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Pathway for decarbonizing residential building operations in the US and China beyond the mid-century

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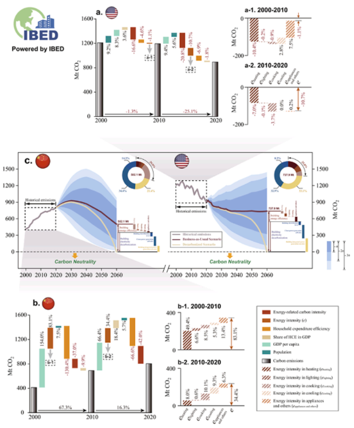
HIGHLIGHTS

- Building decarbonization is assessed by the end-use emission model with DSD and MC simulations.
- Operational decarbonization values in China and the US were 1544 and 1848 $MtCO_2$ in 2001–2020.
- CO_2 peak in China will be 934 Mt in 2031, while the lock-in in the US remains 736 Mt since 2030s.
- Electrification with the corresponding energy decarbonization is the key to building carbon neutrality.
- Heating and appliances are the critical end uses to cut the operational carbon in residential buildings.

GRAPHICAL ABSTRACT



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ABSTRACT

With global carbon budget targets looming, residential buildings in top economies must become carbon neutral as soon as possible to reserve more emission space for emerging carbon-emitting economies. This study is the first to compare the operational decarbonization process of China's and the United States (US) residential buildings from 2000 to 2060 by combining the end-use emission model with the decomposing structural decomposition (DSD) method and Monte Carlo simulation. The results show that from 2001 to 2020 China decarbonized 1544 mega-tons of carbon dioxide ($MtCO_2$) and the US decarbonized 1848 $MtCO_2$. In the business-as-usual scenario, China will hit its emission peak in 2031 (±3) with 934 (±61) $MtCO_2$, while the US will maintain a lock-in level of 736 (±133) $MtCO_2$ since the 2030s. In the decarbonization scenario, operational carbon neutrality for residential buildings in 2060 is promoted by an increase in clean power generation proportion, building-integrated power generation level, building electrification level, and a reduction in end-use energy intensity, which will contribute 34.4 %, 21.4 %, 14.3 %, and 29.9 % in China and 32.9 %, 33.1 %, 8.2 %, and 25.8 % in the US, respectively. Especially, building-integrated power generation in China only costs about 40 % of what it costs in the US. Besides, high-decarbonization strategies for residential building operations are proposed as references for

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governments to formulate targeted climate policies. Overall, this study offers data benchmarks for buildings' carbon neutrality of top economies to further promote synergistic carbon neutrality with the buildings of emerging economies in the age of Post COP27.

Nomenclature

Abbreviations

COP27	27th Conference of the Parties to the United Nations Framework Convention on Climate Change
DSD	Decomposing structural decomposition
EJ	Exajoule
GDIM	Generalized Divisia index method
GDP	Gross domestic product
GEB	Grid-interactive Efficient Building
GJ	Gigajoule
HCE	Household consumption expenditure
HEE	Household expenditure efficiency
$kgCO_2$	Kilogram of carbon dioxide
LMDI	Log-Mean Divisia index
$MtCO_2$	Mega-ton of carbon dioxide
PEDF	Photovoltaics, Energy Storage, Direct Current and Flexibility
SD	Standard Deviation
US	United States

Symbols

C	Operational carbon emissions in residential buildings
E	Operational energy consumption in residential buildings
e	Energy intensity
G	GDP per capita
H	Amount of households
h	The share of HCE in GDP
K	Energy-related carbon intensity
P	Population

1. Introduction

With the frequent occurrences of extreme weather, the global pursuit of carbon mitigation has become more prevalent. The top two emitters, China and the United States (US), have agreed to resume cooperation on climate change in COP 27 [1] and in the 17th G20 leaders' summit, which is of great significance for global carbon neutrality. As one of the principal emission sectors, the building sector held 37 % of carbon emissions and 36 % of energy consumption in the world in 2020 [2]. With the growth needs of emerging economies, global building stock may add more than 230 billion square meters by 2060 with an over 50 % increase in building energy demand [3], which will further exacerbate the burden of carbon mitigation in the global building sector. Moreover, carbon emissions in residential building operations show great potential for decarbonization due to the long-tail effect [4]. Therefore, to achieve the global 1.5 degree targets and to reserve enough emission space for the development of emerging carbon-emitting economies, the residential building operations in major carbon emitters represented by China and the US [5] should work together to achieve net-zero emissions in a timely manner and lay the groundwork for global climate change negotiations.

On the other hand, considerable cost-effectiveness can be achieved in the operational carbon mitigation of residential buildings through policy guidance and technological reforms [6]. Thus, the operational decarbonization potential of residential buildings has been investigated in some existing studies. The operational carbon emission roadmap of China's residential buildings from 2016 to 2050 has been preliminarily discussed using a top-down scenario analysis, which indicates that China's residential buildings will achieve a carbon peak of 1.4 giga tons of carbon dioxide around 2037 [7]. However, this study does not consider in depth the end-use emissions from residents' activities. The decarbonized pathways of residential buildings in the US from 2020 to 2060 have also been predicted through a top-down scenario analysis, and the most optimistic scenario shows that the carbon emissions per capita in the US would decline by 91.0 % compared to 2020 by 2050 [8]. Although these existing studies have predicted the future decarbonization roadmap of residential buildings in China or the US, few studies have compared the future decarbonization levels of China's and the US residential buildings under the same bottom-up methodology. To cover these gaps, the following problems are discussed in this study.

- What are the operational decarbonized results of residential buildings in past decades?
- What are the dynamic operational carbon trajectories around the mid-century?
- How can residential buildings be decarbonized to become carbon-free by the year 2060?

To solve these problems, the end-use emission model is built first to analyze the operational decarbonization levels of residential buildings in China and the US from 2000 to 2020 through the decomposing structural decomposition (DSD) method. Thereafter, dynamic emission scenario analysis to predict the operational decarbonized trajectories of residential buildings is realized via Monte Carlo simulation. Specifically, the contributions of parameters to the change in historical operational decarbonization are obtained in residential buildings. Moreover, the projected decarbonization trajectories, benchmarks of end-uses and emission factors, and the process to realize carbon-free operations in residential buildings are also proposed. In addition, some high-decarbonization strategies for residential buildings are discussed to provide references for the government and other relevant institutions to formulate policies on the decarbonization of residential building operations.

The most important contribution of this study is that it offers an effective tool for different emitters to assess the operational decarbonization potential of residential buildings beyond the mid-century. If the major carbon emitters represented by China and the US can achieve carbon neutrality as soon as possible, more of the carbon budget can be released for the development of other emerging emitters under the global 1.5 degrees goal. It is necessary and urgent to provide a feasible data-driven model for investigating decarbonization pathways in residential building operations. Specifically, this study combines the end-use emission model with a few analytical tools (e.g., DSD method and Monte Carlo simulation) to dynamically explore the potential of decarbonization from the past to the future.

The other sections of this study are as follows: Section 2 presents a brief literature review. Section 3 details the specific methods and data resources. Section 4 shows the decomposition results and the prediction results. Section 5 discusses the benchmarks for decarbonization control, the process to achieve carbon-free status and relevant policy strategies. Section 6 draws the main conclusion of this study.

2. Literature review

As one of the key methods used in this study, the DSD method was first proposed by Jakub Boratynski [9] in 2021 to decompose the demand changes of heating and electricity in the European Union from 2000 to 2014. Due to its simple and intuitive features, the DSD method was applied to identify key parameters affecting historical carbon emissions from global commercial buildings from the perspective of end-use activities [10]. Although the log-mean Divisia index (LMDI) method [11,12] and the generalized Divisia index method (GDIM) [13,14] have been widely utilized to investigate the characteristics of historical carbon mitigation in residential buildings [15,16] and commercial buildings [17,18], there are still some shortcomings in their applications [19]. The results decomposed by the LMDI method are impacted by the interdependence between influencing parameters [20]. The GDIM cannot analyze the historical decarbonization of buildings from the perspective of end-use activities, although it covers the defect of the LMDI method [21] and has been widely used to explore parameters impacting carbon emissions in buildings [22,23] and other sectors [24,25]. However, the DSD method, which covers the above shortcomings, not only makes the decomposition results relatively independent but also studies the interfering parameters of building carbon emissions with end-use activities.

The methods to predict the operational decarbonization trajectories of residential buildings are mainly divided into two kinds, including top-down and bottom-up approaches [26]. The representative models of the top-down approaches are the environmental Kuznets curve [27,28] and the impact of population, affluence [29], and technology model [7], which investigates projected emissions from an overall perspective. However, bottom-up approaches focus on predicting the projected carbon emissions and energy demand of buildings from the perspective of end-use activities [30]. Lawrence Berkeley National Laboratory proposed bottom-up scenario analysis to study the changes in building energy efficiency and decarbonization in China until 2050 by applying the Long-Range Energy Alternatives Planning model [4]. Some scholars have also constructed the emission pathways of China’s building sector through bottom-up scenario analysis based on end-use activities [31]. Moreover, although bottom-up scenario analyses are widely applied in predicting decarbonization pathways in the building sector [32], most of them overlook the uncertainties of parameters impacting building emissions [33]. Hence, Monte Carlo simulation is introduced in this study to predict the projected operational emissions of residential buildings [34].

The literature in the field of building carbon emissions have made some achievements in the identification of influencing parameters, the assessment of decarbonization potential, and the prediction and simulation of future emissions, which provided theoretical support for this study. However, there are still two gaps that should be further considered.

Regarding the research topic in this study, few studies focus on the comparison of historical decarbonization evaluation and projected decarbonization trajectories in China’s and the US residential building operations, although there have been a few studies on the investigation of carbon emissions and energy demand of residential building operations in China [35,36] or in the US [37,38]. Regarding the method in this study, few studies combine the DSD method and Monte Carlo simulation to conduct dynamic emission scenario analysis on residential building operations from the past to the future, although scholars have proposed scenario analysis with various combinations of methods. The DSD method is an advanced decomposition approach rarely applied in analyzing the operational decarbonization of residential buildings, although it has been used in the study of carbon emission changes in commercial building operations. Moreover, uncertainties of key parameters of projected emissions in residential building operations are ignored by most of the existing studies; however, these uncertainties can be addressed by introducing Monte Carlo simulation to dynamically simulate building emissions.

Therefore, to cover the above gaps, this study combines the DSD method and Monte Carlo simulation to dynamically conduct operational emission scenario analysis in China’s and the US residential buildings to decompose historical emissions, determine present decarbonization levels, predict decarbonization trajectories and compare the situations of the two countries. The main contributions of this study are as follows:

This study is the first to compare historical decarbonization and projected decarbonization trajectories in China’s and the US residential building operations. According to the decomposition results of historical emission changes, this study analyzes the projected trajectories of building decarbonization and the process to realize carbon neutrality by 2060. In particular, the change characteristics of historical emissions and the decarbonization strategies of end-use activities are considered and analyzed in this study.

This study provides a useful instrument for various countries to investigate the potential of operational decarbonization in residential buildings from the past to the future. The applications of the DSD method have been extended in this paper to decompose the historical emission changes in residential buildings. In particular, this study combines the DSD model and Monte Carlo simulation to conduct a dynamic emission scenario analysis on China’s and the US residential building operations; this analysis provides benchmarks for carbon neutrality of the residential building sectors in top economies, which can further promote synergistic carbon neutrality with emerging economies in the era of net-zero emissions.

3. Materials and methods

Section 3 introduces the emission modeling of operational carbon in the residential buildings of China and the US. Before simulating future emissions, an end-use emission model with decomposition analysis is conducted in Section 3.1 to characterize historical carbon emissions. Then, a dynamic simulation (i.e., the scenario analysis) that can predict the carbon emissions of residential building operations is illustrated in Section 3.2. Data resources are shown in Section 3.3.

3.1. End-use emission model of residential buildings

To analyze the historical decarbonized levels in residential building operations in China and the US with the influences of end-use activities and to prepare for simulating future emission situations, the DSD method was selected to analyze the contributions of parameters that affect carbon emissions [10]. First, the end-use activities were divided into five categories by different types, including heating, cooling, lighting, cooking, and appliances with others [31]. Therefore, emissions from residential building operations could be composed of the following parts:

$$C = C_{heating} + C_{cooling} + C_{lighting} + C_{cooking} + C_{appliancesandothers} \tag{1}$$

$$\text{Simplified as}: \ C = \sum\nolimits_{i=1}^{5} C_i \tag{2}$$

where C_i (i = 1, 2, 3, 4, 5) expresses the operational carbon emissions associated with five types of end-use activities in residential buildings. To further explore the characteristics of carbon emissions, the key parameters identified by the typical literature were taken into account, including population (P) [39], GDP per capita ($\frac{GDP}{P}$) [7], the share of household consumption expenditure (HCE) in GDP ($\frac{HCE}{GDP}$) [40], household expenditure efficiency (HEE, expressed as $\frac{H}{HCE}$) [41], energy intensity ($\frac{E_i}{H}$) [42] and energy-related carbon intensity ($\frac{C_i}{E_i}$) [43], as explained in Fig. 1. Among them, energy intensity is the energy consumption per household. Then, C_i can be expressed as:

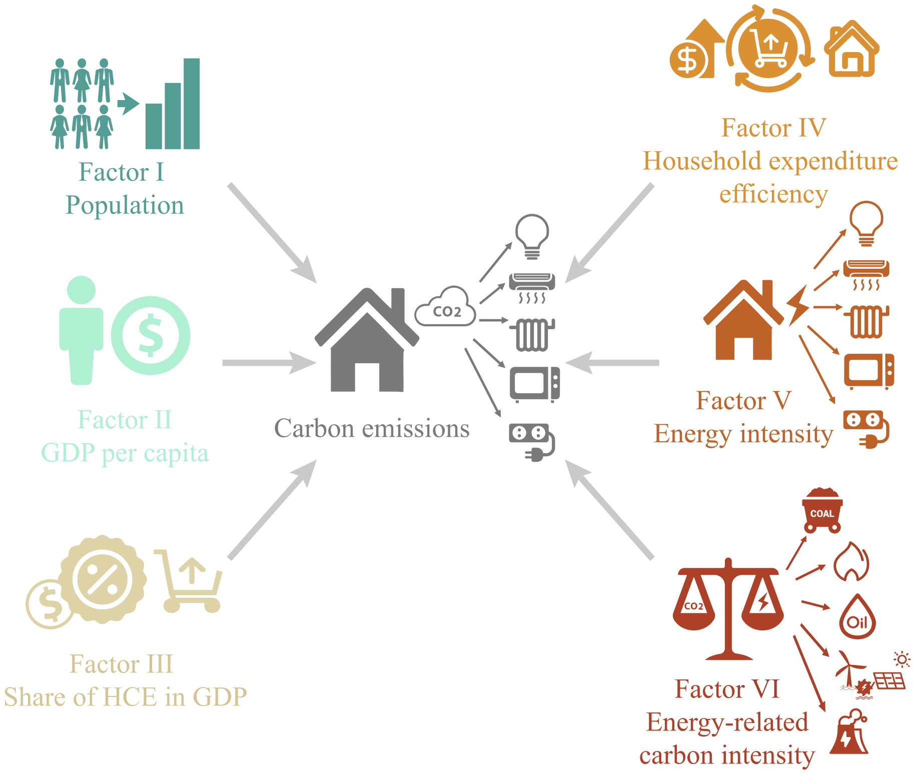

Fig. 1. Parameters in the end-use emission model of residential building operations.

$$C_i = P \bullet \frac{GDP}{P} \bullet \frac{HCE}{GDP} \bullet \frac{H}{HCE} \bullet \frac{E_i}{H} \bullet \frac{C_i}{E_i} \tag{3}$$

$$\text{Simplified as}: C_i = P \bullet g \bullet h \bullet HEE \bullet e_i \bullet K_i \tag{4}$$

Therefore, carbon emissions in residential building operations were characterized as:

$$C = \sum\nolimits_{i=1}^{5} P \bullet g \bullet h \bullet HEE \bullet e_i \bullet K_i \tag{5}$$

According to the DSD method (see the details in Appendix E), the decomposed carbon emission variables can be obtained.

$$\Delta C|_{0\rightarrow T} = \Delta K_D + \Delta P_D + \Delta g_D + \Delta h_D + \Delta HEE_D + \Delta e_D \tag{6}$$

For example, Δe_D means the contribution of energy intensity to carbon emissions:

$$\Delta e_D = \sum\nolimits_{i=1}^{5} \Delta e_i$$

$$= \Delta e_{heating} + \Delta e_{cooling} + \Delta e_{lighting} + \Delta e_{cooking} + \Delta e_{Appliancesandothers} \tag{7}$$

3.2. Dynamic simulation of operational carbon in residential buildings

Scenario analysis is a typical method that can simulate the projected carbon emission trajectories under different policy scenarios [44], and it is widely applied in forecasting building carbon emission trajectories [45]. It is worth noting that the essence of scenario analysis is not to reliably predict the prospective building carbon emissions under the setting scenarios but to explore how future building emissions change following the different parameter settings [46,47]. Then, the decarbonization trajectories can be further obtained according to this changing law [48]. Therefore, two scenarios were mainly considered in this study to simulate the emissions from 2021 to 2060, including a business-as-usual scenario and a decarbonization scenario.

The business-as-usual scenario refers to the scenario following the current socioeconomic and technological level (the proportion of clean power generation, building electrification level, etc. [49]), which aims for the basically achievable goals set by existing policies. The decarbonization scenario considers higher energy efficiency targets and applies technological innovation to achieve technological breakthroughs in clean power generation and energy storage to ultimately realize carbon neutrality in residential building operations. Based on the business-as-usual scenario, this study dynamically simulated the potential carbon emissions of residential buildings considering the uncertainties of impact parameters. Then, the potential change ranges of carbon emissions provided references for setting the decarbonization scenario.

As a typical uncertainty analysis method, Monte Carlo simulation has been widely used in solving problems involving uncertainties [50]. It is undeniable that scenario analysis is competent to study the projected trajectories of building carbon emissions [51], but uncertainties and risks that may happen in the future are overlooked by scenario analysis [52]. Therefore, this study combined scenario analysis and Monte Carlo simulation to dynamically explore the trajectories of building carbon emissions considering the uncertainties in parameters. Meanwhile, energy-related carbon intensities in end-use activities in Eq. (5) are largely impacted by the source and structure of energy. Thus, this study considered the energy-related carbon intensities across different energy structures when studying future building carbon emissions. Overall, the dynamic scenario analysis for future building emissions was based on the following emission models:

$$C = P \bullet g \bullet h \bullet HEE \bullet \sum\nolimits_{i=1}^{5} e_i \bullet (K_{direct} + K_{indirect}) \tag{8}$$

where K_{direct} refers to the direct energy-related carbon intensities in residential buildings, including natural gas, coal, and oil, and $K_{indirect}$ refers to the indirect energy-related carbon intensities in residential buildings uniformly expressed as the energy-related carbon intensities of electricity. Electricity, natural gas, and coal are widely used in residential buildings in China, while electricity, natural gas, and oil are the main energy sources for residential buildings in the US.

The process of dynamic simulation, namely, Monte Carlo simulation, in this study mainly consists of three steps [13]: (1) setting the prior probabilities of each impact parameter in Eq. (8) to present their potential change ranges (see Appendix B), which transformed the static business-as-usual scenario analysis into the dynamic scenario analysis that can consider the uncertainties of impact parameters [see Eq. (9)]; (2) making a large number of simulations (e.g., 100 thousand Monte Carlo simulations) by taking random samples from predefined distributions (e.g., normal distribution); and (3) displaying the simulation results in the form of probability distribution diagrams to identify the special emission status, such as carbon peak or carbon lock-in situations.

$$C_{\text{Dynamic}} = C_{\text{Static}} \bullet \left(1+\varphi \bullet \frac{T-2020}{2060-2020}\right), \varphi \sim N(0,\sigma^2) \tag{9}$$

Then, the potential change ranges of operational carbon emissions in residential building operations, especially the carbon peak and lock-in situations, could be obtained via Monte Carlo simulation, which can provide references for policy-makers to feasibly formulate climate and decarbonization policies for the building sector.

3.3. Data

The data on GDP and population in China and the US were obtained from the World Bank, while the data on HCE came from the Organization for Economic Co-operation and Development. The data on households, energy consumption, and carbon emissions in residential buildings in the US were derived from the US Energy Information Administration. In addition, the data on households in China were acquired from China Statistical Yearbooks. Moreover, the data on energy consumption and carbon emissions in China's residential building operations were obtained from the International Building Emission Dataset. Carbon emissions for the residential buildings in China and the US were assessed at the production side.

4. Results

4.1. Historical decarbonization of residential building operations

Fig. 2 illustrates the decomposition results of carbon emission changes according to the DSD method in China's and the US residential building operations during 2000–2020. First, the changes in carbon emissions contributed by six impact parameters are shown in Fig. 2. Among them, positive changes represent the impact on emission growth, and negative changes represent the impact on carbon mitigation. GDP per capita and energy intensity were the top two contributors to the growth in operational carbon emissions from residential buildings in China (i.e., $\Delta C_g + \Delta C_e|_{2000\rightarrow2010} = 237.1\%$, $\Delta C_g + \Delta C_e|_{2010\rightarrow2020} = 100.8\%$), as presented in Fig. 2 a-1 and a-2. In residential building operations in the US, the two parameters with the greatest impact on carbon emissions were population and GDP per capita (i.e., $\Delta C_P + \Delta C_g|_{2000\rightarrow2010} = 17.5\%$, $\Delta C_P + \Delta C_g|_{2010\rightarrow2020} = 15.0\%$), as shown in Fig. 2 b-1 and b-2. Furthermore, the main parameters promoting the decarbonization of residential building operations in the two countries were also different. Household expenditure efficiency and energy-related carbon intensity were the main parameters for achieving historical decarbonization in residential building operations in China (i.e., $\Delta C_{HC} + \Delta C_K|_{2000\rightarrow2010} = -167.4\%$, $\Delta C_{HC} + \Delta C_K|_{2010\rightarrow2020} = -108.6\%$). However, the main parameters mitigating operational carbon in the US were energy intensity and energy-related carbon intensity (i.e., $\Delta C_K + \Delta C_e|_{2000\rightarrow2010} = -17.7\%$, $\Delta C_K + \Delta C_e|_{2010\rightarrow2020} = -31.5\%$).

In addition, the DSD method further analyzed the decomposition results: the influence of energy intensity associated with five end uses on the operational carbon changes. Energy intensity (i.e., *e*) covering the total influence of five end uses, was the main factor promoting carbon emission growth in residential building operations during 2000–2010 in China, among which the change in energy intensity associated with

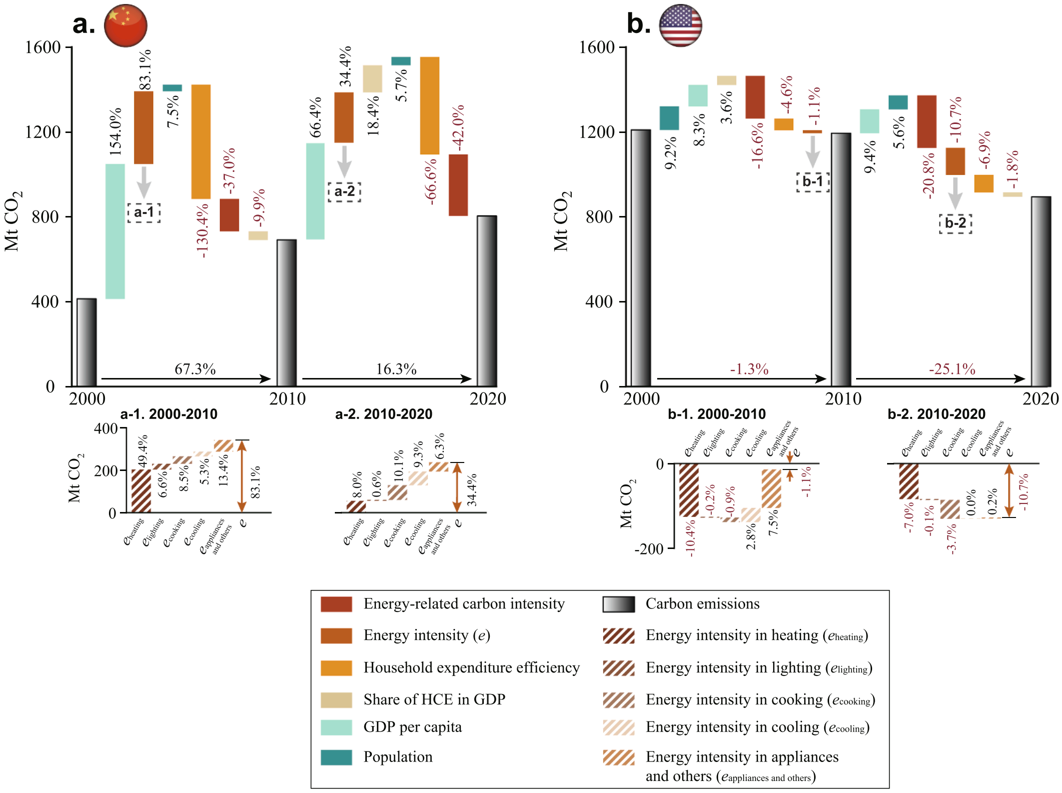

Fig. 2. Carbon changes from 2000 to 2020 in residential building operations in (a) China and (b) the US; share of various end-use emissions to the operational carbon changes in (a-1 & a-2) China and (b-1 & b-2) the US.

heating had the most notable impact on increasing operational carbon (i.e., $\Delta C_{e_{heating}}|_{2000\to2010} = 49.4\%$). In addition, the other energy intensities of the other four end-use activities also had positive effects on carbon emission growth ($\Delta C_{e_{lighting}}|_{2000\to2010} = 6.6\%$, $\Delta C_{e_{cooking}}|_{2000\to2010} = 8.5\%$, $\Delta C_{e_{cooling}}|_{2000\to2010} = 5.3\%$, and $\Delta C_{e_{appliancesandothers}}|_{2000\to2010} = 13.4\%$), as shown in Fig. 2 a-1. Furthermore, the energy intensity associated with five end uses from 2010 to 2020 still played a role in promoting operational carbon emission growth in residential buildings in China, as displayed in Fig. 2 a-2. In the US, the total energy intensity of end-use activities has become a significant driver in decarbonizing residential building operation emissions. Specifically, energy intensity associated with heating had the most significant effect on decarbonization (i.e., $\Delta C_{e_{heating}}|_{2000\to2010} = -10.4\%$), while energy intensity in appliances and others had the largest impact on the increase in carbon emissions (e.g., $\Delta C_{e_{appliancesandothers}}|_{2000\to2010} = 13.4\%$), as shown in Fig. 2 b-1 and b-2. Thus, more attention should be given to decreasing the energy intensities in heating and appliances in the process of operational decarbonization of residential buildings. In addition, the operational decarbonization level in residential buildings in China was 1544 mega-tons of carbon dioxide ($MtCO_2$) from 2001 to 2020, reflecting an average decarbonization efficiency of 11.9 % per year. In comparison, residential building operations in the US decarbonized 1848 $MtCO_2$ from 2001 to 2020, realizing an average decarbonization efficiency of 8.5 % per yr.

In general, energy-related carbon intensity and energy intensity had a great influence on changes in historical carbon emissions (especially decarbonization) in residential building operations in China and the US. In addition, energy intensities associated with heating and appliances contributed the most to the operational carbon emission changes. Moreover, the historical operational decarbonization levels of the two emitters were similar, although their decarbonization efficiency substantially differed. Overall, Section 4.1 solves the first problem raised in Section 1.

4.2. *Potential trajectories of operational carbon in residential buildings*

For the second problem issued in Section 1, it is necessary to first illustrate the static emission trajectories in residential building operations from 2021 to 2060, which were simulated based on the business-as-usual scenario, as shown in dark red lines in Fig. 3. It can be observed that future emissions in China show an inverted U-shape with an emission peak of 927 $MtCO_2$ in 2030. In the US, emissions will gradually enter a carbon lock-in status, with an average of 743 $MtCO_2$ emissions per year starting in 2030. Considering the uncertainties of the impact parameters in Eq. (8), the potential emission change ranges can be obtained according to the set prior probabilities of impact parameters via dynamic scenario analysis, as shown in the blue bands in Fig. 3. The principal aim of this study was to find the carbon neutral trajectories; thus, it is pointless to further study the potential change ranges larger than the static emission trajectories of business-as-usual scenarios. In another part, the potential emission change ranges of −1, −2, and −3 times the standard deviation (SD) correspond to 32.6 %, 47.8 %, and 49.9 % probabilities, respectively, which are the potential ranges of decarbonization trajectories.

Then, the results of energy and emission peak situations in residential buildings in China and the energy and emission lock-in situations in residential buildings in the US are illustrated in Fig. 4, which were realized by 100 thousand Monte Carlo simulations. Fig. 4 a and b indicate the emission and energy situations of the two countries in the future, respectively. The red distributions represent the lock-in levels of emission and energy in the US, while the distributions in blue and green represent the emission and energy peaks and their corresponding peaking time in China. Moreover, since the carbon lock-in situation in the US is a long-term situation that begins in the 2030s, there is little significance in analyzing the time distributions of the lock-in effect. In addition, for reliability concerns, the error values (e.g., standard deviation) are estimated. Thus, residential building operations in China will hit their emission peak in 2031 (±3) with 934 (±61) $MtCO_2$, while residential building operations in the US will maintain their emission level of 736 (±133) $MtCO_2$ since the 2030 s, as shown in Fig. 4 a. Regarding the energy consumption in residential building operations (see Fig. 4 b), China will achieve an energy peak in 2036 (±5) with 24.1 (±2.24) exajoules (EJ), while the US will remain at 22.3 (±3.95) EJ after 2030.

Section 4.2 presents the static emission trajectories and potential ranges of decarbonization trajectories in China's and the US residential building operations, and reflects the distributions of peak and lock-in levels of operational carbon and corresponding energy demand for the two emitters, which initially solves the second problem raised above.

5. Discussion

Although Section 4.1 preliminarily proposes the potential trajectories of future emissions in residential buildings through dynamic scenario analysis, detailed benchmarks deserve to be further discussed to provide corresponding references to high decarbonization by the mid-century. Therefore, the end-use activity benchmarks reflecting technological innovations and development in residential buildings in the business-as-usual scenario are discussed in Section 5.1 based on the output in Section 4.2. In addition, Section 5.2 illustrates the pathways in the decarbonization scenario toward the 2060 carbon neutral goal. Moreover, Section 5.3 introduces some high decarbonization strategies of residential building operations to help residential buildings better achieve their carbon-free goals in the future.

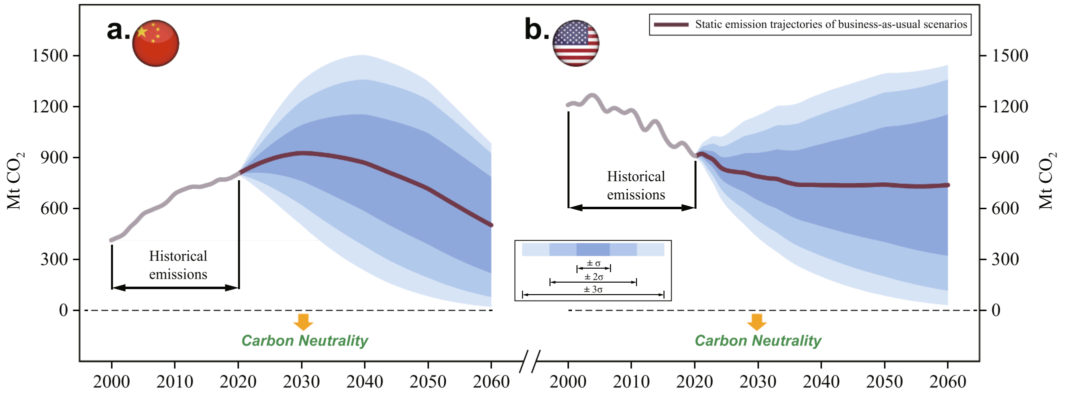

Fig. 3. Static operational carbon trajectories and dynamic ranges of carbon emissions in the business-as-usual scenario of residential buildings in (a) China and (b) the US up to 2060.

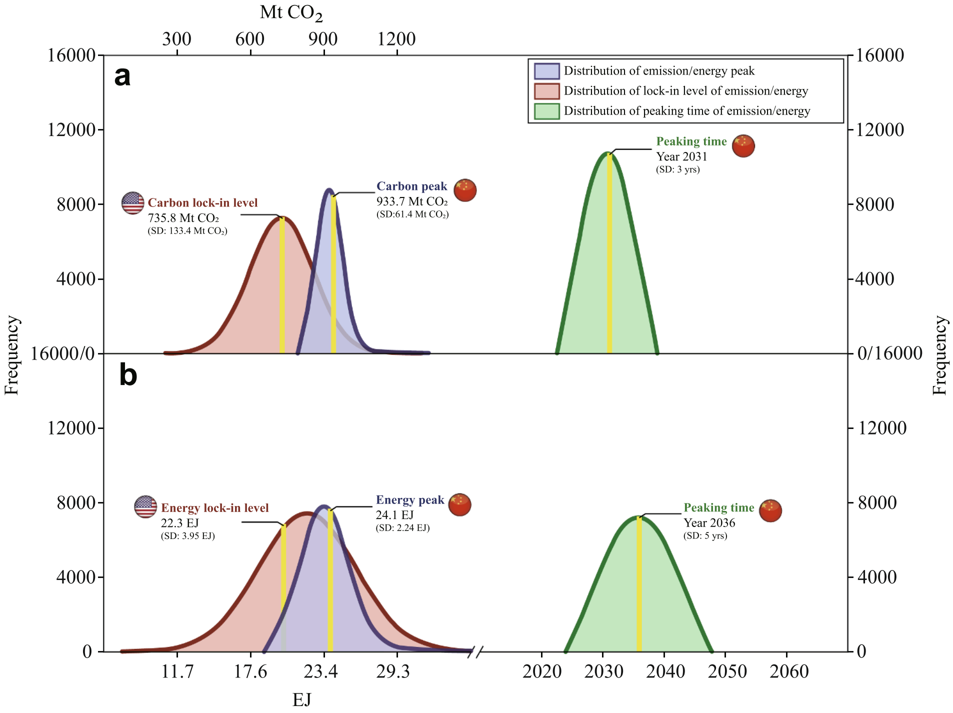

Fig. 4. (a) Operational carbon peak or lock-in distributions in residential buildings in China and the US and (b) corresponding energy peak or lock-in distributions in the residential buildings of the two emitters. **Note:** The red distributions represent the lock-in levels of emission and energy in the US, the distributions in blue represent the emission and energy peaks in China, and the distributions in green represent peaking time of emission and energy in China. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.1. Benchmarks of end uses and emission factors in the business-as-usual scenario

To achieve further decarbonization, sensitivity analysis is used to identify more sensitive parameters in Eq. (8) that affect the emission peak or emission lock-in [53]. The results show that the most sensitive parameters, GDP per capita, energy-related carbon intensity, and energy intensity, are the top three parameters for carbon emissions in residential buildings in both China and the US (see Appendix C). Among the three parameters, energy intensity [54] and energy-related carbon intensity are related to technology development, and they are expected to develop more potential for decarbonization [55]. Hence, energy intensities were further discussed from the perspective of end-use activities, and energy-related carbon intensities were further discussed from the perspective of energy structure.

Fig. 5 presents the energy intensities across different end uses ($e_{heating}$, $e_{cooling}$, $e_{lighting}$, $e_{cooking}$, and $e_{appliancesandothers}$) in the business-as-usual scenario and shows the total energy intensity (e) that expresses the energy use per household over the different end-use activities. Specifically, Fig. 5 a reflects the benchmarks of five end-use energy intensities in residential buildings in China, while Fig. 5 b illustrates the relevant benchmarks in residential buildings in the US. Technically, the

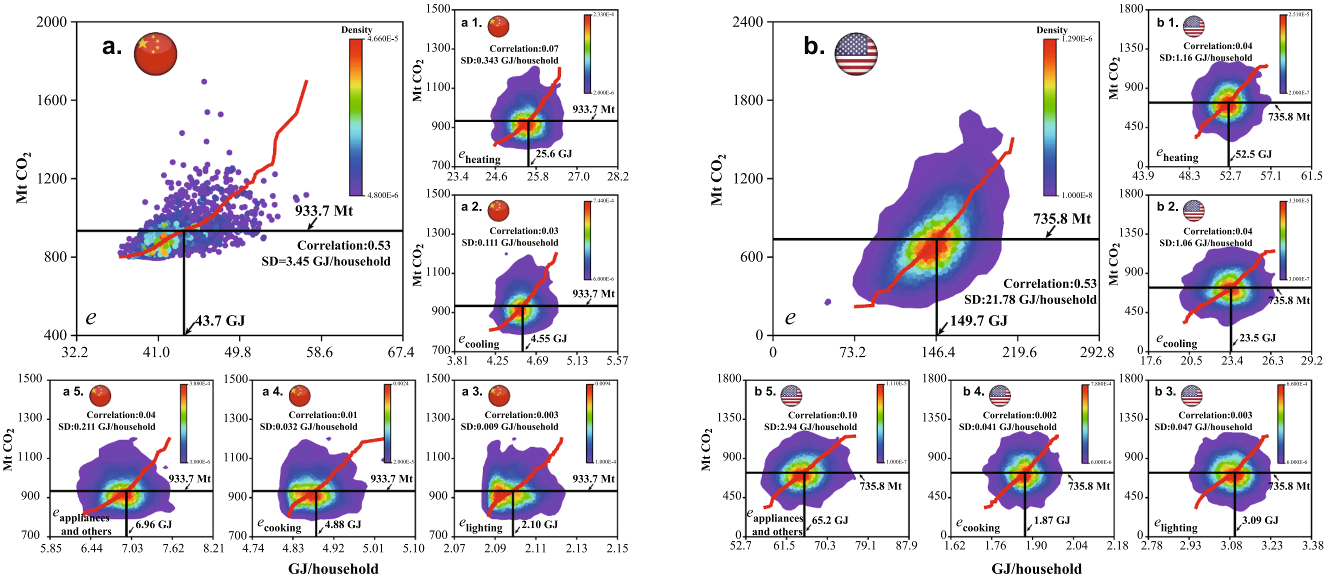

Fig. 5. Benchmarks on (a) the total energy intensity with (a 1–5) five end-use energy intensities for residential buildings in China and (b) the total energy intensity with (b 1–5) five end-use energy intensities for residential buildings in the US in the business-as-usual scenario. **Note:** End-use energy intensities include heating, cooling, lighting, cooking, and appliances with others; the red line in each graph shows where the pairwise points would appear if they were sorted in ascending order. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

benchmarks of energy intensity refer to various energy intensity values that correspond to the emissions peak level of 934 $MtCO_2$ or the emission lock-in level of 736 $MtCO_2$ in fitting curves obtained from the 100 thousand Monte Carlo simulations. When residential buildings in China hit their operational carbon peak in 2031 with a peak of 934 $MtCO_2$, the corresponding values of energy intensity across different end uses should be controlled within 25.6 gigajoules per household (GJ/household) for heating, 6.96 GJ/household for appliances and others, 4.88 GJ/household for cooking, 4.55 GJ/household for cooling, and 2.10 GJ/household for lighting. For residential buildings in the US, when the carbon lock-in level remains at 736 $MtCO_2$ since the 2030s, the corresponding end-use energy intensities are recommended to be controlled within 65.2 GJ/household for appliances and others, 52.5 GJ/household for heating, 23.5 GJ/household for cooling, 3.09 GJ/household for lighting, and 1.87 GJ/household for cooking. It is obvious that a significant gap exists in the energy intensity of each end-use between the two economies due to the vast differences in building structure, household behavior, household expenditure, etc., between China and the US. In total, the total energy intensity for residential building operations in China is 43.7 GJ/household in 2031 and that for residential building operations in the US is 149.7 GJ/household in the 2030s.

In addition, various energy-related carbon intensities that connect energy consumption and carbon emissions were assessed from the perspective of energy structure in residential building operations. According to Fig. 6 a, in residential buildings in China, when operational carbon achieves its peak at the level of 934 $MtCO_2$, the energy-related carbon intensities contributed by the direct and indirect emissions from large to small are 21.9 kg of carbon dioxide per gigajoule ($kgCO_2$/GJ) in electricity, 20.5 $kgCO_2$/GJ in coal, and 3.79 $kgCO_2$/GJ in natural gas. In residential buildings in the US, according to Fig. 6 b, when carbon emissions come to lock-in, the energy-related carbon intensities contributed by the direct and indirect emissions from large to small are 19.8 $kgCO_2$/GJ in electricity, 11.3 $kgCO_2$/GJ in natural gas, and 2.19 $kgCO_2$/GJ in oil. Moreover, the total energy-related carbon intensity in residential building operations in China is 42.0 $kgCO_2$/GJ when it hits the operational carbon peak, and the corresponding intensity in residential building operations in the US is 33.8 $kgCO_2$/GJ in regard to the carbon lock-in situation. By checking the SD in Fig. 6, it is obvious that the total energy-related carbon intensity is largely affected by the indirect emissions associated with electricity use, which means that decarbonization in electricity is essential for buildings to become carbon-free in the future. Overall, Section 5.1 is an extension of the results in Section 4.2, while Sections 4.2 and 5.1 jointly solve the second problem in Section 1.

5.2. *Process to be carbon-free in the decarbonization scenario*

To further realize the decarbonization transformation and finally achieve operational carbon-free status in the mid-century, the operational decarbonization trajectories of residential buildings in China and the US and the corresponding measures for achieving carbon-free status in 2060 in the decarbonization scenario are presented in Section 5.2.

Specifically, Fig. 7 illustrates the decarbonization trajectories of China's and the US residential building operations during 2021–2060 (see yellow curves) and the process to become carbon-free up to 2060 from the business-as-usual to the decarbonization scenario. According to the previous analysis, the decrease in energy intensity and energy-related carbon intensity can be attributed to technological innovation [56], which can increase decarbonization potential. Hence, the impacts of energy-related carbon intensity can be subdivided into three parts primarily, including clean power generation (off-site) [55], building-integrated power generation (on-site) [57,58], and building electrification level [59,60]. Therefore, the decarbonization scenario mainly investigated the off-site power generation structure, the building electrification rate, the building energy efficiency level measured by the energy intensity, and the building-integrated power generation capability during 2021–2060 [61,62].

It is believed that if 80 % of building electrification level, 17.9 GJ/household of energy intensity, 31 % of building-integrated power generation (on-site), and 90 % of clean power generation (off-site) are realized in China by mid-century (see Appendix D for the detailed scenario parameters), China's residential building operations will be able to achieve carbon-free status. From the business-as-usual scenario to the decarbonization scenario, a total decarbonization of 502 $MtCO_2$ can be

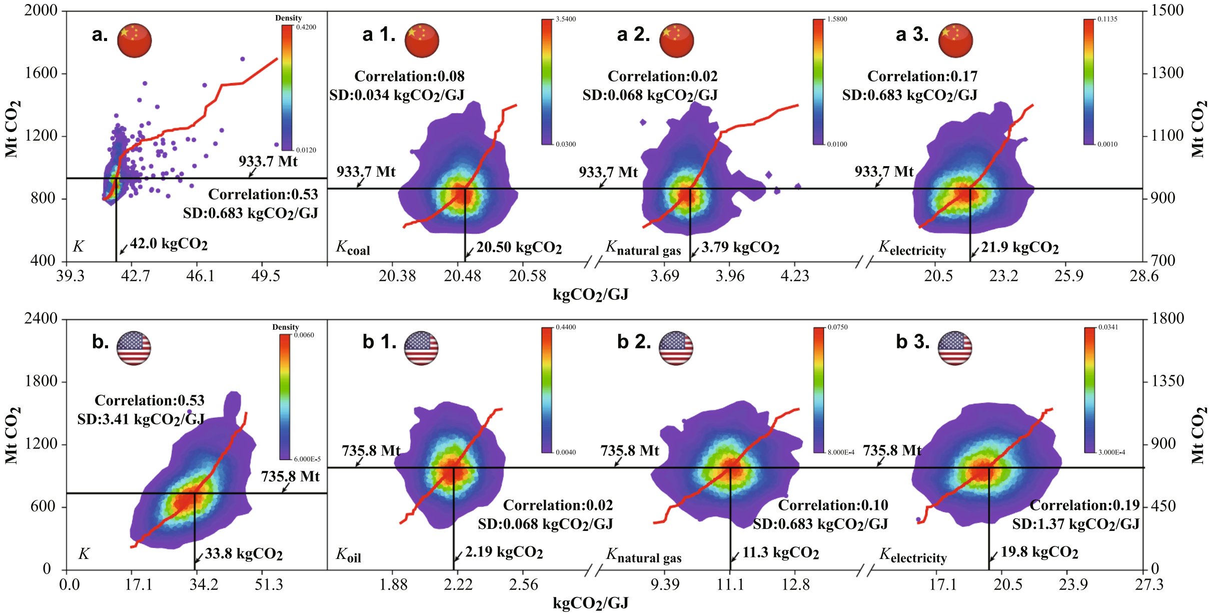

Fig. 6. Benchmarks on (a) the total energy-related carbon intensity with (a 1–3) its three detailed energy-related carbon intensities in residential buildings in China and (b) the total energy-related carbon intensity with (b 1–3) its three detailed energy-related carbon intensities in residential buildings in the US. **Note:** The detailed energy structure in China refers to coal, natural gas, and electricity. In the US, the detailed energy structure refers to oil, natural gas, and electricity; the red line in each graph shows where the pairwise points would appear if they were sorted in ascending order. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

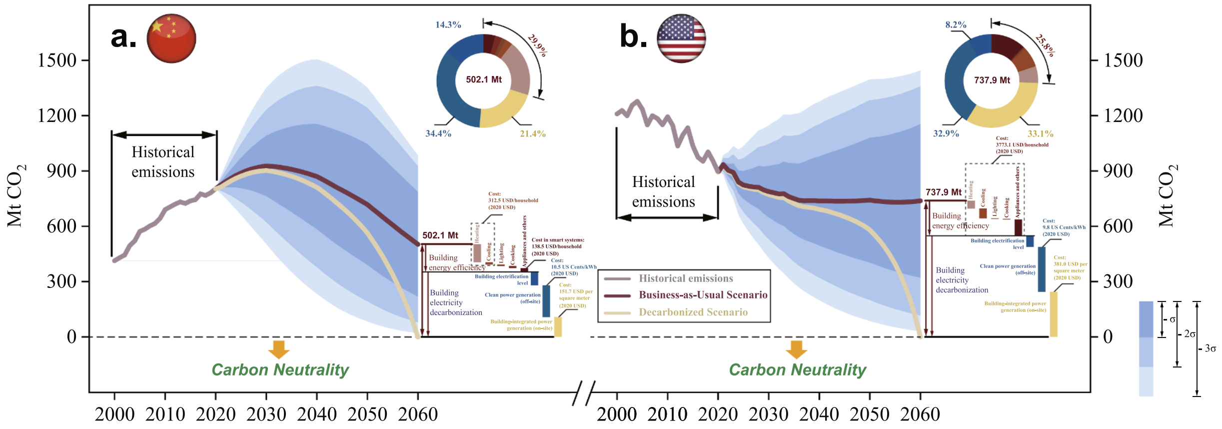

Fig. 7. Decarbonization trajectories and the process to carbon-free residential building operations up to 2060 in (a) China and (b) the US.

observed in 2060 if the decarbonization measures mentioned above are all covered, as shown in Fig. 7 a. Specifically, off-site clean power generation, building energy efficiency improvement, building-integrated power generation, and building electrification level will cut the operational carbon emissions by 173 (34.4 %), 150 (29.9 %), 107 (21.4 %), and 72 $MtCO_2$ (14.3 %), respectively. Thereinto, the decarbonization of 150 $MtCO_2$ (29.9 %) can be attributed to the contribution of energy efficiency improvement in five end uses: 97 $MtCO_2$ (19.3 %) decarbonized in heating, 21 $MtCO_2$ (4.2 %) decarbonized in appliances and others, 13 $MtCO_2$ (2.6 %) decarbonized in cooling, 12 $MtCO_2$ (2.4 %) decarbonized in cooking, and 7 $MtCO_2$ (1.4 %) decarbonized in lighting.

In the US, if 95 % of building electrification level, 88.2 GJ/household of energy intensity, 50 % of building-integrated power generation (on-site), and 90 % of clean power generation (off-site) are achieved by mid-century, residential building operations in the US will achieve carbon neutrality. A total decarbonization of 738 $MtCO_2$ can be observed in 2060 from the business-as-usual scenario to the decarbonization scenario. Fig. 7 b demonstrates that building-integrated power generation, off-site clean power generation, building energy efficiency improvement, and building electrification level will cut the operational carbon emissions by 244 (33.1 %), 243 (32.9 %), 190 (25.8 %), and 60 $MtCO_2$ (8.2 %), respectively. Specifically, the decarbonization of 190 $MtCO_2$ (25.8 %) can be attributed to the contribution of energy efficiency improvement in five end uses: 89 $MtCO_2$ (12.1 %) decarbonized in appliances and others, 52 $MtCO_2$ (7.1 %) decarbonized in cooling, 43 $MtCO_2$ (5.8 %) decarbonized in heating, 3 $MtCO_2$ (0.4 %) decarbonized in lighting, and 3 $MtCO_2$ (0.4 %) decarbonized in cooking. It can be observed that passive decarbonization (electrification with the corresponding energy decarbonization) is the key to cutting operational carbon in both China and the US. In the technical perspective, China has significant potential to become carbon-free by intensely deploying off-site clean power generation capability. Compared with the decarbonization pattern in China, the US prefers to achieve carbon neutral goal of residential building operations via building-integrated power generation. As for the end-use activities, the heating in China's residential buildings has the largest decarbonization potential while the US residential buildings should pay more attention in cutting the operational carbon in appliances considering its high levels of household appliances and building electrification level.

Besides, Fig. 7 discusses the cost of main decarbonization measures required to achieve the carbon neutral goal by 2060. To account for potential technological innovations in the coming decades that could lead to a rapid decrease in cost, such as the cost of rooftop photovoltaics, all costs were measured at current currency prices, and the 2020 USD was used for the cost analysis [63]. As shown on the labels of steps in Fig. 7, while the costs of clean power generation (off-site) in China and the US would be similar in 2060 (10.5 and 9.8 US Cents/kWh, respectively) [64], building-integrated power generation in China would only cost about 40 % (151.7 USD per square meter) of what it costs in the US [65]. These findings suggest that with technical support and financial subsidies, it is feasible for developing countries to deploy building-integrated power generation for cost-effective decarbonization in residential building operations. Here, Section 5.2 initially solves the third problem in Section 1.

5.3. High-decarbonization strategies for residential buildings

Sections 5.1 and 5.2 demonstrate that decarbonization in the power sector plays an important role in building carbon neutrality. However, for the building sector itself, more attention should be given to widely deploying building-integrated power generation represented by building-integrated photovoltaics, which is also reflected in the formulations of building decarbonization routes in China and the US.

In China's residential buildings, photovoltaics [66], energy storage [67,68], direct current, and flexibility [69] (PEDF) are new energy technologies in building power distribution systems [70]. The specific connotations of PEDF technologies are shown in Fig. 8 and explained as follows. PEDF is an organic whole, and its main purpose is to realize flexible power consumption of buildings (i.e., the friendly interaction between buildings and the power grid) by using building-integrated photovoltaic power generation [71], building energy storage [72], and a direct current power distribution system [73]. PEDF can transform a building from being a power consumer to being a power provider. Once the power-generation capacity of a building has met its own demand, its surplus can be transferred to the power grid [74]. In addition, the building will become a flexible energy consumption node [75], as its PEDF technologies allow for scheduling [76]. PEDF can enable buildings to take power from the grid at night to avoid peak power consumption during the day.

Meanwhile, the concepts of grid-interactive efficient buildings (GEBs) in the US are also widely respected to promote building decarbonization [77]. The concepts of GEBs in the US are similar to those of PEDF technologies in China and are specifically introduced in a report named *a National Roadmap for Grid-Interactive Efficient Buildings* drafted by the US Department of Energy and Lawrence Berkeley National Laboratory [78]. The report emphasizes that distributed energy resources (on-site power generation) are the basis for GEBs to reduce the power demand from the power grid [79], especially at the peak power demand time [80]. Moreover, GEBs can utilize smart technologies to shed loads at the peak power demand time and shift loads from the peak power demand time to the valley power demand time to reduce the burden of the power grid [81,82]. In addition, compared with the PEDF technologies in China, the GEBs also consider improving the energy efficiency of buildings, especially by improving their envelope structure to decrease

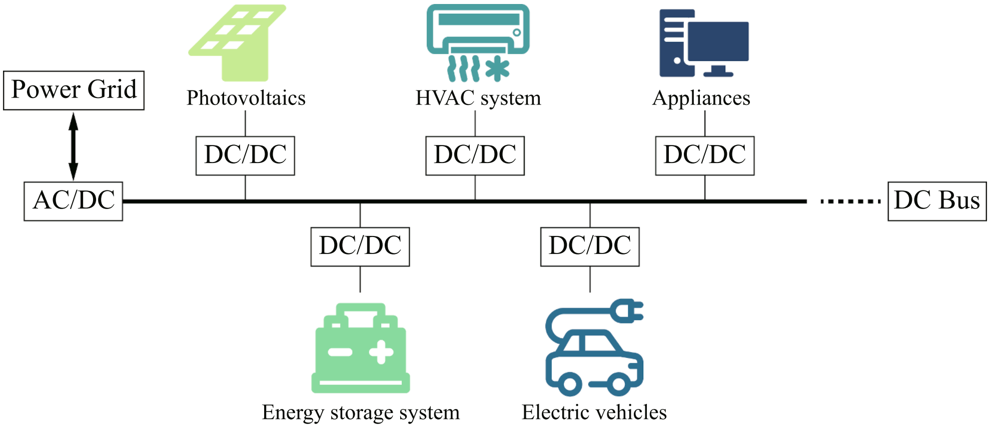

Fig. 8. Operating principle of the PEDF system in residential building operations. **Note:** alternating current (AC), direct current (DC), heating, ventilation, air conditioning and cooling (HVAC).

energy consumption and carbon emissions [83,84].

The purposes of PEDF technologies in China and GEB technologies in the US are similar, and both are proposed as means of promoting the innovation and upgrading of building-integrated power generation technologies, which is consistent with the analysis results in this study: Both China and the US will need to rely on electricity decarbonization, including on-site and off-site power generation, to achieve carbon neutrality in residential building operations. However, China's decarbonization strategy will involve replacing coal with natural gas, followed by a transition to electricity and decarbonization of the electricity sector. In contrast, the US will focus on replacing natural gas with electricity and decarbonizing the electricity sector to achieve decarbonization in residential buildings. The decarbonization potential of building-integrated power generation is substantial and worth promoting to assist with realizing carbon-free residential building operations. Moreover, the contributions of end-use energy efficiency cannot be ignored. Residential building operations in China should pay more attention to improving the energy efficiency of heating, which can be realized by changing the type of energy consumption and improving the structure of the envelope. In the US, the energy efficiencies of appliances should be focused on. In addition, with the promotion of the decarbonization process in buildings, the cost-effectiveness and economic feasibility of building-integrated power generation in residential building operations should be given more attention. Overall, the third problem in Section 1 is entirely solved by Sections 5.2 and 5.3.

6. Conclusions

This study proposed feasible data-driven roadmaps for comparing the decarbonization from China's and the US residential buildings during 2000–2060 by combining the end-use emission model with the DSD method and Monte Carlo simulation. Specifically, historical operational decarbonization was estimated by the DSD method considering changes in end-use activities. Moreover, Monte Carlo simulation conducted in the operational emission scenario analysis dynamically assessed potential carbon trajectories, benchmarks of end uses and emission factors, and the process of realizing carbon-free residential buildings. In addition, some high-decarbonization strategies were discussed to promote the realization of complete carbon-free status by mid-century. Core findings are shown below.

6.1. Core findings

- Operational decarbonization in residential buildings in China and the US was 1544 and 1848 $MtCO_{2,}$ respectively, from 2001 to 2020. Although the operational decarbonization value of the US was slightly higher than that of China, the decarbonization efficiency was opposite: China possessed an 11.9 % per year decarbonization efficiency, while the US maintained an 8.5 % per year decarbonization efficiency. Moreover, energy-related carbon intensity and energy intensity that belong to the residential building sector had a substantial impact on the changes in historical carbon emissions or decarbonization in residential buildings operations in China and the US. Furthermore, energy intensities in heating and appliances contributed the most to the total energy intensity. Therefore, these impact factors, especially key end-use activities, should be given more attention to achieve decarbonization transformation.
- In the business-as-usual scenario, the operational carbon peak in China will be 934 (±61) $MtCO_2$ in 2031 (±3), while carbon lock-in in the US will remain 736 (±133) $MtCO_2$ after 2030. When an operational carbon peak of 934 $MtCO_2$ in residential buildings is reached in China, the total energy intensity should be controlled at 43.7 GJ/household, and energy-related carbon intensity should be controlled within 42.0 $kgCO_2$/GJ. When US residential buildings reach the carbon lock-in of 736 $MtCO_2$, the total energy intensity should be controlled within 149.7 GJ/household, and energy-related carbon intensity should be controlled at 33.8 $kgCO_2$/GJ. For end-use activities, energy intensity in heating and appliances will contribute over two-thirds of the total energy intensity in China and the US (China: 25.6 and 6.96 GJ/household; the US: 52.5 and 65.2 GJ/household). For the energy supply structure, electricity and coal will contribute the most to the total energy-related carbon intensity (21.9 and 20.5 $kgCO_2$/GJ) in China. In the US, the top two energy sources are electricity and natural gas (19.8 and 11.3 $kgCO_2$/GJ).
- To realize operational carbon neutrality, clean power generation, energy efficiency of end uses, building-integrated power generation, and building electrification level contribute 34.4 %, 29.9 %, 21.4 %, 14.3 % in China and 32.9 %, 25.8 %, 33.1 %, 8.2 % in the US, respectively. In China, when the above four indicators achieve 90 %, 17.9 GJ/household of energy intensity, 31 %, and 80 %, respectively, by mid-century, China will achieve operational carbon neutrality in residential buildings (the corresponding decarbonization potential is 173, 150, 107, and 72 $MtCO_{2,}$ respectively). Decarbonization from energy efficiency in China will be mainly affected by the end uses of heating and appliances. In the US, when the above four indicators realize 90 %, 88.2 GJ/household of energy intensity, 50 %, and 95 %, respectively, by mid-century, US residential building operations will achieve their carbon-free target (the corresponding decarbonization potential is 243, 190, 244, and 60 $MtCO_{2,}$ respectively). Decarbonization from energy efficiency in the US will be mainly affected by the end uses of cooling and appliances.

6.2. Forthcoming studies

Several gaps in this work deserve to be further studied. For the emission boundary of the residential building sector, it is worth conducting an investigation to compare the carbon emissions throughout the full life cycle in the top two emitters. In addition, historical decarbonization assessment at the near-real-time level should become the next knowledge gap to be covered, which will be more effective in identifying changes in operational decarbonization during extreme events such as the COVID-19 pandemic. Moreover, the fundamental purpose of comparing carbon–neutral trajectories for residential building operations in China and the US is to promote global building carbon neutrality. Therefore, it remains important to model the future decarbonization trajectories of global buildings, especially for emerging carbon-emitting economies prioritize the electrification of buildings and the decarbonization of power systems as early as possible. Due to the difference in socioeconomic development processes, building carbon emissions in developing countries may exhibit completely different emission pathways than those in developed countries. Some countries lagging in development will barely see a turning point in building carbon emissions by 2060. Moreover, with the gradual decarbonization of buildings, cost-effectiveness analysis is being taken into account in measures of decarbonization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.121164.

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