation sector). As the proposed model addressed the above-mentioned gaps, it can be used as a valuable policy simulation tool to test policy effectiveness and provides better guidance on formulation of policy-making of building sector's decarbonization.

Table 1
Future scenario setting.

No	Single strategy scenario (Strategy)	Combined scenario				Input parameter	Sources
		Base	CS1	CS2	CS3		
M1	Improving the building efficiency standard of new building		√	√	√	Energy saving-rate of new buildings ($ESB_{i,j,\ t}$)	(MOHURD, 2021, 2022b)
M2	Building energy renovation on existing buildings		√	√	√	Building energy renovation rate of existing buildings ($ER_{i,j,t}$)	(GOC, 2021; MOHURD, 2022b)
M3	Improving the energy efficiency of end-use service equipment		√	√	√	Adjustment factor of equipment energy efficiency ($\alpha_{i,j,t}^{user}$)	(MOHURD, 2020, 2022b)
M4	Direct renewable energy application in building		√	√	√	Renewable energy utilization rate ($r_{i,j,t}^{renew}$)	(MOHURD, 2021, 2022b)
M5	Building electrification		√	√	√	Electricity utilization rate ($r_{i,j,t}^{ele}$)	(GOC, 2021)
M6	Decarbonization of electricity generation			√	√	Percentage of renewable energy in electricity generation ($r_{i,j,t}^{renew\ in\ ele}$)	(GOC, 2021; Grid, 2021)
M7	Eliminating the boiler with weak efficiency			√	√	Energy conversion efficiency of heating ($\eta_t^{heating}$)	(CMEE, 2017; NEA, 2017)
M8	Clean energy application in central heating generation			√	√	Percentage of renewable energy in heating generation($R_{i,j,t}^{renew\ in\ heating}$)	(CMEE, 2017; NEA, 2017)
M9	Building stock regulation				√	Per capita floor area ($AS_{i,j,t}$)	(GOC, 2021)
M10	Green behaviors guidance				√	Adjustment factor of end-user service demand ($\beta_{i,j,t}^{user}$)	(GOC, 2021; MOHURD, 2022b)

Note: *i, j* and *t* represent building types, climate zone and year, respectively.

This paper is structured as follows. Section 2 introduces the quantization model for carbon emissions of China's building sector, the emission mitigation strategies, and four combined scenarios. Additionally, the LDMI model is presented in this section. The simulation results of the models are analyzed in Section 3. The key driving factors for future emission trends are discussed in Section 4. The main emission strategies for building sector at the national and building type levels are discussed in Section 5. Section 6 compares this study with existing studies. Finally, Section 7 describes the main findings and implications of this study, along with recommendations for future research.

2. Methods and data

2.1. Model framework

We first developed a multi-layers Chinese building carbon emissions model to quantify the future carbon emission and energy consumption of China's building sector. The framework is shown in Fig. 1.

The first advantage of the model is that it fully considers the energy utilization characteristics of Chinese buildings. Specifically, the framework included three layers: **1) L1, Climate area.** The climatic conditions have a significant impact on the heating and cooling energy consumption of buildings. Referring existing studies (Delmastro et al., 2015; Wang et al., 2022; Zhou et al., 2018) divided China into three areas: northern, transition, and southern areas. In the northern area, the urban residential and public and commercial buildings mainly adopt central heating. In the transition area, distributed heating is the main heating method. Meanwhile, the residents living in the southern area do not require heating; The climate area division is showed in Table A1, and considered that one province has only one climate area characteristic according to data accessibility. **2) L2, Building type.** There is an obvious difference in different building types. Owing to data limitation, all buildings in this study were categorized into three types: urban residential (UR), rural residential (RR), and public and commercial (P&C) buildings. UR and RR buildings include all energy-using activities in apartments and houses. P&C buildings include activities related to trade, finance, real estate, public administration, health, food and lodging, education, and other commercial services. In addition, because central heating (CH) in the northern area has huge carbon emissions and is considered a separated sector in the Chinese energy balance sheet, we included CH as the fourth building type (Guo et al., 2021). **3) L3, End-use service.** According to previous studies, we divided the energy consumption of China's building sector into six end-use services: heating, cooling, cooking, hot water, lighting, and other appliances (Guo et al., 2021; Yang et al., 2017; Zhou et al., 2018). The energy intensities of all end-use services are impacted by growth in residents' end-use service demands depending on the economic condition and improvement of technologies within the building sector. In addition, according to the definition of IEA, we divided carbon emissions into direct carbon emissions, caused by direct primary energy consumption (coal, oil, and natural gas) of buildings, and indirect carbon emissions, caused by CH and electricity generation (IEA, 2020b). The bottom of the framework is the model output, indicating that the energy consumption and carbon emission of each energy type can be output. The detailed calculation process is showed in the supplementary materials.

The second advantage of the model is that it considers the techniques metabolism with building stock dynamic. Specifically, the adopted building energy efficiency standard has an obvious impact on the heating and cooling energy consumption of buildings. Different from the equipment update of other end-use services, the adopted building energy efficiency standard usually updates with the building metabolism (Yang et al., 2022). In other words, new and renovation buildings indicate the inflow of new building energy efficiency standard techniques, and demolition buildings indicate the outflow of old building energy efficiency standard techniques. In this study, we established nine building stock turnover models, including three building types (UR, RR and P&C) and three climate areas to calculate the number of new, renovation and demolition buildings, to elucidate the metabolism of building energy efficiency standard and quantify the impact of strategies related with building energy efficiency standard (see in the supplementary material).

2.2. Scenario setting

The parameters of the model can be divided into three categories: socioeconomic, demand-related, and technique-related parameters. Socioeconomic parameters mainly include population, urbanization, urban and rural residential income, and output value of a tertiary industry. The impact of socioeconomic-parameter-related strategies on carbon emission mitigation of China's building sector was not considered in this study. Therefore, the socioeconomic parameters were the same in different studied scenarios, and were derived from a medium scenario (SSP2) of Chen et al. (2020). The demand-related parameters included six end-use services and three building floor area demands of residents. All parameters were affected not only by socioeconomic parameters but also by building-related emission mitigation strategies, such as building stock regulation and green behavior guidance. The technique-related parameters included the techniques of building sector

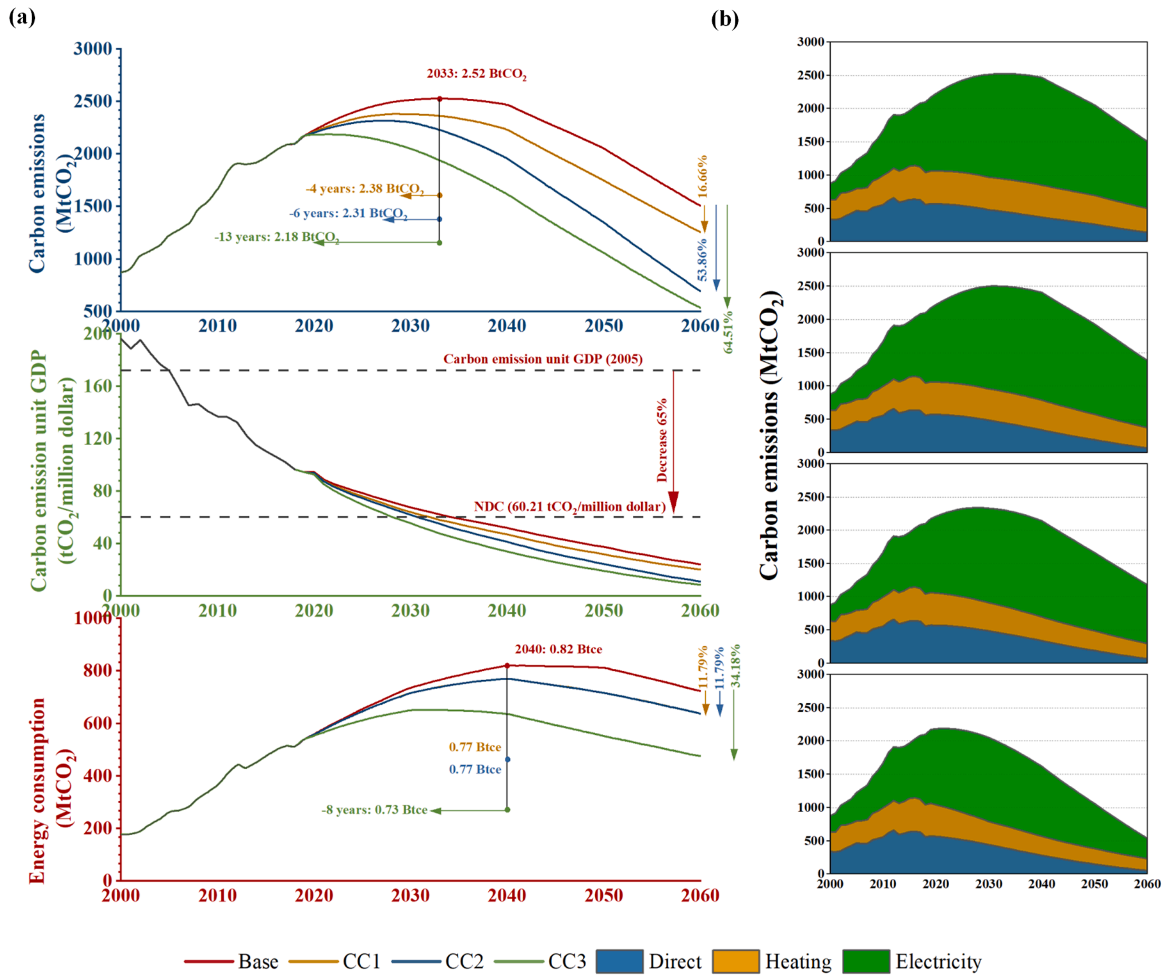

Fig. 2. China's national-level carbon emissions from 2000 to 2060.

and multi energy generation sectors (heating and electricity generation). The techniques controlling energy consumption and carbon emissions in the consumer end were regarded as building sector techniques such as improving building energy efficiency standard and direct renewable application in building. Meanwhile, the techniques controlling the carbon emission in the production end were regarded as the techniques of other sectors, such as eliminating outdated boilers and clean electricity generation.

This study reviewed the building-related emission mitigation policies and summarizes 10 emission mitigation strategies within building sector and other sectors. The third advantage of this model is that the model parameters completely covered most building-related emission mitigation strategies, indicating the model can be a great policy test tool. Each strategy was set as a single strategy scenario. Based on the characteristics of each strategy, we developed four combined scenarios (Table 1): base scenario, single building sector scenario (CS1), collective effort of multi sectors scenario (CS2), and collective effort of overall society scenario (CS3). The specific value is showed in supplementary material.

A base scenario refers to the present energy saving and carbon mitigation strategies. With an increase in residents' income and development of tertiary industry, the end-use service demands of each building types shows a grid increasing trend, thereby improving the energy consumption and carbon emissions. In a single building sector scenario, the stronger strategies of building sector are adopted to limit the excessive increase in energy consumption and carbon emissions to achieve carbon peak goals of building sector. These strategies include improving building energy efficiency of new buildings (M1), promoting the energy renovation of existing buildings (M2), improving the energy efficiency of end-use service equipment (M3), direct renewable energy application in building (M4), and building electrification (M5). Furthermore, to accelerate the achievement of carbon peak time, reduce the carbon peak value, and increase the possibility of achieving carbon neutrality in building sectors, the collective efforts of other sectors are required to eliminate indirect carbon emissions, especially for the heating and electricity generation sectors. This combined scenario includes stronger requirement for the decarbonization of electricity generation (M6), elimination of outdated boilers (M7), and application of clean energy in central heating generation (M8), such as renewable energy and natural gas. To maximize the emission mitigation and possibility of achieving carbon neutrality of buildings, the emission mitigation strategies of all sectors may not be sufficient, thus necessitating residents' participation and formulation of overall social collaboration. In this scenario, government policies and propaganda should be used to guide the green behavior of residents (M10) and to control excessive growth of building stock (M9).

2.3. Emission decomposition by LMDI

Owing to the multiplier stack effect of all elements in the Kaya Identity (Kaya, 1989), it is difficult to calculate the contribution of each driving factor in carbon emissions. Furthermore, direct subtraction between different cumulative scenarios may lead to misestimation of the emission mitigation contribution of each strategy. Combined with the Kaya Identity, the LMDI decomposition method has been widely adopted in empirical studies since it lacks both residual values and total decomposition (Ang et al., 1998; Ma et al., 2019). In this study, the LMDI decomposition method was used to identify the main driving factors for future carbon emission trend (issue 2) and to quantify the emission mitigation potential of each strategy (issue 3). To save content space, we only take central heating of P&C as an example to show the calculation process with a few simple formulas.

$$\Delta C_{CH,PUB} = C^{t}_{CH,PUB} - C^{0}_{CH,PUB} = \Delta EF_{CH} + \Delta EI_{CH,PUB} + \Delta AS_{PUB} + \Delta P \quad (1)$$

where $C^{t}_{CH,PUB}$ and $C^{0}_{CH,PUB}$ represent the central heating carbon emissions of P&C in the tth and base years, respectively. ΔEF_{CH}, $\Delta EI_{CH,PUB}$, ΔAS_{PUB}, and ΔP_{PUB} represent the contribution of energy-related emission factors, area-related heating energy intensity, per capita floor area of P&C, and population on the carbon emission change of P&C' central heating, respectively, and all them have similar calculation process. To save content space, we only show the formula of ΔP (Eq. (2))

$$\Delta P = \frac{C^{t}_{CH,PUB} - C^{0}_{CH,PUB}}{\ln\left(C^{t}_{CH,PUB}\right) - ln\left(C^{0}_{CH,PUB}\right)} ln\left(\frac{P^{t}}{P^{0}}\right) \quad (2)$$

3. Carbon emissions of China's building sector

3.1. Carbon emissions of China's building sector at the national level

Combining with the parameters of four combined scenarios, the model simulates the future carbon emissions of China's building sector. Fig. 2 shows the carbon emissions, energy consumption, and emission structure of China's building sector for each scenario until 2060. For the base scenario, China's building sector will achieve the carbon peak, with carbon emissions of 2.52 $BtCO_2$ and energy consumption of 0.77 billion tons of standard coal equivalent (Btce), in 2033, which is three years later than 2030, the proposed year of achieving China's carbon peak. For the CS1 scenario, which only considers the stronger strategies of China's building sector, the carbon emissions of China's building sector will reach the peak value in 2029, arriving by 2.38 $BtCO_2$, decrease by 5.83% of the peak value in the base scenario. This indicates, for a long time to come, the China's building sector will face a rigid carbon emission growth since quick growth demand in end-use service and per capita floor area, which cannot be offset by emission mitigation derived from current policies (Guo et al., 2021). Moreover, the positive effort of China's building sector can effectively promote the realization of its carbon peak before 2030. Therefore, China's building sector should adopt stronger carbon emission mitigation strategies, such as higher building energy efficiency standard, building energy renovation in existing buildings, direct renewable energy application in buildings, and so on (MOHURD, 2021). With the collective efforts of multi sectors (CS2), China's building sector will achieve its carbon peak in 2025, by emitting 2.30 $BtCO_2$. Meanwhile, compared with the base scenario, the carbon emissions of CS2 in 2060 will decline by more than 50%, from 1.26 $BtCO_2$ to 0.69 $BtCO_2$. Furthermore, the result of CS3 represents more active efforts derived from overall society will effectively mitigate the emission growth of China's building sector because the carbon peak will be achieved in 2022, with the 2060 carbon emissions of CS3 accounting only for 35.49% of the base scenario.

It is noteworthy that owing to the continuous optimization of energy structure, including the primary and secondary energy consumption (heating and electricity) of buildings, the energy-related emission factor of China's building sector shows a continuous decrease trend (CABEE, 2020), which might lead to a significant delay in achieving the peak of energy consumption, compared to the peak of carbon emissions for all scenarios. Specifically, the final energy consumption peaks of the base, CS1, CS2, and CS3 scenarios will be achieved in 2040 (0.82 Btce), 2040 (0.77 Btce), 2040 (0.77Btce), and 2032 (0.72Btce), respectively. Meanwhile, compared with the base year, the peak energy consumption of the base, CS1, CS2, and CS3 scenarios will increase by 51.66%, 42.40%, 42.40%, and 20.33% of energy consumption, respectively. The results are consistent with the fact, in present, and the per capita building energy intensity (residential, commercial, and public services) is still lower in China than in developed countries, being only 21%, 72%, and 23% of that in the US, Japan, and the UK, respectively (IEA, 2021b). In future, the energy consumption of China's building sector will face a strong growth with increased income of residents. Guo et al. (2021), Zhang et al. (2022a), and Guo et al. (2020) have reported similar conclusions.

Fig. 2a shows the carbon emission unit gross domestic product (GDP). The Chinese government set its Nationally Determined Contributions (NDC) goal in Paris Agreement in 2015, requiring that carbon emission unit GDP should reduce by 60–65% by 2030 compared with 2005 (UNFCCC, 2015), and reset 65% as its new NDC target in 2020. For China's building sector, in the past 15 years, the carbon emission unit GDP has continuously decreased, decreasing from 172.04 tCO_2/million dollar in 2005 to 94.52 tCO_2/million dollar, indicating a lower NDC realization degree (45.06%) than the national NDC realization degree (48.10%) (IEA, 2021b). The base (67.93 tCO_2/million dollar), CS1 (64.24 tCO_2/million dollar), and CS2 (62.16 tCO_2/million dollar) scenarios do not meet the NDC goals (60.21 tCO_2/million dollar). The collective effort of society benefits the building sector to meet this target and reduced 67.79% of carbon emission unit GDP compared with 2005. Furthermore, in 2060, base, CS1, CS2, and CS3 can achieve 85.91%, 88.26%, 93.50 and 95.00% reductions in carbon emission unit GDP compared with 2005, respectively.

The carbon emission structure in different scenarios is shown in Fig. 2b. For all scenarios, the direct carbon emissions of China's building sector has reached the peak in 2016, emitting 0.64 $BtCO_2$, which was led by large-scale "coal to gas" and "coal to electricity" transitions in China (Chen and Chen, 2019; Liu et al., 2013). According to the data of China Association of Building Energy Efficiency (CABEE, 2020), the proportion of gas and electricity increased from 25.08% and 6.23% in 2005 to 48.07% and 32.09% in 2018, respectively. The carbon emissions of central heating arrived the peak in 2016, reaching 0.50 $BtCO_2$, that might have been caused by promoting higher building standard and clean centralized heating generation in the north area, such as *Clean Heating Plan for Northern Regions in Winter (2017–2021)* (NEA, 2017), and *"2 + 26" Cities Interim Policy on Urban Air Pollution Control* (CMEE, 2017). For all scenarios, in the future, electricity carbon emissions of China's building sector will always have the largest proportion in overall carbon emissions in China's building sector and has been predicted to be vary with time (Guo et al., 2021). Specifically, in 2060, the electricity carbon emissions of CS2 considering the collective efforts of China's building and other energy generation sectors decreased by 45.23% (0.48 $BtCO_2$) of electricity carbon emissions of CS1, considering only the efforts of China's building sector). This indicates that the collective efforts of multi-sectors play an important role in the achievement of carbon peak and carbon neutrality in China's building sector.

In addition, all results indicate carbon capture, use, and storage (CCUS) techniques must be adopted to eliminate the residual building carbon emissions for the realization of carbon neutrality in China's building sector before 2060. For indirect carbon emissions, the electricity and heating generation sectors need to eliminate at least 0.30 $BtCO_2$ and 0.18 $BtCO_2$, respectively. Owing to the cost of replacing the existing energy infrastructure by renewable energy and energy supply security and stability, it is difficult to completely eliminate fossil fuels in the energy conversion and processing sector. The best scenarios of some previous studies show that the proportion of renewable energy cannot reach 100% in electricity generation and can only reach 70–80% (Chen et al., 2020; Fu et al., 2020; ICCSD, 2020). For direct carbon emissions, 0.05 $BtCO_2$ need to be offset, which may be achieved by increasing green area buildings (Chen et al., 2020a, 2020b) and carbon sink potential caused by cement carbonization (Xi et al., 2016).

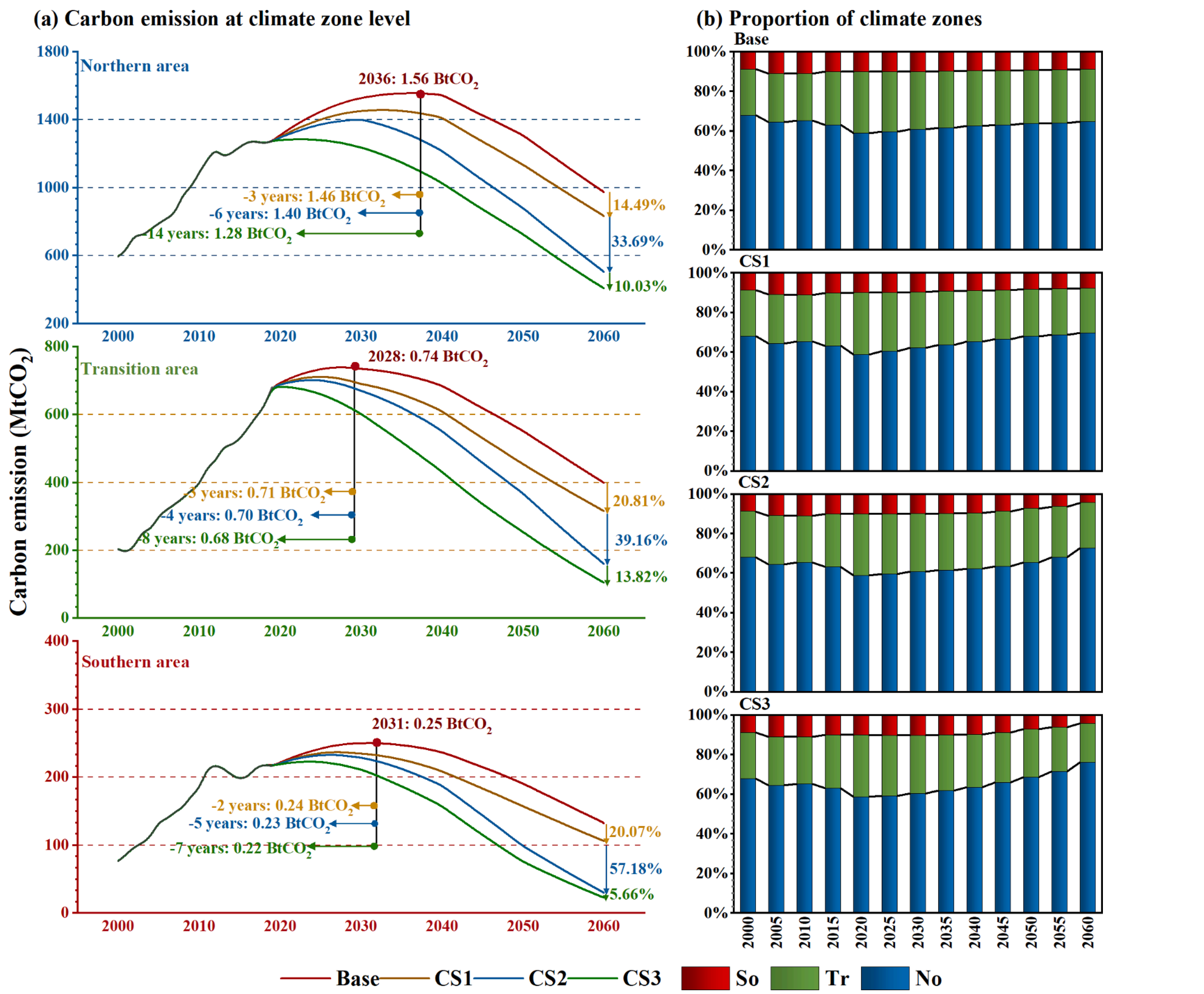

Fig. 3. Carbon emissions from 2000 to 2060 at climate zone level (Note: So, Tr, and No represent the southern, transition, and northern areas of China, respectively.).

3.2. Building carbon emissions at zone area level

The carbon emissions vary between different climate areas, as shown in Fig. 3. Specifically, for all scenarios, owing to the lager building area and CH, the northern area accounts for the largest proportion of total carbon emissions (Fig. 3b), nearly twice the total carbon emissions of the transition zone and southern area. It is worth noting that, in recent years, the proportion of the transition zone in the total China's building sector carbon emissions have shown an increasing trend, likely caused by the increased heating demand of the residents of this area (Hu et al., 2016).

Fig. 3a represents the carbon emissions of different areas. In the base scenario, the northern area (2036, 1.55 $BtCO_2$) will peak later than the transition area (2028, 0.74 $BtCO_2$) and southern area (2031, 0.25 $BtCO_2$). In CS1, the southern area and transition area will peak before the Chinese 2030 carbon peak target. However, because of the massive heating demand and high energy-related emission factor of electricity generation, only stronger strategies of China's building sector cannot make the northern area achieve China's building sector peak (2033, 1.45 $BtCO_2$) before 2030, indicating the important role of the clean production of electricity and heating. Furthermore, under the collective efforts of multi sectors, the carbon emissions of the northern area will reach peak in 2030 (1.40 $BtCO_2$), and reduce by 48.18% in 2060 compared with the base scenario. Further, the carbon emissions of the southern and transition areas in 2060 decreased by 77.25% and 59.97% of the base scenario, respectively. In addition, under overall society efforts, the northern, transition, and southern areas will emit 0.41, 0.10, and 0.02 $BtCO_2$ in 2060, decreasing by 68.06%, 84.63%, and 89.52% of the carbon emissions in base year, respectively.

3.3. Building carbon emissions at the building-type level

The carbon emissions vary between different building types, as shown in Fig. 4. Fig. 4a shows the carbon emission trends in different scenarios. In 2019, the CH and P&C accounted for the two largest shares of China's building sector carbon emissions, emitting 0.50 and 0.90 $BtCO_2$, respectively. In contrast, owing to the fast Chinese urbanization process and low energy intensity of RR, RR accounted for the smallest share, being only 16.73% (0.36 $BtCO_2$).

For all scenarios, the carbon emissions of CH have achieved the peak value of 0.51 $BtCO_2$ in 2016. Compared with the base scenario, CS1, CS2, and CS3 will have a significant emission mitigation potential of 15.83%, 38.47%, and 51.80% in 2060, respectively. This indicates the importance of multi-sector collective efforts and reasonable regulation of the heating behavior in heating emission mitigation.

For other building types, in the base scenario, UR, RR, and P&C will reach the carbon peak in 2040, 2024, and 2035, emitting 0.61 $BtCO_2$, 0.38 $BtCO_2$, and 1.09 $BtCO_2$, respectively. In order to achieve the "Carbon peak 2030" target, P&C need to adopt stronger strategies at least in China's building sector, while UR need the collective efforts of multi sectors. Specifically, in CS2, urban residential, and P&C reach peak ten years and seven years earlier, respectively. It is worth noting

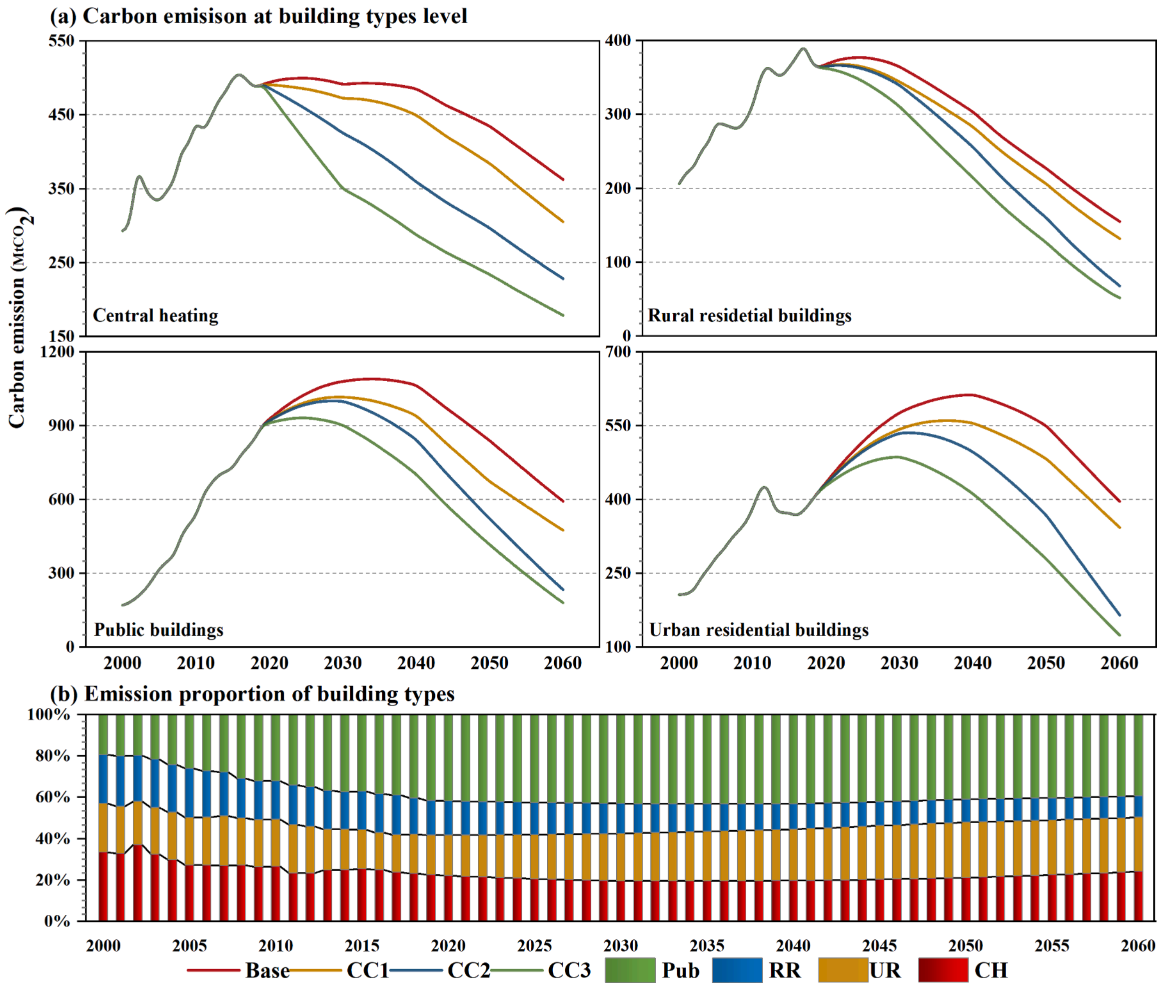

Fig. 4. Carbon emissions from 2000 to 2060 at the building type level (Note: P&C, RR, UR, and CH represent public and commercial buildings, rural residential buildings, urban residential buildings and central heating, respectively.).

that, under overall society effort (CS3), in 2060, all building types show more than 50% emission mitigation compared with the base scenario. Among them, RR have the largest emission mitigation potential and can mitigate 86% of carbon emission in the base scenario.

In summary, the Section 3 response the research issues 1.

4. Driving factors of future carbon emissions in China's building sector

Based on the Kaya identity, the carbon emissions of China's building sector are divided into six driving factors: demand in end-use services, technique in end-use services, energy-related emission factor, per capita floor area, urbanization, and population. The future carbon emissions in the base scenario were decomposed to identify the key driving factor of their major driving factors, and the period of base scenario was divided into two stages: from the base year to the carbon peak year (2019–2033), and from the carbon peak year to 2060 (2033–2060). The results are shown in Fig. 5.

In the first stage, on the one hand, the growth in per capita floor has made the largest positive contribution to China's building sector carbon emissions, reaching 0.60 $BtCO_2$. In practice, the per capita building floor area in China is 36 m^2, which is significantly lower than that in major developed countries (e.g., 92 m^2 for the United States and 67 m^2 for Germany) (Zhou et al., 2018). Continuing rapid urban growth will make the overall building stock to expand continuously for years to come (Ma et al., 2019). Meanwhile, increased per capita floor represents increased energy consumption, especially for heating, cooling, and lighting, which together account for approximately 70% of China's building sector energy consumption (CABEE, 2020) and are obligatory objects of the Chinese building energy efficiency standard. The next positive driving factor is the growth in end-use service demand, which contributes 0.58 $BtCO_2$ to the peak value. Among the six end-use services, cooling, heating and other appliances are the three major contributors, accounting for 32.53% (0.19 $BtCO_2$), 29.00% (0.17 $BtCO_2$), and 24.27% (0.17 $BtCO_2$) of the contribution of growth in end-use service demand, respectively. Specifically, the transition area is the major zone causing demand growth in cooling, whereas the northern rural area is the major zone causing demand growth in appliance and heating. Being related to the most basic demands, the demands in cooking are nearly saturated, only contributing 2.75 $MtCO_2$. In addition, urbanization and population will also lead to an increase in China's building sector carbon emissions.

On the other hand, improving end-use service techniques is the largest driving factor of China's building sector emission mitigation, having an emission mitigation of 0.53 $BtCO_2$. Among the six end-use services, the technologies related with heating, cooling, and lighting are the three main emission mitigation contributors, accounting for 41.78%, 27.60%, and 18.99%, respectively. Meanwhile, owing to the limitation of energy conversion efficiency, the contribution of the technologies related to cooking and hot water was not obvious. Decrease in energy-related emission factor also has an obvious emission potential for the carbon peak of China's building sector, and it is noticing, because of higher emission factor of electricity than coal or gas, the building electrification significantly promote carbon emissions of China's building sector (0.18 $BtCO_2$), although the decarbonization of electricity

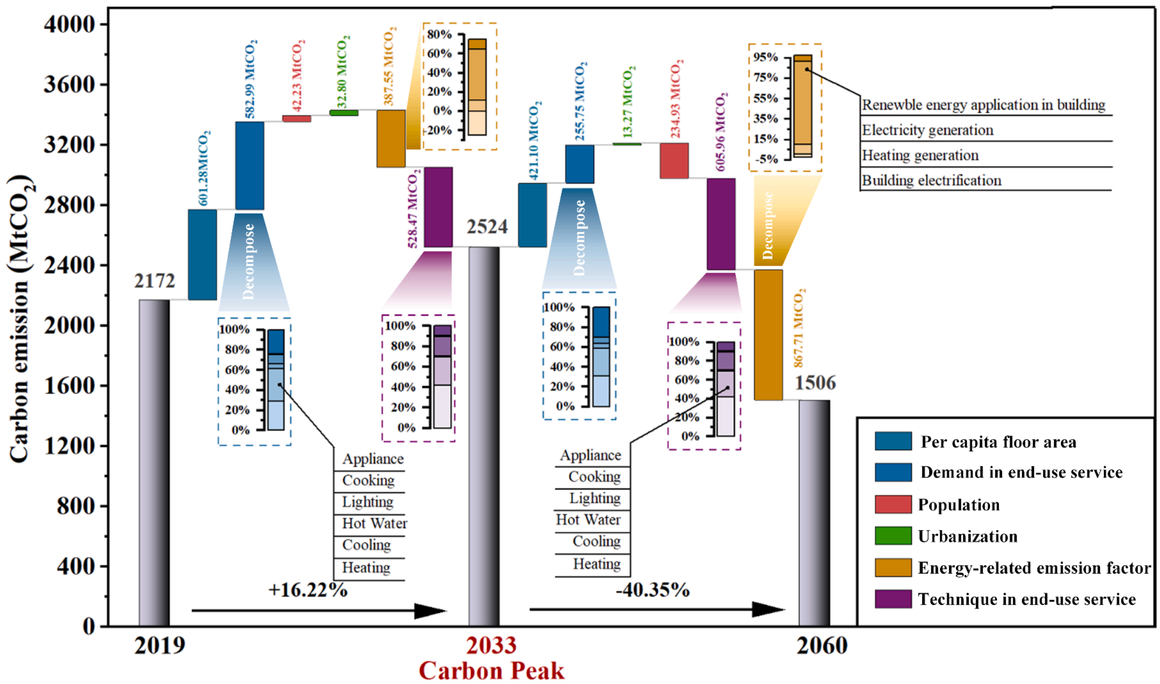

Fig. 5. Emission mitigation of driving factors from 2019 to 2060.

generation has the largest emission mitigation (0.40 $BtCO_2$) in it. This indicates the necessity of fully considering the equipment energy efficiency and reasonably ranging the building electrification process to accelerate carbon peak time and reduce carbon peak. For example, in China's transition area, which has an increasing heating demand and a moderate climate, the electricity emission factor of the northern China power grid was 3.68 $kgCO_2$/kgce in 2018, which was twice that of natural gas. The energy efficiency ratio (EER) of a heating pump was higher than 3, EER of a gas-fired boiler was less than 1, indicating that the building electrification process (gas-fired boiler to heating pump) is environmentally friendly in the area. However, the EER of an electric boiler was less than 1, indicating that this building electrification process will lead to increased carbon emission. Therefore, China's transition area should promote heating pumps for heating.

In the second stage, similar to the first stage, the growth per capita floor will be the major factor contributing to the carbon emissions of China building sector, reaching 0.44 $BtCO_2$, and P&C contribute more than half (56.70%). The demand growth in end-use services will also significantly increase the carbon emissions of China's building sector, but the contribution of the second stage will obviously be lower than that of the first stage because of demand saturation, increasing only by 0.26 $BtCO_2$. The largest increase will derive from other appliances, which is related to the residents' higher requirements such as entertainment. Different from the first stage, population is a negative driving factor for the carbon emissions of China's building and will contribute an emission mitigation of 0.05 $BtCO_2$. Contrarily, in the second stage, the major emission mitigation driving factors change from improvement in end-use services techniques (0.60 $BtCO_2$) to decrease in emission factor (0.87 $BtCO_2$). Moreover, the other sectors (electricity and CH generation) play an important role in decreasing the comprehensive emission factor of buildings, especially with electricity generation accounting for 86.85%. Meanwhile, the contribution of renewable energy application in buildings in the second stage is less than that in the first stage. This indicates that considering the change in emission factors of electricity generation, the emission mitigation of China's building sector should have different focus in different stages. Specifically, more attention should be paid to improve building energy efficiency and on-site renewable energy application before carbon peak, and to out-site renewable energy application and even CCUS in the second stage. Our conclusion is consistent with the reports of the World Resources Institute (WRI, 2021) and Lin (2020). In addition, owing to the energy demand gap between urban and rural residents, urbanization will also promote the carbon emissions of China's building sector in the second stage (0.03 $BtCO_2$), although will have less contribution than the first stage.

In summary, the Section 5 response research issue 2.

5. Main emission mitigation strategies of China's building sector

5.1. Emission mitigation strategies at national level

In this study, we decomposed the gap of carbon emissions between the base scenario and the best scenario (CS3) in 2060 to quantify the emission mitigation and final energy saving potential of 10 stronger strategies. Fig. 6 represents the emission mitigation contribution of strategies in 2060. The top three emission mitigation strategies are decarbonization of electricity generation (M6: 47.85%, 0.46 $BtCO_2$), building stock regulation (M9: 14.24%, 0.14 $BtCO_2$), and residential green behavior guidance (M10: 13.68%, 0.13 $BtCO_2$). Residential behavior has obvious impact on the energy intensity of end-user services. Referring to existing studies and a practical case study (Chauhan et al., 2022; Du et al., 2018; Fathabadi, 2014; Hu et al., 2016; Jiang, 2015), according to validate residential behavior limitation and guidance policies, such as heating metering charges, tired energy prices, and intelligent energy control System, central heating, heating, cooling, lighting and appliance can achieve a 15%, 30%, 30%, 20% and 20% energy-saving, respectively (see in supplementary material).

For emission mitigation strategies within the building sector, the direct application of renewable energy on building (M4) has the largest emission potential (0.05 $BtCO_2$). On the contrary, improvement in the energy efficiency standard of new buildings (M1: 4.46%, 0.04 $BtCO_2$) and improvement on end-use service equipment efficiency (M3: 2.26%, 0.02 $BtCO_2$) have small emission potential. For one thing, saturated building floor area demand and low building stock turnover lead a low demand on new buildings and technique lock-in of building energy efficiency standard, making it difficult to improve the energy efficiency of heating and cooling buildings. Therefore, a higher building energy

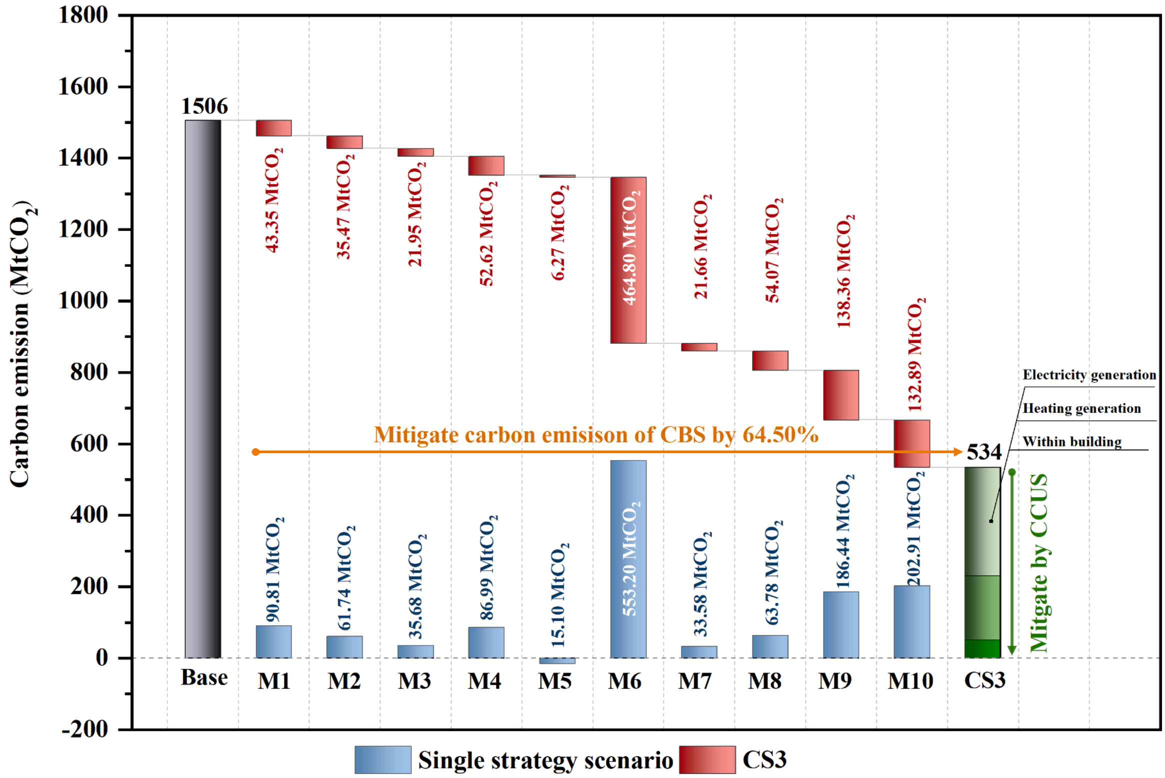

Fig. 6. Emission mitigation contribution of strategies in national level in 2060 (Note: M1 to M10 can be found in Table.1).

renovation rate is needed to achieve "last kilometer" of building emission mitigation (Liu et al., 2022). For other thing, although end-use services equipment can be easily updated (Zhang et al., 2011), limited energy conservation efficiency makes it difficult to improve the energy efficiency of appliance usage, lighting, cooking, and hot water. Therefore, efforts of other sectors and society and improved CCUS techniques are necessary to achieve the "last kilometer" of buildings emission mitigation in China.

The blue bars in Fig. 6 show the emission mitigation potential of each single strategy scenario in 2060, all strategies excluding building electrification have high emission mitigation contribution in single-strategy scenarios than in combination scenarios. This confirmed that direct subtraction between the cumulative effect of multi-strategies may lead to a serious error in calculating the emission mitigation of each strategy, further indicating the need for building electrification process need to cooperate with decarbonization process of electricity generation to achieve low emission peak values and early emission peak time.

5.2. Emission mitigation strategies at building type level

Fig. 7a, 7b, 7c and 7d show the emission mitigation contribution of each strategy in CH, RR, P&C, and UR.

For CH, the top five emission mitigation strategies are: 1) clean energy application in heating generation (M8, 41.45%, 0.05 $BtCO_2$); 2) green behavior guidance (M10, 32.51%, 0.04 $BtCO_2$); 3) building stock regulation (M9, 20.53%, 0.03 $BtCO_2$); 4) improvement in energy efficiency standard of new buildings (M1, 16.94%, 0.02 $BtCO_2$); 5) eliminate outdated boilers (M7, 16.68%, 0.02 $BtCO_2$). Two of five strategies are related with CH sources (M8 and M7), indicating that efficient and clean CH sources are needed for future emission mitigation, such as cogeneration boilers, industrial waste heat, and renewable energy heating pumps (e.g. geothermal and water heat).

For RR, P&C, and UR, in the process from the scenario to the deep decarbonization scenario (CS3), due to less new buildings and limited energy efficiency improvements derived from building energy efficiency standards, the contribution of new building was relatively low (M1), which led to a sever techniques lock-in and made it difficult to decrease the energy intensity. Reducing the energy-related emission factor (M4, M5, and M6) and reasonably limiting the energy demand (M2, M9, and M10) and benefits to breaking this lock-in and achieving building neutrality. Furthermore, the remaining carbon emissions can be offset by carbon sink and CCUS, contributing to a carbon emission of 52, 180, and 124 $MtCO_2$ to RR, P&C, and UR buildings, respectively.

Higher decarbonization of electricity generation can contribute more than half of the emission mitigation for the three building types (LNBL, 2020; Zhang et al., 2022b) and the coordination of building electrification can expend this carbon mitigation. On-site renewable energy utilization accounted for more than 6% of the emission mitigation. Because of the density biomass, per capita residential floor area, and plot ratio, RR had a larger potential to achieve these strategies. Rural areas are the present focus of the government's deployment of renewable energy technologies, such as *Rooftop PV promotion pilot city* by the NEA (2021).

Reasonably plan building stock (M9) contributes more than 10% of the carbon reduction for the three building types. Due to the movement of population to urban areas, RR has the lowest emission mitigation potential (11.43%), and P&C has the largest emission mitigation potential (14.96%). In the future, due to the post-pandemic era and development of the e-commerce economy, the demand for P&C may be significantly reduced. Therefore, the building stock must be planned carefully. Compared with P&C, RR and UR receive more benefits from green behavior guidance (M10), which has the second greatest contribution to carbon reduction for three building types. Green behavior guidance allows the energy demand to be maintained at a reasonable

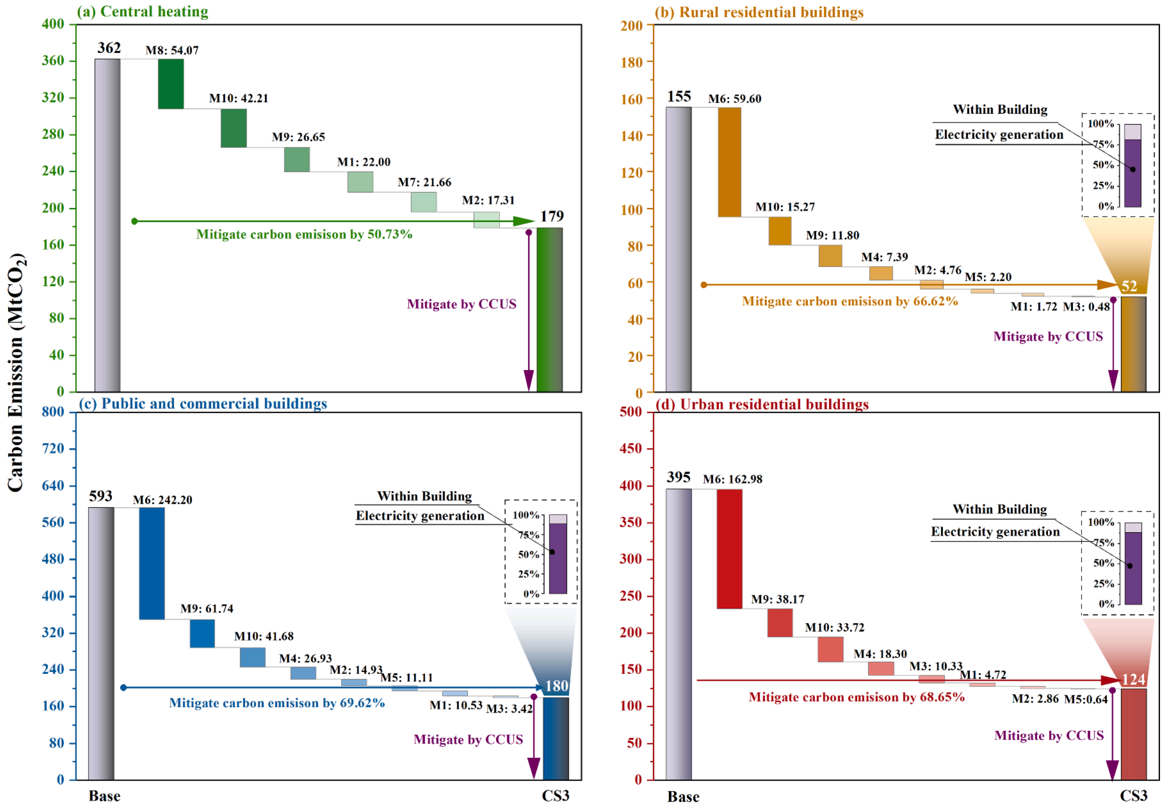

Fig. 7. Emission mitigation contribution of strategies at the building-type level in 2060 (Note: M1 to M10 can be found in Table 1).

level. Selecting appropriate equipment and energy management systems and establishing energy price modes and carbon trading markets are important parts of M10.

Furthermore, we reviewed the emission mitigation policies in *Action Plan of Carbon Peak in China's Urban and Rural construction* (MOHURD, 2022a). Most policies can be covered by our model (see Fig. 8), indicating that our approach can be used to test the effectiveness of the policies and provide some reference for the formulation of the specific targets in regional and building types level. Specifically, for renewable energy utilization in site, the plan requires, by 2025, the rooftop PV coverage of new public buildings will reach 50% and renewable energy replacement rate for urban buildings will reach 8%. Our results indicate that renewable energy utilization on site has larger decarbonization potential in rural area since more biomass energy sources and building volume ratios. The plan lacks a specific target and our model suggests a 15% renewable energy replacement rate to achieve deep decarbonization of rural buildings in 2060. Next, the plan aims to reduce new buildings to optimize urban planning, revitalize the stock buildings and reduce all types of vacant houses. Our results indicate that these policies rank second at emission mitigation potential (138.36 $MtCO_2$ in national level), and further suggests a red line of per capita floor area of 45, 53, and 14 m^2 for UR, RR, and P&C, respectively (see in supplementary material). Moreover, the plan requires new residential and P&C buildings to adopt a building energy efficiency standard with 75% and 78% energy-saving rate, respectively, and new residential buildings in cold and severe cold areas to adopt the building energy efficiency standard with 83% energy-saving rate in 2030. Our results indicate that building energy efficiency standard has a substantial decarbonization effect. However, due to the saturated building stock and low improvement in energy-saving rate, the decarbonization of higher building energy efficiency is lower. Considering that China's building sector has begun to develop from the incremental to stock age, our study strongly recommends the implementation of a broader and deeper building energy renovation before 2060 to break building carbon lock-in and achieve further decarbonization (Yan et al., 2022). Finally, the plan emphasizes promotion of building electrification to reduce direct emissions from buildings. Our results suggest that the building electrification process should be matched with decarbonization of electricity generation, and fully consider the energy efficiency of electrification appliance. As our model integrates these two elements, it can help in devising a detailed strategy for building electrification.

In summary, Section 5 responds to the third research issue in the Introduction.

6. Comparing with existing studies

To ensure the accuracy and robustness of the historical data and simulation results, we compared the results of this study and those of existing literature. For historic data, we selected the building stock and carbon emission of China's building sector to build the comparison. Fig. 9a presents the carbon emission of China's building sector in 2019. The carbon emission in this study was 2.17 $BtCO_2$, which was slightly higher than the results of Hu et al. (2022): 2.16 $BtCO_2$; IEA (2021a): 2.09 $BtCO_2$; and Guo et al. (2021): 2.07 $BtCO_2$; however, the deviation was less than 5%. The results of Chen and Bi (2022) (2.40 $BtCO_2$) were higher than our results. UR and P&C are the major reasons for this discrepancy, which may be because their study considered that all UR and P&C building of northern area of China would adopt CH. In practice, CH penetration is only implemented for 69% and 55% of UR and P&C buildings, respectively. Fig. 8b represents the building stock of existing studies in 2019. The building stock of this study was 68.68 billion m^2 (UR: 45.13%; RR: 35.51%; P&C: 19.35), which is higher than Hu et al. (2022) (Total: 64.5 billion m^2; UR: 43.72%; RR: 35.65%; P&C: 20.78%) but lower than CABEE (2020) (Total: 72.64 billion m^2; UR: 46.38%; RR: 34.89%; P&C: 18.72%). The gap between this study and these two existing studies was lower than 7% and the proportion of three building

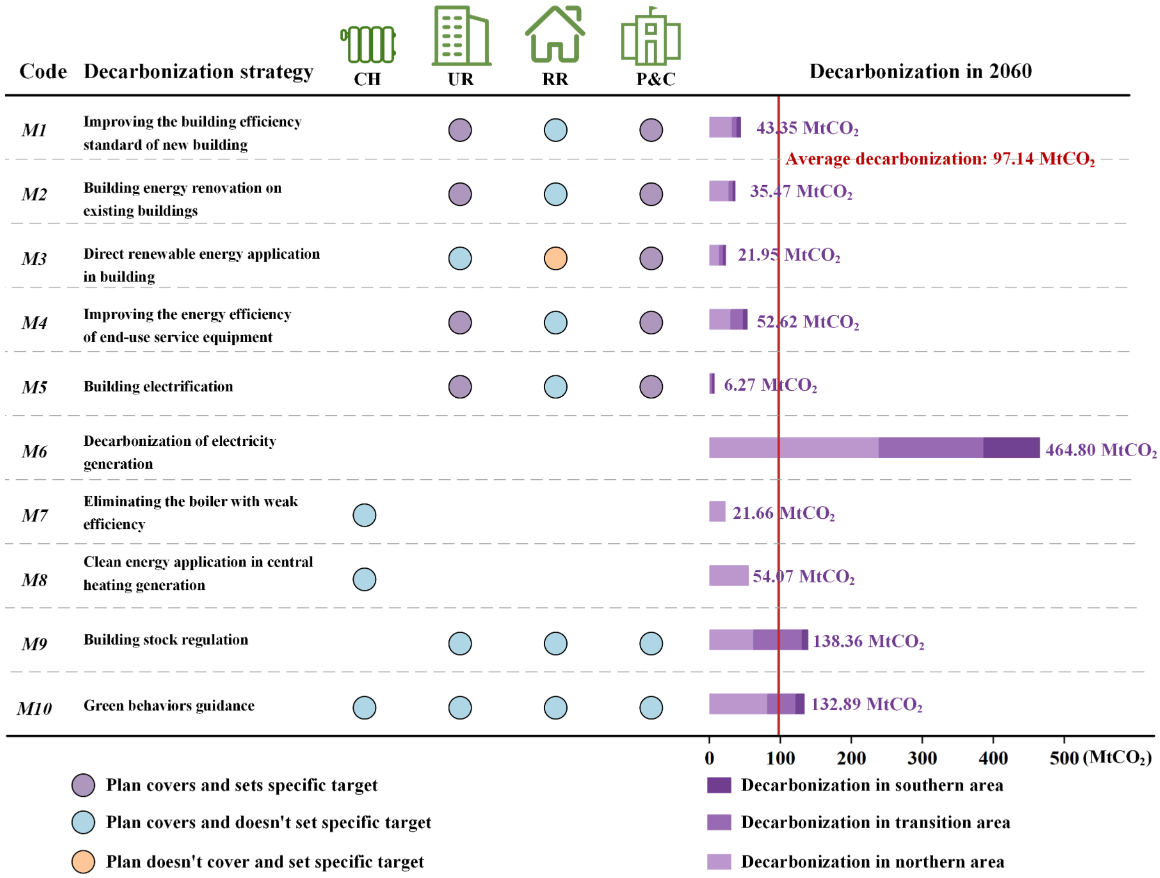

Fig. 8. Comparison between *Action Plan of Carbon Peak in China's Urban and Rural construction* and model parameters.

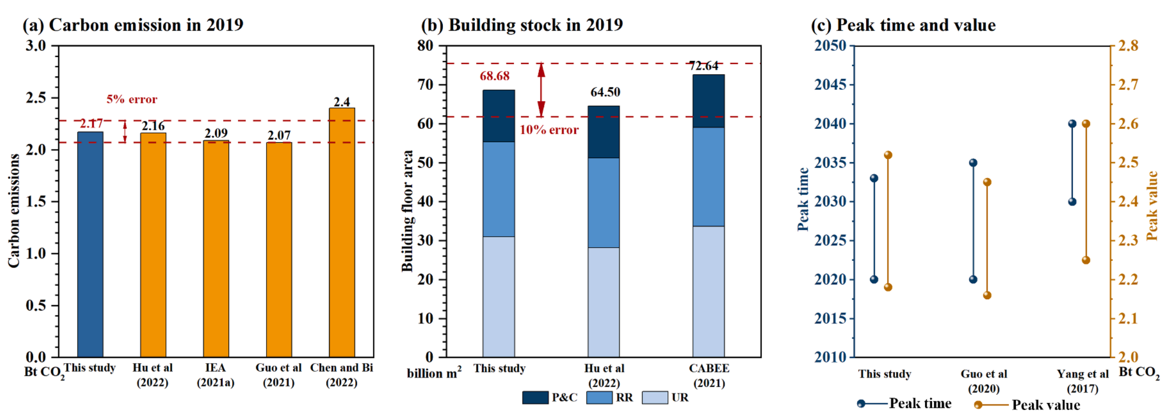

Fig. 9. Comparison between this study and past studies.

types was close, indicating that the results of building stock turnover model in this study are credible.

For future simulations, few existing studies selected 2060 as the end of simulation of China's building sector. Therefore, we selected the carbon peak time and value as the comparison indicator. Fig. 9c compares this study with Guo et al. (2020) and Yang et al. (2017), which had similar carbon emission in 2019 and building types. All studies stated that China's building sector will struggle to achieve peak carbon by 2030 under current conditions. The carbon peak time of Yang et al. (2017) was from 2030 to 2040, which was later than that of Guo et al. (2020) (from 2020 to 2035) and this study (from 2020 to 2033). The range of carbon peak values in three studies was similar, and the carbon peak values of Yang et al. (2017) of (2.25 - 2.60 $BtCO_2$) is slightly higher than Guo et al. (2020) (2.16 - 2.45 $BtCO_2$) and this study (2.18 - 2.52$BtCO_2$). The later peak time and higher peak value of Yang et al. (2017) might be because this study did not integrate policies related with cleaner electricity and heating production and adopted a high energy-related emission factor.

7. Conclusions and future research directions

In this study, we proposed a multi-layer dynamic carbon emission quantification model to forecast the potential future emission trend of China' building sector up to 2060. Furthermore, the detailed future carbon emission trend in four buildings types and three climate zones were explored. In addition, the LDMI decomposition method was used to identify to the main driving factors for future carbon emission trend and key emission mitigation strategies for each building type. The main conclusions are as follows:

1) Under base scenario, China's building sector will reach carbon emission peak in 2033, with emissions of 2.52 $BtCO_2$ and 1.51 $BtCO_2$ in the peak year and 2060, respectively. Single building sector (CS1), multi sector cooperation, (CS2), and society (CS3) will accelerate carbon peak time in 2029, 2027, and 2022, respectively, significantly mitigating the carbon emissions of the base scenario in 2060 by 16.66%, 53.86%, and 64.51%, respectively.
2) There is an obvious difference of carbon emission trend among building types or climate zones. Northern area and UR have later carbon peak time. Furthermore, to meet the carbon peak goal of China, the southern area and P&C need the stronger strategies of building sector at least, while the northern area and UR need the collective efforts of multi sectors.
3) Growth in end-use service demands and building stock always are the major driving factors promoting carbon emissions. The major emission mitigation driving factor change from the improvement of technologies related to end-use services to decarbonization of electricity generation after carbon peak time of building sector.
4) The key strategies differed between building types. For CH, the major emission mitigation strategy is clean energy application in heating generation. For other building types, the decarbonization of electricity generation has the largest emission mitigation contribution, and building electrification will amplify this contribution. Furthermore, to minimize the carbon emissions of building sectors, the utilization of electricity should be enhanced.

The single emission mitigation strategies, combined scenarios, and multi-layer dynamic emission quantification model provide a valuable reference for the studies analyzing the future carbon emissions of buildings sectors. Meanwhile, the model parameters include most of the main emission mitigation policies of the building sector and can serve as a valuable policy simulation tool to formulate reasonable carbon emission targets.

Although some meaningful findings were obtained in this study, several gaps can be filled with future endeavors. First, because of limitations in terms of data, this study only collected the energy intensity of six end-user services at the climate zone level. Future studies should consider developing the carbon emission simulation at the provincial level, which benefits formulating reasonable provincial carbon emission control targets for the building sector and more detailed and targeted emission mitigation strategies. Second, this study focused on the carbon emission mitigation at the building's operation stage, including the direct (scope 1) and indirect (scope 2) carbon emissions. Future studies should develop a more complete scenario simulation of building-related carbon emissions that integrates the embodied carbon emission (scope 3) into the boundary of the model. Finally, this study selected the number instead of level of emission mitigation strategies to build the combined scenario. Further studies should determine different levels of each emission mitigation strategy to test their sensitivity to carbon emissions and combine with the cost of techniques and regional development to determine the reasonable goals of emission mitigation strategies and formulate more specific emission technique roadmaps.

CRediT authorship contribution statement

Kairui You: Conceptualization, Validation, Methodology, Visualization, Formal analysis, Writing – original draft. **Hong Ren:** Conceptualization, Formal analysis, Writing – review & editing. **Weiguang Cai:** Conceptualization, Data curation, Validation, Writing – review & editing. **Ruopeng Huang:** Formal analysis, Visualization, Writing – review & editing. **Yuanli Li:** Formal analysis, Visualization, Writing – review & editing.

Declaration of Competing Interest

The author(s) declare no potential conflicts of interest for the research, authorship, and/or publication of this article.

Data availability

The authors do not have permission to share data.

Acknowledgements

The authors would like to acknowledge financial support provided by the National Social Science Fund of China (19BJY065). The authors are grateful to the editors and the anonymous reviewers for their insightful comments and suggestions.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106679.

Appendix

See Table A1

Table A1
The Climate area division.

Climate area	Provinces
Northern area	Beijing, Tianjin, Heilongjiang, Liaoning, Jilin, Shanxi, Shaanxi, Inner Mongolia, Qinghai, Xinjiang, Hebei, Henan, Shandong, Gansu, Ningxia
Transition area	Shanghai, Chongqing, Sichuan, Jiangsu, Anhui, Zhejiang, Jiangxi, Hunan, Hubei
Southern area	Guangdong, Guangxi, Fujian, Yunnan, Guizhou, Hainan

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