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Global transition of operational carbon in residential buildings since the millennium

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ABSTRACT

The residential sector is the third-largest energy consumer and emitter globally and as such is at the forefront of the energy transition and net-zero emissions pathway. To accelerate the pace of decarbonization of residential buildings, this study is the first to present a bottom-up assessment framework integrated with the decomposing structural decomposition method to evaluate the emission patterns and decarbonization process of residential building operations in 56 countries spanning 12 regions worldwide from 2000 to 2020. The results show that (1) the operational carbon intensity of global residential buildings has maintained an annual decline of 1.2% over the past two decades, and energy intensity and average household size have been key to this decarbonization; (2) end uses have held an increasingly important role in decarbonizing global residential buildings (-46.3 kgs of carbon dioxide per household per year), with the largest contributors being appliances(38.3%), followed by space heating (21.2%) and lighting (12.6%); and (3) although the total decarbonization of global residential buildings was 7.1 gigatons of carbon dioxide and achieved a decarbonization efficiency of 9.4% per yr during this time period, regional decarbonization inequality and uneven distribution remained quite large, especially in emerging economy regions. Moreover, the uncertainty and robustness of the assessment framework are also tested, and adaptive high decarbonization strategies are further proposed for global residential buildings. Overall, this study reviews and compares global and regional performances and motivations for decarbonization to support national decarbonization efforts to reach net-zero emissions and advance the global residential building sector toward a carbon-free century.

1. Introduction

The climate goal set out in the Paris Agreement to keep global warming well below 2° and work toward 1.5° leaves limited emission space for human activity and will be impossible to achieve without immediate and high decarbonization in all emission sectors [1]. The building sector is by far the world's largest energy consumer and emitter, with operational carbon from buildings reaching another record high of 10 gigatons CO_2 ($GtCO_2$) in 2021, 5% higher than when the Paris Agreement was signed in 2015 [2]. Residential buildings are considered the last mile toward building carbon neutrality due to their potential energy demand and high lock-in effect, consuming more than 60% of the building sector's energy and releasing nearly half of building-related carbon emissions [3]. Moreover, the latest evidence shows that residential buildings offer greater potential and cost-effectiveness in improving energy efficiency and carbon mitigation compared to non-residential buildings [4]. Therefore, decarbonization of residential buildings is a crucial step toward achieving building carbon neutrality and the Paris climate goals.

To fast-track carbon neutrality in residential buildings, nearly 160 countries worldwide have set ambitious reduction targets and have included building decarbonization as part of their nationally determined contributions [5]. Although these mitigation efforts have raised the national ambition level and provided guidance for a low-carbon transition in residences, not every country has contributed equally, and these efforts have focused primarily on the supply side (e.g., improving material efficiency [6] and energy-fuel decarbonization [7]). Indeed, there is growing evidence that end-use decarbonization will be fundamental to achieving this goal in the foreseeable future [8], especially for residential buildings with vast energy demand [9]. However, few studies have reviewed and assessed the decarbonization of residential building operations by region or country worldwide to determine the baseline of historical decarbonization and the potential for high

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Abbreviation

DSD	Decomposing structural decomposition
$GtCO_2$	Gigatons of carbon dioxide
$kgCO_2$	Kilograms of carbon dioxide
LMDI	Log-mean Divisia index
$MtCO_2$	Megatons of carbon dioxide

Nomenclature

C	Carbon emissions of residential building operations
C_j $(j = 1, 2, \cdots, 6)$	Carbon emissions released by end-use j
c	Carbon intensity (for residential building: carbon emissions per household)
DC	Total decarbonization
DCE	Decarbonization efficiency
DCI	Decarbonization intensity
E	Energy consumption
E_j $(j = 1, 2, \cdots, 6)$	Energy used by end-use j
e	Energy intensity
GDP	Gross domestic product
g	GDP per capita
H	Amounts of households
HFC	Household final consumption
h	Household consumption capacity
k	Emission factors
P	Population size
p	Average household size
S	End-use structure

decarbonization [10], especially a detailed assessment of the mitigation potential for measures related to end uses (e.g., space heating, appliances) [11]. Therefore, to address these gaps, this study proposes the following three questions for the global residential building sector:

- What are the global and regional patterns of operational carbon change since 2000?
- How do end uses perform in decarbonizing residential building operations worldwide?
- What influences the decarbonization process and how can it be accelerated to reach net-zero emissions?

To answer these three questions, a bottom-up framework is developed to assess the historical decarbonization of residential building operations from household end-use activities in 56 countries from twelve major emitting regions worldwide (totally covering nearly 70% of operational carbon in global residential buildings) over the past two decades. Decomposing structural decomposition (DSD) is integrated to identify the effects of the socio-economy, technological innovation, and end-use activity on residential decarbonization. Furthermore, uncertainty analysis and robustness checks are used to validate the results of the assessment framework. Thereafter, the historical process and decarbonization efficiency of residential buildings are assessed, and the historical decarbonization performance across regions is investigated and compared based on three emission scales. Finally, high decarbonization strategies are proposed to achieve a carbon-free residential building sector.

As its most important contributions, this study aims to be the first to assess and compare global and regional historical decarbonization and the corresponding potential of residential building operations at a household scale and to provide a benchmark for countries to fairly set decarbonization targets and remaining emission quotas. The high decarbonization of these major emitters will also inform the development of the remaining emerging emitting economies and reserve more emission space. To this end, this study estimates the spatial-temporal evolution patterns of the carbon intensity (i.e., carbon emissions per household) in global residential building operations and investigates the effects of socio-economy, technological innovation, and end uses on residential decarbonization in 56 countries spanning 12 regions worldwide, particularly measuring the decarbonization benefits across six different end-use activities by considering the end-use structure and the corresponding emission factor change.

The rest of this study proceeds as follows: Section 2 provides a literature review. Section 3 introduces the method and dataset, covering building emission models, the DSD approach, and decarbonization assessment models. Section 4 presents the global and regional operational carbon patterns and the contributions of household end uses in decarbonizing residential buildings. Section 5 discusses the uncertainty analysis and robustness check, historical decarbonization assessment of global residential buildings, and the corresponding decarbonization strategies. Finally, Section 6 summarizes the core findings of the study and proposes several upcoming research topics.

2. Literature review

High decarbonization of the residential sector requires all stakeholders to assume common but differentiated responsibilities [12] and design decarbonization practice pathways accordingly [13]. On the one hand, national and transnational assessments of decarbonization processes and mitigation potential are needed to lay the groundwork for climate negotiations [14]. For instance, Stefan et al. [15] stated that a 20–52 $GtCO_2$ reduction could be achieved by 2050 through material efficiency improvements in the residential sector in 20 countries worldwide, and Tarun M et al. [16] estimated the decarbonization potential of behavior change in residences in 25 countries at approximately 0.35 $GtCO_2$ per yr. Recently, Camarasa et al. [17] compiled decarbonization strategies for 32 countries and indicated that these measures would eliminate nearly 4 $GtCO_2$ from the building sector by the mid-century. On the other hand, end-use decarbonization on the demand side [18] has been considered the optimal means to realize full decarbonization of the residential sector [19]; as a result, many studies have investigated the decarbonization effectiveness of end uses, particularly at the national or regional level. Schipper et al. [20] and Greening et al. [21] examined the effect of residential end-use on carbon emissions in Organization for Economic Cooperation and Development countries, and similar studies were subsequently performed in China [22], the United States [23], Japan [24], and Singapore [25]. Additionally, some scholars have assessed the decarbonization potential of specific end uses (e.g., space heating [26], space cooling [27]) for residential building operations. However, to date, few studies have assessed the end-use decarbonization of residential buildings across regions due to differences in monitoring, accounting, and technical details.

The modeling strategy for end uses in residential buildings can be categorized into two branches: bottom-up and top-down [28]. The top-down approach aims to investigate the interrelationships between the residential sector and economic output using aggregated data, which lacks technical detail but places more emphasis on observed macroeconomic trends [29]. Conversely, the bottom-up modeling approach tends to use stratified input data to characterize end-use attributes in the residential sector, and it emphasizes modeling technical options to identify areas for improvement [30]. In terms of quantitative techniques for solving models, decomposition analysis with simple operation and interpretability is the preferred tool for quantifying changes in operational carbon emissions. The adaptive weighting Divisia method was pioneered in 1997 to decompose the impact of residential end uses on carbon intensity [20]; then, the log-mean Divisia index (LMDI) approach without residuals was used to investigate end-use activities in residential buildings [31]. In 2014, a new decomposition framework named the generalized Divisia index method was proposed by Vaninsky [32], given the limitation that LMDI overemphasizes the relationship between variables and fails to output stable results [33]. In 2021, Boratyński [34] further developed a simpler and more versatile decomposition technique (i.e., DSD mentioned in Section 1) based on the existing decomposition framework that is mathematically proven to degenerate to the existing classical model under certain conditions, and the validity of the method was verified via numerical cases and practical applications.

Given the current state of research on the operational decarbonization assessment of global residential buildings, the following two gaps should be noted:

Regarding the methodology of decarbonization assessment, although bottom-up modeling strategies have been widely used to investigate residential end uses, knowledge gaps in the quantitative techniques used for model solving remain [35]. Existing methods tend to solve for decomposed data or use a multilevel parallel approach to solve for aggregated indicators [36]. Compared to traditional methods, DSD can more intuitively quantify and capture the impact of multilevel data and their individual share effects on aggregated indicators. The original DSD has also been used in our previous studies to assess the decarbonization of commercial buildings in the 16 selected countries, and the results suggest a valid tool [37]. However, to date, the improved DSD has not been utilized to analyze the end-use structure and the corresponding emission factor change of residential buildings' end-use activities.

Regarding the topic of decarbonization assessment, existing residential decarbonization assessments have focused on major emitting regions (e.g., China [38], the United States [39], and the European Union [40]) or have assessed the world as a whole [41]. Although some global models [42,43] have extensively assessed the current status and possible future evolution of residential sector decarbonization, they are often limited by spatial and temporal scopes and resolution versus technical details (e.g., end-use characteristics); importantly, these efforts focus primarily on absolute decarbonization targets, ignoring the disparity in historical emissions responsibility and socioeconomic drivers among economies. As a result, they do not provide insightful information on the assessment of regional emission reduction performance and the allocation of emission space and decarbonization responsibilities. To the best of our knowledge, none of the existing decarbonization assessment studies assess and compare global and regional decarbonization potential and differences for residential building operations with a high degree of regional heterogeneity and technology-level detail.

The status quo indicates the urgent need to deeply assess and inspect the progress and potential for decarbonization of the global residential building sector to get the urge for more efficient mitigation action. Additionally, regional decarbonization performance should be emphasized to enhance regional cooperation and thus jointly realize a carbon-free residential building sector. To the best of our knowledge, this study seeks to address these gaps and makes the following contributions:

- A modeling framework based on end-use activities is proposed to analyze global and regional operational carbon patterns of residential buildings since the start of this century. On the demand side, the building emission model is established from bottom to up, and DSD is integrated to estimate the spatial-temporal evolution of operational emissions patterns in global residential buildings. Specifically, this study is the first to quantify the effect of six end-use activities (i.e., space heating, space cooling, water heating, cooking, lighting, and appliances & others) on the decarbonization of residential building operations at the household scale worldwide, while analyzing the end-use structure and the corresponding emission factor change. In addition, the uncertainty and robustness of the proposed assessment framework are assessed in detail.
- The historical decarbonization benchmark and the corresponding potential in global residential buildings are assessed and compared for the first time. This study reviews the historical decarbonization dynamics of residential buildings over the past two decades in 56 economies spanning 12 regions worldwide, covering nearly 70% of operational carbon emissions in global residential buildings. Besides, this study is the largest cross-economy multiscale assessment of the decarbonization of the residential building sector available. To fully measure global and regional performance in carbon mitigation, this study assesses the operational decarbonization level at three emission scales: total decarbonization, decarbonization per household, and decarbonization per capita. The decarbonization efficiency of 56 emitters in decarbonizing residential building operations is also assessed. Moreover, adaptive high decarbonization strategies are discussed to accelerate the overall process of global residential building decarbonization and eliminate the risk of regional decarbonization poverty.

3. Methods and materials

This study developed a bottom-up assessment framework to measure and analyze the drivers and evolving patterns of decarbonization in global residential building operations, which consists of the following components. First, a building emissions model with residential end-use characteristics is constructed in Section 3.1 to estimate and characterize operational carbon emissions per household. Second, in Section 3.2, the DSD technique is integrated to confirm the social-economic and technical drivers of emissions. Third, a decarbonization assessment model is introduced in Section 3.3 to investigate the historical decarbonization levels of residential buildings globally. Finally, Section 3.4 outlines the dataset used for the assessment framework.

3.1. Operational carbon emission model with end-use characteristics

The carbon emissions from residential building operations are caused mostly by the end-use activities of households. In this study, end-use activities in residential buildings were divided into six categories: space heating, space cooling, water heating, lighting, cooking, and appliances & others. Thus, the operational carbon emissions from residential buildings can be defined as follows:

$$C = C_{\text{Space heating}} + C_{\text{Space cooling}} + C_{\text{Water heating}} + C_{\text{Lighting}} + C_{\text{Cooking}} + C_{\text{Appliances \& others}} \tag{1}$$

Refined as $C = \sum_{j=1}^{6} j$

The notation C_j ($j = 1, 2, \cdots, 6$) indicates the operational carbon emissions released by six end uses in residential buildings. Correspondingly, the operational carbon intensity (i.e., carbon emissions per household) of residential buildings can be further defined as $c_j = \frac{c_j}{H}$ (H denotes the amounts of households).

To evaluate the operational carbon emissions, six potential influencing factors were taken into account to characterize the building emission model, including average household size ($\frac{P}{H}$), gross domestic product (GDP) per capita ($\frac{GDP}{P}$), household consumption capacity ($\frac{HFC}{GDP}$, where *HFC* is the abbreviation of household final consumption), energy intensity ($\frac{E}{HFC}$), end-use structure ($\frac{E_j}{E}\frac{E_j}{E}$, where E_j represents the energy use associated with the end use *j*), and emission factors ($\frac{j}{E_j}$).

$$c_j = \frac{j}{H} \equiv \frac{P}{H} \cdot \frac{GDP}{P} \cdot \frac{HFC}{GDP} \cdot \frac{E}{HFC} \cdot \frac{E_j}{E} \cdot \frac{j}{E_j} \tag{2}$$

Simplified as $c_j = p \cdot g \cdot h \cdot e \cdot s_j \cdot k_j$

Therefore, the operational carbon emission model with end-use characteristics can be defined as follows:

$$c = \sum_{j=1}^{6} p \cdot g \cdot h \cdot e \cdot s_j \cdot k_j \tag{3}$$

3.2. Decomposing structural decomposition method

Here, the DSD method was utilized to decompose the established emission model. Following the computational procedure of DSD [34], Eq. (3) can be expanded into the full differential equation as:

$$\mathrm{d}c = \frac{\partial c}{\partial p}\mathrm{d}p + \frac{\partial c}{\partial g}\mathrm{d}g + \frac{\partial c}{\partial h}\mathrm{d}h + \frac{\partial c}{\partial e}\mathrm{d}e + \sum_{i=1}^{6}\left(\frac{\partial c_j}{\partial s_j}\mathrm{d}s_j + \frac{\partial c_j}{\partial k_j}\mathrm{d}k_j\right) \tag{4}$$

Then, the following linear equation system can be established from Eq. (4) by adding the relaxation component $\mathrm{d}F_i$ and the displacement component $\mathrm{d}F$:

$$\begin{cases} \mathrm{d}c = \frac{\partial c}{\partial p}\mathrm{d}p + \frac{\partial c}{\partial g}\mathrm{d}g + \frac{\partial c}{\partial h}\mathrm{d}h + \frac{\partial c}{\partial e}\mathrm{d}e + \sum_{i=1}^{6}\left(\frac{\partial c_j}{\partial s_j}\mathrm{d}s_j + \frac{\partial c_j}{\partial k_j}\mathrm{d}k_j\right) \\ \mathrm{d}s_j = dF_i + \mathrm{d}F \\ \sum_{j=1}^{6}\mathrm{d}s_j = 0 \end{cases} \tag{5}$$

For facilities research, the linear system Eq. (5) can be further represented in matrix form as:

$$\boldsymbol{\Lambda} \cdot \mathrm{d}\boldsymbol{\alpha} = \boldsymbol{\Omega} \cdot \mathrm{d}\boldsymbol{\beta} \tag{6}$$

where dα and dβ denote the endogenous and exogenous vectors, respectively, which satisfy $\mathrm{d}\alpha = [\mathrm{d}c, \mathrm{d}s_1, \cdots \mathrm{d}s_6, \mathrm{d}F]^{\mathrm{T}}$ and $\mathrm{d}\beta = [\mathrm{d}p, \mathrm{d}g, \mathrm{d}h, \mathrm{d}e, \mathrm{d}k_1, \cdots, \mathrm{d}k_6, \mathrm{d}F_1, \cdots, \mathrm{d}F_6]^{\mathrm{T}}$. Λ and Ω denote the coefficient matrices that are related only to variables dα and dβ; thus, set $\Lambda = \lambda(\alpha, \beta)$, $\Omega = \omega(\alpha, \beta)$, and satisfies:

$$\Lambda = \begin{pmatrix} 1 & -\frac{\partial c_1}{\partial s_1} & -\frac{\partial c_2}{\partial s_2} & -\frac{\partial c_3}{\partial s_3} & -\frac{\partial c_4}{\partial s_4} & -\frac{\partial c_5}{\partial s_5} & -\frac{\partial c_6}{\partial s_6} & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{pmatrix}$$

$$\Omega = \begin{pmatrix} \frac{\partial c}{\partial p} & \frac{\partial c}{\partial g} & \frac{\partial c}{\partial h} & \frac{\partial c}{\partial e} & \frac{\partial c_1}{\partial k_1} & \cdots & \frac{\partial c_6}{\partial k_6} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{7}$$

Then, Eq. (6) can be easily solved by

$$\mathrm{d}\alpha = \Lambda^{-1} \cdot \Omega \cdot \mathrm{diag}(\mathrm{d}\beta) \cdot \gamma \tag{8}$$

where the notation $\mathrm{diag}(\mathrm{d}\beta)$ refers to a diagonal matrix constructed by the vector β and γ represents a vector with all its elements taking values of one.

Notably, the above equations are strictly valid only for infinitesimal variations of the variables. Therefore, to obtain more accurate decomposition results, the actual changes in exogenous variables must be divided into a sufficient number of intervals. Referring to the work of [34], the number of intervals N was set to 16,000 in this study. For each interval n, the effect $\Theta^{(n)}$ caused by the exogenous variables can be calculated using the Euler method in numerical integration as:

$$\begin{cases} \Theta^{(n)} = \left(\Lambda^{(n-1)}\right)^{-1} \cdot \Omega^{(n-1)} \cdot \mathrm{diag}(\mathrm{d}\beta) \\ \mathrm{d}\alpha^{(n)} = \Theta^{(n)} \cdot \gamma \\ \beta^{(n)} = \beta^{(n-1)} + \mathrm{d}\beta \\ \alpha^{(n)} = \alpha^{(n-1)} + d\alpha^{(n)} \\ \Lambda^{(n)} = \lambda\left(\alpha^{(n)}, \beta^{(n)}\right) \\ \Omega^{(n)} = \omega\left(\alpha^{(n)}, \beta^{(n)}\right) \end{cases} \tag{9}$$

where $n = 1, 2, \cdots, N$ and $\mathrm{d}\beta = \frac{\Delta\beta}{N}$. Then, the required decomposition, by repeatedly accumulating the contributions for each interval, can be expressed as

$$\Theta = \sum_{n=1}^{N} \Theta^{(n)} \tag{10}$$

The items θ_{ij} of the Θ matrix indicate the effect caused by the change in the exogenous variable $\Delta\alpha_j$ on the change in the endogenous variable $\Delta\beta_i$. Since this study focused on the building emission model, the effect of exogenous variables on the change in operational carbon intensity can be expressed as follows:

$$\Delta c|_{0\to T} = \Delta p + \Delta g + \Delta h + \Delta e + \Delta s + \Delta k \tag{11}$$

where $\Delta c|_{0\to T}$ denotes the change in operational carbon intensity over period T and the terms on the right-hand side of Eq. (11) denote the contribution level of each driver. Notably, Δs and Δk denote the aggregate effect of the energy use share from each end use (i.e., end-use structure effect) and the aggregate effect of the emission factors from each end use, respectively, which can be further decomposed to the individual end-use activity based on the linear properties of the decomposition indicators by:

$$\begin{cases} \Delta s = \Delta s_{\text{Space heating}} + \Delta s_{\text{Space cooling}} + \Delta s_{\text{water heating}} + \Delta s_{\text{Lighting}} \\ \quad + \Delta s_{\text{Cooking}} + \Delta s_{\text{Appliances \& others}} \\ \Delta k = \Delta k_{\text{Space heating}} + \Delta k_{\text{Space cooling}} + \Delta k_{\text{water heating}} + \Delta k_{\text{Lighting}} \\ \quad + \Delta k_{\text{Cooking}} + \Delta k_{\text{Appliances \& others}} \end{cases} \tag{12}$$

Eq. (12) reveals the effect of changes in end-use structure and emission factors of different end uses on the operational carbon intensity in residential buildings.

3.3. Operational decarbonization assessment

Based on the decomposition outcomes mentioned above, the operational decarbonization intensity (DCI, i.e., decarbonization per household) of global residential buildings can be further assessed by the detrimental effects of factors driving the operational carbon intensity, as follows:

$$DCI|_{0\to T} = -\sum\left(\Delta c_i|_{0\to T}\right) \tag{13}$$

where $\Delta c_i \in \{\Delta p, \Delta g, \Delta h, \Delta e, \Delta s, \Delta k\}$ and satisfies $\Delta c_i|_{0\to T} \le 0$. According to the definition of carbon intensity, the total decarbonization (DC) can be written as:

$$DC|_{0\to T} = DCI|_{0\to T} \times H|_{0\to T} \tag{14}$$

Furthermore, to gain insight into the operational decarbonization potential of residential buildings, the decarbonization efficiency (DCE) is defined as the ratio of operational carbon emissions to operational decarbonization [44] and can be defined as:

$$DCE = \frac{DC|_{0\to T}}{C|_{0\to T}} \times 100\% \tag{15}$$

3.4. Datasets

This study gathered historical data from 56 major economies worldwide spanning from 2000 to 2020. For analytical purposes, these economies were categorized into a set of modeling regions based on their climatic and socioeconomic conditions, namely Europe & New Zealand, China, Northeast Asia, Africa, Australia, South America, United States, Canada, and India. Notably, Europe and New Zealand were grouped together and discussed as one region due to their climate zone similarity. Furthermore, South America and Europe & New Zealand were separated into five distinct sub-climate regions, as detailed in Appendix B. Appendix C provides descriptive statistics for the raw data utilized in this study, including population size, the amounts of households, GDP, HFC, and energy consumption with corresponding carbon emissions from residential building operations. The data for the population and economy-related indicators were collected from the World Bank (data.worldbank.org). GDP and HFC were calculated in purchasing power parity, measured by the constant 2020 US dollars, and the corresponding indices were adopted. The remaining data were gathered from the International Building Emission Dataset (IBED, https://ibed.world/), which was established on the basis of IEA Database (see Appendix I).

4. Results

4.1. Global and regional patterns of operational carbon change in residential buildings

Fig. 1 reveals the global trends and regional patterns of carbon intensity in residential building operations between 2000 and 2020. Overall, the operational carbon emissions from residential buildings of twelve major emitting regions worldwide (all the samples covering 56 countries) increased by 128.8 megatons of carbon dioxide ($MtCO_2$) in the past two decades, but the operational carbon intensity decreased by 764.3 kgs of carbon dioxide per household ($kgCO_2$/household) with an average decline of 1.2% per yr, and this trend was more pronounced (before 2010: -0.2%, after 2010: -2.2%). At the regional level, the global decrease in carbon intensity was primarily attributed to the developed economies with higher emissions levels, with the most significant decrease occurring in the United States (-4344.9 $kgCO_2$/household, decrease 38.7%), followed by Canada (-2669.7 $kgCO_2$/household, decrease 34.3%), Australia (-2184.0 $kgCO_2$/household, decrease 29.1%), and the Europe & New Zealand (-1713.8 $kgCO_2$/household, decrease 38.1%). In contrast, the major emitters located in Asia have all experienced varying degrees of growth in operational carbon intensity since 2000, for example, in Northeast Asia (48.1 $kgCO_2$/household, increase 1.3%), China (366.7 $kgCO_2$/household, increase 32.6%), and India (488.0 $kgCO_2$/household, increase 57.7%). Concurrently, the operational carbon intensity in South America (55.1 $kgCO_2$/household, increase 5.2%) has increased slightly. Besides, it is important to note that the operational carbon intensity in African countries (South Africa and Morocco) increased strongly (increase 53.4%) in the past two decades and was as high as 5224.5 $kgCO_2$/household in 2020, third only to that in the United States (6883.6 $kgCO_2$/household) and Canada (5311.7 $kgCO_2$/household).

Further details of these regional emission patterns are illustrated in Fig. 1c. From 2000 to 2020, GDP per capita was the most critical

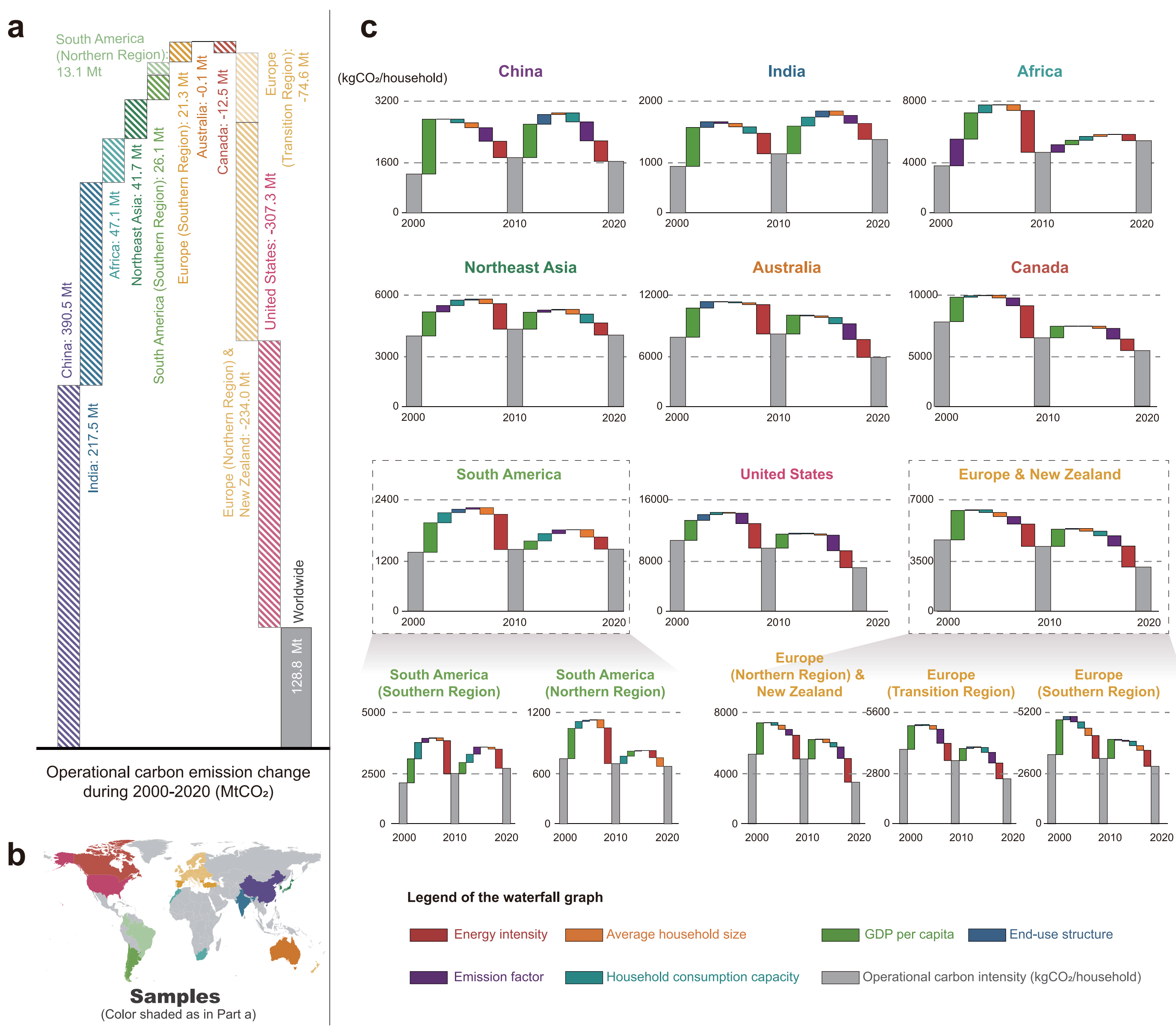

Fig. 1. Global and regional patterns in the carbon emission change of residential building operations: (a) The share of each major emitting region in the total operational carbon emissions change in 2020 compared with 2000; (b) Definition of the twelve emitting regions examined in this study, shaded as in (a); (c) Effects of each driver on the change in operational carbon intensity of global residential buildings in the 2000–2010 and 2010–2020 periods. Note: all the world maps refer from https://www.un.org/geospatial/mapsgeo/generalmaps.

driver increasing the carbon intensity of residential building operations worldwide, which drove the operational carbon intensity of the twelve emitting regions to increase by 56.1 and 26.7% during 2000–2010 and 2010–2020, respectively, especially in emerging economies (e.g., China (140.8 and 60.2%) and India (83.6 and 46.9%)). It is worth noting that the contribution of driving carbon intensity growth has been gradually decreasing due to the decoupling of economic growth and carbon emissions from residential building operations. For instance, it led to an increase in operational carbon intensity by 28.0%, 25.1%, 16.2%, and 10.9% during the periods of 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively. Furthermore, end-use structure was another key to promoting operational carbon intensity, causing the carbon intensity of the twelve emission regions to increase by an average of 4.0% and 1.8% during the 2000–2010 and 2010–2020 periods, respectively. However, energy intensity was the biggest driver in decarbonizing residential building operations, leading to reductions of 20.4, 23.1, 19.8, and 4.3% in carbon intensity during the periods 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively, followed by average household size, which contributed to a 3.8, 2.8, 2.6, and 3.2% reduction in carbon intensity during the same periods. Household consumption capacity and emission factors had an unstable effect on regional change in residential carbon intensity. For instance, while household consumption capacity functioned as a negative contributor in most regions during the period 2000–2005, it served as a positive one in the period 2005–2015. The effect of emission factors on operational carbon intensity was predominantly negative in the majority of 56 countries, indicating significant progress in the decarbonization of residential energy systems. For example, in China, the effect of emission factors on the operational carbon intensity during the periods 2000–2005, 2005–2010, 2010–2015, and 2015–2020 was 17.6%, 16.1%, 21.1%, and 16.1%, respectively. However, it should be noted that Africa, Northeast Asia, and South America exhibited a different trend, suggesting the need for further attention and targeted decarbonization efforts in these regions.

Overall, the above results portray global and regional patterns of operational carbon emissions in residential buildings and respond to Issue 1 posed in Section 1.

4.2. Role of end uses in decarbonizing global residential building operations

To further reveal the effect of each end-use activity on operational carbon intensity in residential buildings and thus seek a practical path for high decarbonization in the building sector, this study investigated the effect of end-use structure and emission factors on the carbon intensity of residential building operations based on different end-use activities. Specifically, based on the decomposition results of carbon intensity provided in Section 4.1, the effects of end-use structure and emission factors were further decomposed into six end-use activities and presented in this section.

Figs. 2 and 1 (see Appendix D) present the effects of the change in end-use structure on the global operational carbon intensity between 2000 and 2020. During the decade 2000–2010 (see Figs. 2a and 1a), the combined effect of the end-use structure contributed to varying degrees (ranging from 2.0 (China) to 920.2 (United States) $kgCO_2$/household) on the increase in carbon intensity of residential building operations in the twelve major emitting regions. Concretely, from 2000 to 2010, the end-use with the largest structural effects contributing to the operational carbon intensity was space heating, which drove an average annual increase in residential buildings' operational carbon intensity of 3.7 $kgCO_2$/household in 56 countries, especially in major emitting regions such as the United States (53.2 $kgCO_2$/household/yr) and Australia (51.9 $kgCO_2$/household/yr), followed by appliances & others (2.6 $kgCO_2$/household/yr worldwide), space cooling (0.8 $kgCO_2$/household/yr worldwide). In contrast, the end-use structure effects from the remaining three end-use activities had a less significant effect on operational carbon intensity. Since 2010 (see Figs. 2b and 1b), the effect of end-use structure on the increase in operational carbon intensity has generally weakened and even reversed in a few regions (e.g., Canada and Australia), with the contribution levels among regions becoming more similar. The reason for this phenomenon is attributed mainly to the contribution of changes in the share of more energy-intensive end uses (space heating, appliances & others, and space cooling) to carbon intensity diminishing and stabilizing after 2010, whereas the effect of less energy-intensive end uses (cooking, lighting, and water heating) on the decarbonization of residential buildings became more pronounced in several emitting regions.

Figs. 3 and 1 (see Appendix E) emphasize the effect of emission factors from different end uses on the operational carbon intensity change in residential buildings across different regions. Overall, emission factors played an important role in decarbonizing residential buildings in most regions of the world, and the effect has increased by 78.2% since 2010, with the most significant effect in the United States, followed by Australia, Canada, Europe & New Zealand, China, and India. Regarding end-use activities (see Figs. 3c and 1c), the largest contributor decarbonizing residential building operations was the emission factor associated with appliances & others (-19.5 $kgCO_2$/household/yr), followed by that associated with space heating (-13.8 $kgCO_2$/household/yr) and lighting (-6.3 $kgCO_2$/household/yr). Regionally, the effect of the emission factors of each end use on decarbonization varied significantly. For instance, most end-use activities in North America (the United States and Canada) contributed more obviously to operational decarbonization in residential buildings than did those in other regions, especially for appliances & others (-110.4 (United States) and -19.0 (Canada) $kgCO_2$/household/yr) and space heating (-31.4 (United States) and -36.6 (Canada) $kgCO_2$/household/yr), which are largely attributed to the local stringent building energy codes and efficiency standards in North America region [45]. For the residential buildings in Australia, the effect of the emission factor from water heating (-42.5 $kgCO_2$/household/yr) on decarbonization was particularly notable and offset the negative effects from space heating (12.1 $kgCO_2$/household/yr). For the Europe & New Zealand, emission factors associated with appliances & others (-20.0 $kgCO_2$/household/yr) and space heating (-19.3 $kgCO_2$/household/yr) made the largest contribution to decarbonization, followed by water heating (-7.9 $kgCO_2$/household/yr), cooking (-4.6 $kgCO_2$/household/yr), and lighting (-3.3 $kgCO_2$/household/yr), while space cooling (-1.2 $kgCO_2$/household/yr) had little effect. In China, emission factors from all end-use activities contributed positively and progressively to decarbonization, with 45.6% of these coming from space heating (-22.4 $kgCO_2$/household/yr), which is attributed to the transition of household heating fuels (e.g., the "coal to gas" action [46]) and heating pump technologies in China since 2000s, especially in northern China [47]. Regarding India, as its number of cooling degree days is much higher than its number of heating degree days and the demand for space cooling is correspondingly obvious [48], the decarbonization effect of residential emission factors came mainly from space cooling (-6.8 $kgCO_2$/household/yr, accounting for 76.9% of the total effect). The latest evidence shows that rapid economic development has driven more electrified households to purchase air conditioners to relieve heat stress [49]. Moreover, for the remaining regions (Africa, South America, and Northeast Asia), emission factors by end uses played an important inhibitory role in decarbonizing residential buildings, especially in less developed Africa, but these effects were declining structurally.

Fig. 1 in Appendix F displays global and regional changes in emission factors for appliances and cooking from 2000 to 2020, reflecting the effect of clean energy applications on different end-use activities. Fig. 1a and c show that end-uses with high electrification, such as appliances (which experienced an average decrease in emission factors of -2.02% per year), have greater potential for decarbonization compared to those with low electrification, such as cooking (which experienced an average decrease in emission factors of -1.14% per year), due to the increased utilization of renewable generation in household electricity consumption, which decarbonizes the final energy use obviously. How-

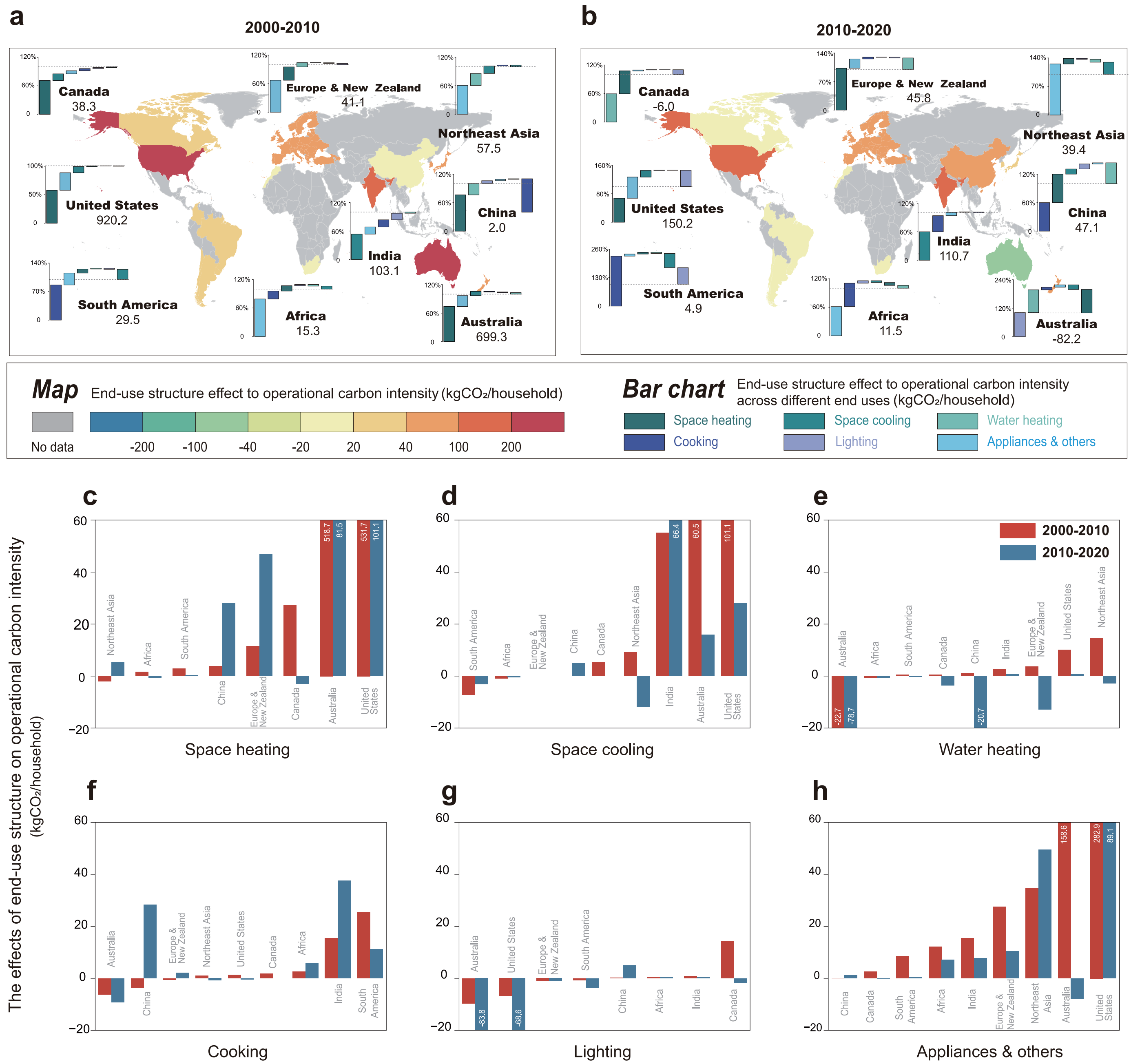

Fig. 2. Effects of end-use structure on the operational carbon intensity change of residential buildings worldwide (total and by end-use activities): (a-b) Total effects of end-use structure on the carbon intensity change of regional residential building operations in 2000–2010 and 2010–2020, respectively; (c-h) Effects of each end-use's share on the carbon intensity change of regional residential building operations in 2000–2010 (blue bars) and 2010–2020 (red bars). Notes: Please refer to Appendix D for information on sub climate-regions in South America and Europe & New Zealand. Due to data availability, space heating was not considered in India, and lighting was not considered in Northeast Asia.

ever, there is a growing trend in the emission factor of cooking in several regions, particularly in Africa, which can be attributed to the increase in the proportion of commercial primary energy, namely coal and natural gas, in this sector and the decline in the proportion of biomass, such as firewood. Hence, decarbonizing end uses with low electrification remains a significant challenge in the global transition towards low-carbon residential building operations.

Overall, over the past two decades, residential end uses have played an increasingly important role in global building decarbonization due to changes in end-use structure and energy efficiency, but the effect of end-use activities on operational carbon intensity has varied markedly between regions. Globally, end-use activities contributed to an average annual reduction in the carbon intensity of global residential buildings of -46.3 kgCO_2/household from 2000 to 2020, with the largest contribution from appliances & others (-17.7 kgCO_2/household/yr), followed by space heating (-9.8 kgCO_2/household/yr), lighting (-5.8 kgCO_2/household/yr), space cooling (-5.1 kgCO_2/household/yr), cooking (-4.0 kgCO_2/household/yr), and water heating (-3.8 kgCO_2/household/yr). These results reveal the role of households' end-use activities in decarbonizing residential building operations in major global regions, answering Issue 2 posed in Section 1.

5. Discussion

As a key component of the global endeavor toward carbon neutrality, an analysis of historical operational carbon emissions from residen-

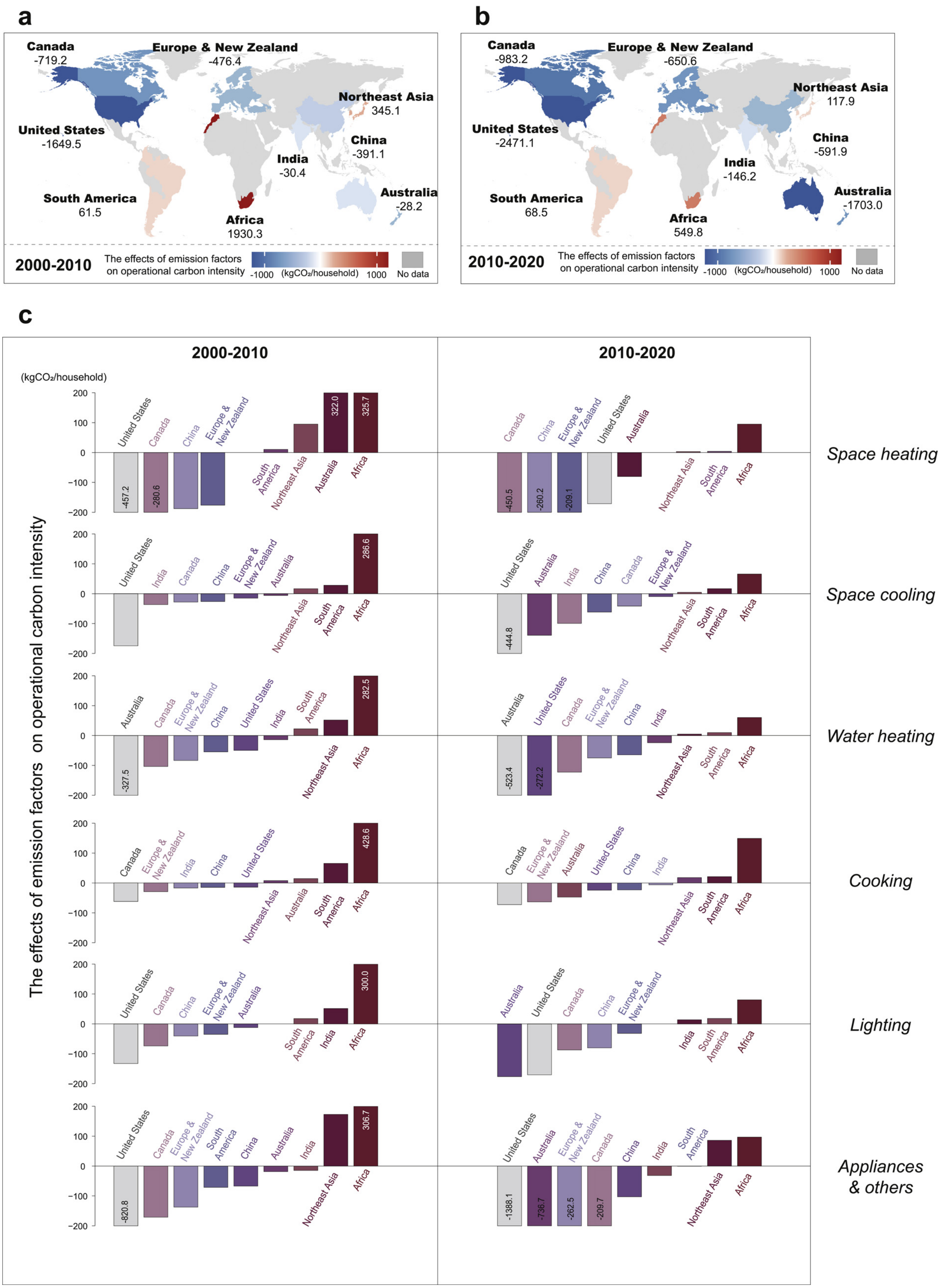

Fig. 3. Effects of emission factors on the carbon intensity change in residential building operations worldwide (total and by end-use activities): (a-b) Total effect of emission factors on the carbon intensity change in regional residential building operations in 2000–2010 and 2010–2020; (c) Effects of each end-use emission factor on the carbon intensity change in regional residential building operations in 2000–2010 and 2010–2020. Notes: Please refer to Appendix E for information on sub climate-regions in South America and Europe & New Zealand. Due to data availability, space heating was not considered in India, and lighting was not considered in Northeast Asia.

tial buildings shows that although carbon intensity has declined overall in twelve major emitting regions during the past two decades, the historical decarbonization performance for these emitters remains unclear. Therefore, Section 5.1 investigates the uncertainty and robustness of the assessment framework proposed in this study to ensure the decarburization results are reliable. Then, Section 5.2 traces global, regional, and national historical decarbonization and further analyzes and compares the results based on different emission scales, given the disparities in emission characteristics across regions or countries. Finally, Section 5.3 further discusses adaptive high decarbonization strategies applied for the global residential building sector.

5.1. Uncertainty analysis and robustness check

Uncertainty analysis and robustness testing are integral components of the assessment framework and the final step in answering Issues 1 and 2 posed in Section 1. These approaches are deployed in this section to further verify the accuracy and reliability of the results.

For the uncertainty analysis, according to the computational procedure of the model framework, the uncertainty of the quantization result depends mostly on whether there is a finite residual value. For the conventional methods, LMDI can be mathematically proven to be a perfect decomposition without errors [50], and the generalized Divisia index method [51] controls the range of residuals of the decomposition by presetting the computational accuracy [52]. DSD attempts to approximate the actual results of numerical integration by setting reasonable parameters, but few studies have discussed the convergence and accuracy of the method. Here, DSD was used to decompose the operational carbon intensity of the nine main modeled regions, and the tunable parameter was selected uniformly in $[1,10]^6$; the evolutionary relationships between uncertainty and parameters are illustrated in Fig. 1 (see Appendix G). With increasing parameter values, the regional decomposition results gradually stabilize, and the error gradually decreases and converges to zero when the parameter exceeds 1000. In addition, when the tunable parameter increases to 16,000, the mean absolute percentage error of the decomposition results is 0.001%. In short, the DSD method used for the framework is an accurate quantification technique.

On the other hand, to further assess the robustness of the estimation results, the classic decomposition analysis method (LMDI) was employed to decompose the building emission model constructed in this study, and the results obtained via LMDI were compared with those generated by DSD. For the detailed calculation procedure of LMDI, refer to the relevant practice hand-book [53] or toolbox [54]. Fig. 1 (see Appendix H) compares the results outputted by the two methods for the nine main modeled regions using regression analysis. All scatters formulated by the decomposition results generated by DSD and LMDI are distributed on the linear fitting curve, and the statistics show an average coefficient of determination (R^2) of 0.98 (ranging from 0.95 to 1) for the regional comparison results, which indicates that the decomposition results of DSD and LMDI are largely consistent. The 95% confidence interval again corroborates the reliability of the results.

Overall, the above uncertainty analysis and robustness check verify the reliability of the results of the framework and Sections 4 and 5.1 completely answer Issues 1 and 2 raised in Section 1.

5.2. Historical decarbonization in global residential building operations

Fig. 4 depicts the historical operational carbon emission trajectory and decarbonization dynamics of global residential buildings over the past two decades. Estimates from the assessment framework presented in this study illustrate that the total decarbonization of global residential buildings showed an overall increasing trend at an average annual rate of a 1.5% change between 2000 and 2020. The annual average total decarbonization was 353.4 (±76.0) $MtCO_2$, and it peaked in 2011, which is equivalent to offsetting 9.4% of global operational carbon emissions over the same period. In other words, if existing efforts to reduce building carbon emissions are ignored, the estimated operational carbon emissions (i.e., the sum of observed carbon emissions plus estimated decarbonization) released from global residential buildings were approximately 1.08–1.12 times the actual observed values today. Throughout the entire study period, the estimated operational carbon emissions in global residential buildings increased from 3.7 $GtCO_2$ in 2000 at an annual rate of 1.3% to peak emissions of 4.2 $GtCO_2$ in 2011 and then maintained a steady downward trend over the past decade. However, some recent near real-time monitoring data [55] suggest that this trend will soon be broken due to a strong rebound in global carbon emissions in the post-COVID-19 period (as embargoes are lifted and economies recover around the world), suggesting that the residential building sector will need to invest more effort in achieving high decarbonization to cope with the upcoming rebound.

Fig. 5 explores in more detail the global, regional, and national historical processes (i.e., the total cumulative decarbonization) of residential building operations over the past two decades to identify specific regions or countries with higher total decarbonization or decarbonization efficiency that are therefore more likely to be attractive mitigation targets. At the global level (Fig. 5a–f), the process of decarbonizing residential building operations has been accelerating: by 2020, the cumulative decarbonization in the residential building sector totaled 7.1 $GtCO_2$ worldwide, which is equivalent to nearly nine times the operational carbon emissions of China's residential buildings in 2020. The top three emitters, China, the United States, and India, consistently led the global residential building decarbonization process, contributing, as a whole, more than half of the global decarbonization (54.0%), whereas the remaining 53 countries were distributed between 1.8 $MtCO_2$ (Malta) and 369.4 $MtCO_2$ (Germany). At a regional level (Fig. 5g–h), from 2000 to 2020, the operational carbon emissions in twelve emitting regions

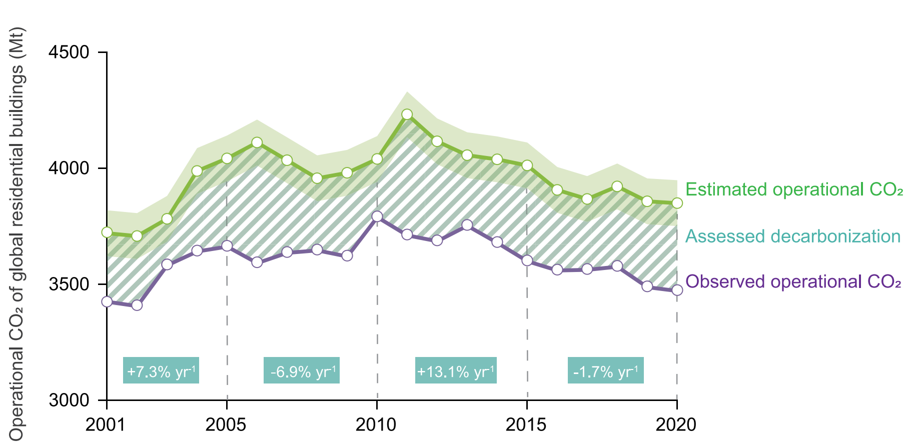

Fig. 4. Temporal evolution of historical operational carbon emission and its decarbonization in global residential buildings (2001–2020). Note: the shading in the line chart indicates one standard deviation.

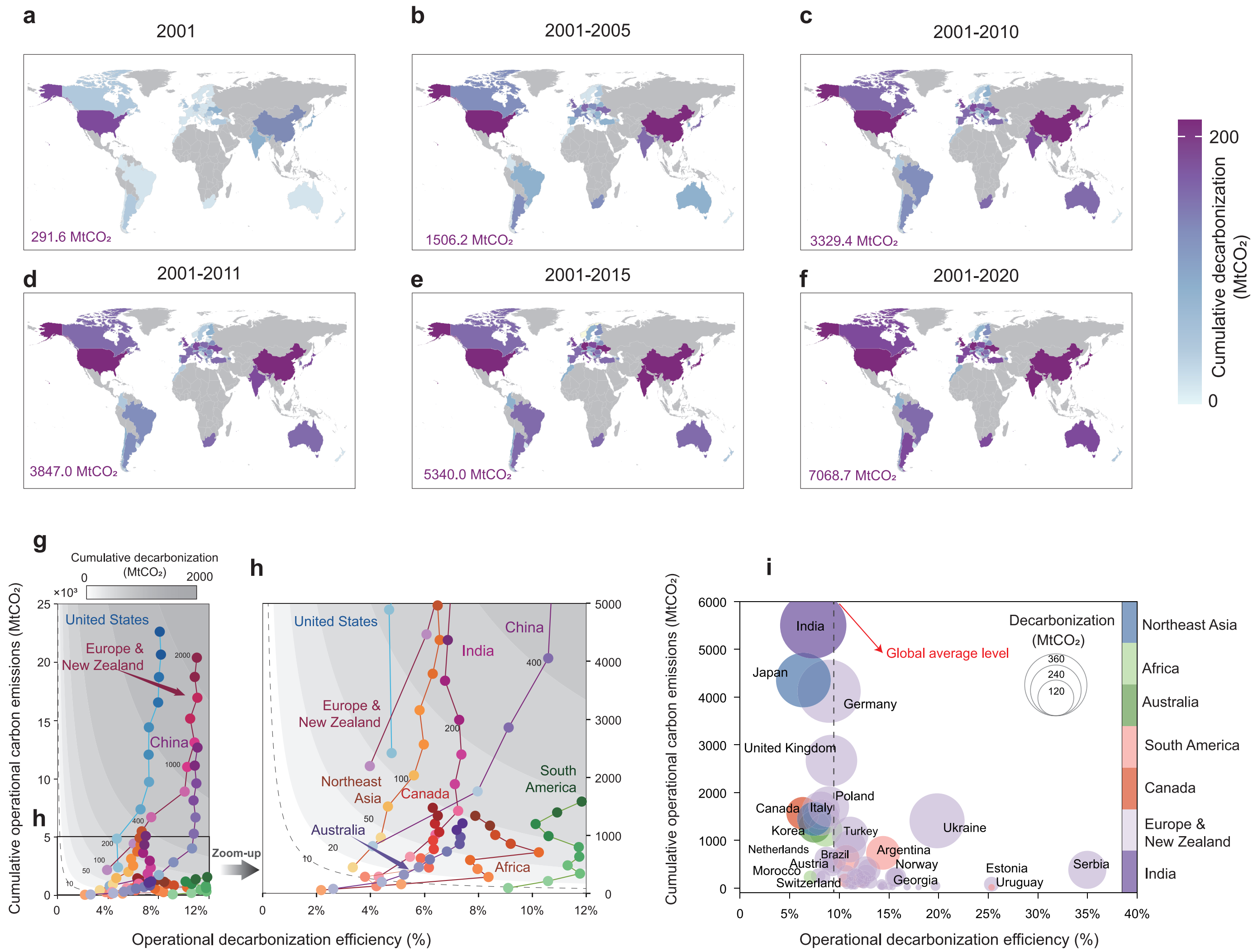

Fig. 5. Global, regional, and national trends in cumulative decarbonization of residential building operations: (a-f) The spatial and temporal evolution of historical decarbonization of global residential buildings (2001–2020); (g-h) Regional trends in cumulative operational decarbonization and the corresponding decarbonization efficiency from 2001 to 2020 (light to dark colored dots); (i) Cumulative decarbonization and the corresponding decarbonization efficiency across emitters during the period 2001–2020. Notes: the figures in the lower-left corner of (a–f) indicate the total global cumulative decarbonization in the corresponding time periods. Background contours in (g–h) are in units of cumulative decarbonization. The cumulative carbon emissions for the United States (23.5 $GtCO_2$, decarbonization efficiency: 8.1%) and China (13.5 $GtCO_2$, 11.1%) are not plotted in (i) due to scale limitations.

rose rapidly, and the decarbonization efficiency in most regions began to stabilize after 2010. Specifically, the cumulative decarbonization of the three emission giants, the United States, Europe & New Zealand, and China, consistently led the other major emitting regions, with their cumulative total decarbonization accounting for 81.3% of the total global decarbonization. Despite the relatively low operational carbon emissions of residential buildings in China, their decarbonization efficiency (11.1%) was similar to that of Europe & New Zealand (11.0%) and even approximately 3 percentage points higher than that of the United States (8.1%), and also higher than that of other emitting regions. For the remaining emission regions (as shown in Fig. 5h), the residential building operations with the highest decarbonization efficiency were in South America (11.8%), followed by Africa (7.9%), Australia (7.4%), India (7.0%), and Northeast Asia (6.7%), while the lowest decarbonization efficiency was observed in Canada (6.3%), with a higher emission level. Fig. 5i analyzes the decarbonization potential of different economies at a national level, and it is worth noting that China and the United States, as the top two emitters, contributed nearly half (48.6%) of the global total decarbonization, whereas the decarbonization efficiency of larger emitters such as India, Japan, Germany, and the United Kingdom were all approximately 6–9%, which was below the global average level (9.4%). In contrast, some emerging emitters had higher decarbonization potential, for example, Serbia (34.9%), Uruguay (25.3%), Estonia (25.3%), and Ukraine (19.8%), which is expected to become the hot spot in the age of post-COP 27[1].

Moreover, Fig. 6 further analyzes and compares the decarbonization level of residential building operations worldwide at different emission scales (total decarbonization, decarbonization intensity, and decarbonization per capita). Overall, as shown in Fig. 6a–i, the assessment results at different emission scales varied significantly and showed remarkable regional heterogeneity. Globally, from 2000 to 2020, although the total decarbonization of residential buildings generally increased, decarbonization per capita and decarbonization per household gradually stabilized or even decreased, and by 2020, the global decarbonization of residential building operations totaled 374.9 $MtCO_2$, and the decarbonization intensity and decarbonization per capita were

[1] COP 27 is the abbreviation of 2022 United Nations Climate Change Conference.

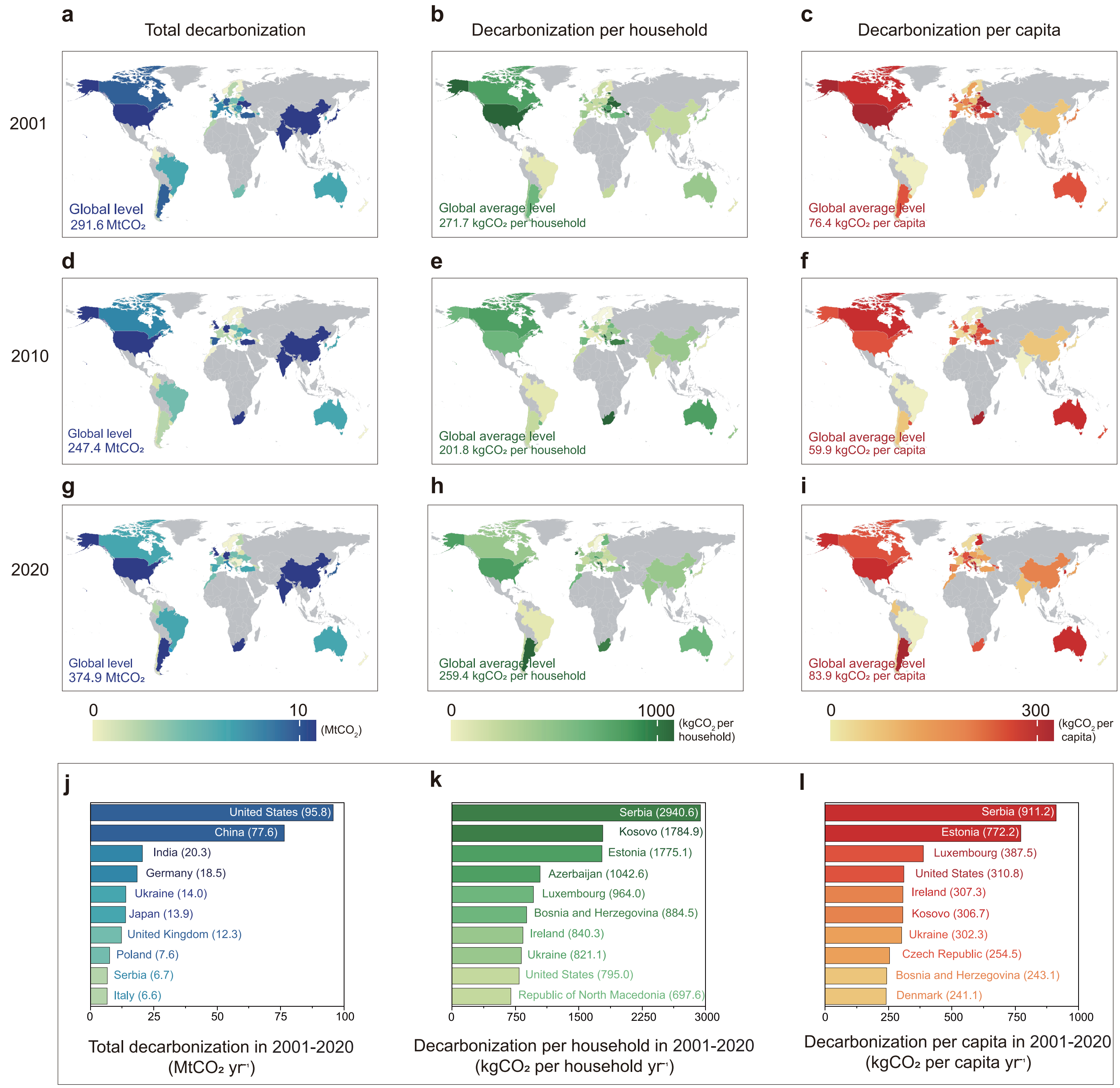

Fig. 6. Multiscale assessment of the historical decarbonization level of global residential building operations: (a-i) Temporal evolution of historical decarbonization levels in global residential buildings by (a, d, g) total decarbonization, (b, e, h) decarbonization per household, and (c, f, i) decarbonization per capita; (j–l) Top 10 countries in average annual decarbonization level of global residential building operations across different emission scales.

259.4 $kgCO_2$/household and 83.9 $kgCO_2$ per capita, respectively. Regionally, although the total decarbonization levels in China and the United States were relatively close, their decarbonization trends were diametrically opposed, with China's total decarbonization maintaining a steady increase at an average annual growth rate of 9.3% during the past two decades, whereas the opposite was true for the United States (-1.2%). In addition, total decarbonization rose rapidly in most emerging economies, especially in South Africa (37.3%) and India (12.6%), whereas the total decarbonization in most developed countries, such as the United Kingdom, Germany, Italy, and Japan, started to decline after peaking in 2010. In contrast, the decarbonization intensity and decarbonization per capita were relatively close and stable across countries, and the economies with higher decarbonization intensity or decarbonization per capita were mainly clustered in Europe. Fig. 6j–l present the top ten countries with the highest average annual decarbonization levels at three different emission scales and reveal that the countries with higher total decarbonization of residential buildings were not necessarily the ones with higher decarbonization intensity or decarbonization per capita, especially in developing countries. For instance, although China and India were second only to the United States in total annual average decarbonization of residential buildings, their decarbonization per capita and decarbonization per household of residential building operations were less than one-fifth that of the United States and were at the bottom of the list globally. A similar mismatch can be observed in Brazil's residential buildings, where total decarbonization was higher than that of most countries, despite having the lowest decarbonization per capita and decarbonization per household of the 56 countries. Conversely, most small European countries, such as Serbia and Estonia, had higher decarbonization intensity and decarbonization per capita despite their low total decarbonization. Furthermore, the decarbonization levels of the United States, Ukraine, and Serbia were relatively high at three scales and were all in the top ten, whereas decarbonization levels were poor at all emission scales in less developed economies with high carbon intensity, such as Morocco, Uruguay, and Albania.

It should be noted that the proposed assessment framework in this study exhibits several limitations. First, the investigation primarily scrutinized the emission patterns and historical decarbonization levels of residential buildings in 56 countries over the period from 2000 to 2020. All countries were aggregated into twelve major regions, which diluted the spatial resolution and yielded a somewhat biased global perspective. Further research could estimate the remaining variation within larger estimated world regions, such as China and the United States, or perform case studies at a global level. Furthermore, given the existing regional inequalities in global operational decarbonization and unprecedented pace of urbanization, cities will be the primary focus of future high decarbonization efforts. Therefore, considerably more city-level work must be conducted to achieve building carbon neutrality, particularly in developing countries.

Overall, the above discussion reviews and compares the global, regional, and national decarbonization performance of residential building operations, providing an initial response to Issue 3 posed in Section 1.

5.3. High decarbonization strategies applied for global residential building operations

Currently, 137 countries worldwide have committed to achieving carbon neutrality by approximately 2050. For carbon neutrality in the building sector, a growing number of countries have committed to modifying buildings and regulations as part of their nationally determined contributions. To date, 79 out of 196 countries or regions have mandatory or voluntary regulations or codes for building energy efficiency. Although these extensive efforts have raised the national ambition levels for building carbon neutrality, there remains a lack of accurate historical decarbonization benchmarks to guide the building sector toward a transition to a zero-emission, efficient and flexible model.

The assessment results of this study indicate that the global carbon intensity of residential building operations has generally decreased in the past two decades, especially in developed countries, while it is still increasing slowly in developing countries. Since the year 2000, due to the marginal effect of socioeconomic and technological drivers on carbon abatement, such as population expansion, economic growth, increases in living standards, and energy efficiency improvements, global residential building operations have decarbonized 7.1 $GtCO_2$, and the decarbonization process is accelerating, with the United States and China dominating the global decarbonization process. However, the differences in their decarbonization trends and efficiencies are significant. Moreover, decarbonization in emerging economies such as India is also rapidly emerging. The disproportionate nature of decarbonization efficiency further portrays the regional differences and inequality in decarbonization potential. Residential buildings with higher decarbonization efficiency are often found in countries or regions that are overlooked, while most developed countries still have decarbonization efficiencies below the global average. This can be attributed to the early implementation of decarbonization measures in these countries and the diminishing marginal effect of these measures' decarbonization. Nevertheless, significant potential for emission reduction and mitigation remains in developed countries. Therefore, they should take more responsibility for achieving deep decarbonization and creating more emission space for the development of emerging economies. Hence, these countries should take more responsibility for decarbonization and free up more emission space for the development of emerging economies. The bottom-up assessment framework also reveals that the various end-use activities of residential households play a critical role in the decarbonization of residential building operations globally, especially for appliances, space heating, and lighting.

Despite the decline in carbon intensity and notable decarbonization achievements in global residential buildings since 2000, the current decarbonization process is still far from the emission reductions needed to align with the Paris Agreement's 1.5–2° target, and this historical gap varies across emitting regions. On the other hand, as the building sector gradually recovers in the post-COVID-19 era, there is a great risk that pent-up demand in the residential building operation could be released or even rebound [56], especially in emerging economies with substantial potential energy demand. Therefore, to further accelerate the decarbonization pace of the global residential sector and close the ambition gap across countries, continued efforts to optimize the residential end-use structure and improve energy efficiency are still needed; thus, the following recommendations are offered for residential buildings:

(a) Electrification of residential end uses. Heat pump systems provide the most cost-effective decarbonization opportunities and pathways for heating and cooling needs in residential building operations [57]. For areas with low heat density, air source heat pumps, water source heat pumps, and ground source heat pumps should be used to reduce the decarbonization costs of heating and cooling, whereas for residential buildings with high heat density, low-grade energy sources should be maximized, including combined heat and power production, industrial waste heat, and waste incineration waste heat, such as 5th generation district heat and cold grids in Europe [58]. For cooking, advanced electric cooking technologies such as induction cookers and microwave ovens should be used to replace coal-fired cookers and traditional biomass cookers [59].

(b) Decarbonizing electricity supply. The proportion of zero-carbon alternative energy sources such as renewable energy (e.g., wind power [60], photovoltaic [61]) and nuclear power should be vigorously increased [62]. There should also be a significant increase in building photovoltaic power generation, developing integrated photovoltaics technology [63] and constructing residential buildings that integrate distributed photovoltaic power generation, distributed energy storage, low-voltage DC power distribution, and flexible power consumption [64]; these factors improve the resilience of buildings [65]. We believe electrification with the corresponding energy decarbonization is the key to building carbon neutrality [66], especially for the emerging economies: according to Fig. 6, China and India ranked 2nd and 3rd worldwide in total decarbonization of residential building operations. However, their performance in terms of per capita and per household decarbonization was not significant. This is concerning, particularly for high-population economies such as China and India, whose large residential building stocks may face the risk of operational carbon lock-in the future. Achieving carbon neutrality as early as possible is a significant challenge for these emerging economies, and it is crucial to accelerate the electrification of residential buildings and the decarbonization of power systems. This measure is necessary to achieve carbon neutrality in a practical way, subject to the availability of technological and financial resources [67]. Furthermore, some latest reports [2] show that the above measure is effective, and building electrification with clean electricity supply is booming in the African households.

(c) Improving the thermal performance. Passive ultralow energy, near-zero energy, and zero energy buildings should be vigorously developed to reduce the demand for heating, air conditioning, and lighting in households [68]. New wall materials can be adopted to design high-performance building envelope structures to enhance building energy efficiency [69]. The above measures are particularly beneficial for residential buildings that may not be suitable for extensive electrification retrofitting. In regions where active strategies like building electrification may not be cost-effective (e.g., some sever cold zones of the north China), passive strategies can be explored as a viable solution. Enhancing the thermal performance of buildings to reduce energy demand and associated emissions is one such passive strategy worth considering.

(d) Using efficient equipment and appliances. For lighting, more energy-efficient light-emitting diode lights should replace existing lighting equipment and be used for cooling. For cooling, storage systems based on phase change materials can be used to replace existing cooling technologies [70]. Moreover, more stringent building energy efficiency standards should be set, such as the Title 24 Act enacted in California [71].

(e) Carbon sequestration technology for green residences. Carbon capture and storage technologies should be vigorously developed for residential buildings to expand the carbon reduction and sequestration potential of buildings, such as increasing and protecting plant communities in residential areas [72], increasing carbon sinks in building green spaces (e.g., rooftop gardens [73] and vertical greening [74]), and using carbon-fixing building materials (e.g., recycled concrete [75] and eco-cement [76]) to absorb and consume residential carbon emissions.

Overall, this study reviews and compares the historical process and current status of decarbonization of residential building operations worldwide and further provides corresponding high decarbonization strategies to rapidly push future global residential buildings toward net-zero emissions, thus fully answering Issue 3 raised in Section 1.

6. Conclusion

This study developed a bottom-up modeling framework from the demand side to assess the decarbonization process of residential building operations in 56 countries worldwide over the past two decades. First, the DSD approach was integrated to characterize the evolutionary pattern of operational carbon intensity. Then, the uncertainty and robustness of the proposed assessment framework were discussed. Moreover, this work assessed and compared the global, regional, and national historical decarbonization performance and the corresponding potential in residential building operations. Finally, the decarbonization strategies of global residential buildings were further discussed given the current decarbonization progress. The key findings are summarized below:

6.1. Key findings

- The operational carbon intensity of global residential buildings continued to decline from 2000 to 2020, dominated by developed regions with higher carbon intensity. Over the past two decades, the carbon intensity of residential building operations in the twelve emitting regions declined by 764.3 $kgCO_2$/household, with an average annual change of 1.2%, mostly attributed to developed economies with high carbon intensity such as United States, Canada, and Europe & New Zealand, while the operational carbon intensity in developing economies located in Asia and Africa still increased. Regarding the drivers behind these regional changes, energy intensity and average household size were the largest contributors decarbonizing global residential building operations, and GDP per capita was the most critical factor driving the increase in carbon emissions in all emitting regions, especially in developing regions.
- End-use activities held an increasingly important role in decarbonizing global residential buildings, with the largest contribution from appliances & others (-17.7 $kgCO_2$/household/yr), followed by space heating (-9.8 $kgCO_2$/household/yr) and lighting (-5.8 $kgCO_2$/household/yr). Due to changes in the energy structure and energy efficiency of residential end uses, the effect of end-use structure on the increase in carbon intensity in the twelve emission regions has gradually weakened since 2010, even reversing from an initial positive effect on a negative contribution in individual regions (Canada and Australia). In addition, the emission factors across end uses have led to a continuous decline in operational carbon intensity in most emitting regions (especially for space heating and appliances), and this effect has further strengthened over the past decade.
- The decarbonization process of global residential building operations accelerated. In 2020, the decarbonization from residential building operations across 56 economies was 259.4 $kgCO_2$/household or 83.9 $kgCO_2$ per capita. Globally, residential building operations cumulatively decarbonized 7.1 $GtCO_2$ with a decarbonization efficiency of 9.4%, which is equivalent to approximately nine times the operational carbon of China's residential buildings in 2020, with nearly 80% of this decarbonization coming from the top three emission giants, including United States, China, and Europe & New Zealand. At a national level, the larger emitters (the United States, China, and India) were less efficient in terms of decarbonization, while those with higher decarbonization efficiency tended to be the emerging emitters (Serbia and Ukraine) that are easily overlooked. The multiscale assessment shed light on the regional imbalances in decarbonizing global residential building operations, such that most emerging economies had high total decarbonization, but their decarbonization intensity and decarbonization per capita remained at the bottom of the global scale.

6.2. Future work

As mentioned in Section 5.2, several questions remain unanswered and should be addressed in future work. First, continuous high-frequency monitoring and quantification of operational carbon emissions from residential buildings should be performed to closely monitor and evaluate the effectiveness of climate-action efforts in mitigating potential emissions. Additionally, a data-driven scenario framework should continue to be developed to explore future decarbonization roadmaps toward a carbon-neutral century.

Appendix

Please find the appendix in the supplementary materials (e-component) of this submission.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2023.100145.

References

[1] Terhaar J, Frölicher TL, Aschwanden MT, Friedlingstein P, Joos F. Adaptive emission reduction approach to reach any global warming target. Nat Clim Chang 2022;12:1136–42.
[2] IEA. 2022 Global status report buildings and construction, https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction; 2022 [accessed November 20].
[3] Berrill P, Wilson EJH, Reyna JL, Fontanini AD, Hertwich EG. Decarbonization pathways for the residential sector in the United States. Nat Clim Chang 2022;12:712–18.
[4] Wu W, Skye HM. Residential net-zero energy buildings: review and perspective. Renew Sustain Energy Rev 2021;142:110859.
[5] Evans M, Roshchanka V, Graham P. An international survey of building energy codes and their implementation. J Clean Prod 2017;158:382–9.
[6] Zhong X, Hu M, Deetman S, Steubing B, Lin HX, Hernandez GA, et al. Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. Nat Commun 2021;12:6126.
[7] Wang J, Zhong H, Yang Z, Wang M, Kammen DM, Liu Z, et al. Exploring the trade-offs between electric heating policy and carbon mitigation in China. Nat Commun 2020;11:6054.
[8] Ebrahimi S, Mac Kinnon M, Brouwer J. California end-use electrification impacts on carbon neutrality and clean air. Appl Energy 2018;213:435–49.
[9] Mittelviefhaus M, Georges G, Boulouchos K. Electrification of multi-energy hubs under limited electricity supply: de-/centralized investment and operation for cost-effective greenhouse gas mitigation. Adv Appl Energy 2022;5:100083.
[10] Jing R, Hua W, Lin J, Lin J, Zhao Y, Zhou Y, et al. Cost-efficient decarbonization of local energy systems by whole-system based design optimization. Appl Energy 2022;326:119921.
[11] Wang H, Chen W, Shi J. Low carbon transition of global building sector under 2- and 1.5-degree targets. Appl Energy 2018;222:148–57.
[12] Pye S, Li FGN, Price J, Fais B. Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era. Nat Energy 2017;2:17024.
[13] Yan R, Chen M, Xiang X, Feng W, Ma M. Heterogeneity or illusion? Track the carbon Kuznets curve of global residential building operations. Appl Energy 2023 Forthcoming.
[14] Roelfsema M, van Soest HL, Harmsen M, van Vuuren DP, Bertram C, den Elzen M, et al. Taking stock of national climate policies to evaluate implementation of the Paris Agreement. Nat Commun 2020;11:2096.
[15] Pauliuk S, Heeren N, Berrill P, Fishman T, Nistad A, Tu Q, et al. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. Nat Commun 2021;12:5097.
[16] Khanna TM, Baiocchi G, Callaghan M, Creutzig F, Guias H, Haddaway NR, et al. A multi-country meta-analysis on the role of behavioural change in reducing energy consumption and CO2 emissions in residential buildings. Nat Energy 2021;6:925–32.
[17] Camarasa C, Mata É, Navarro JPJ, Reyna J, Bezerra P, Angelkorte GB, et al. A global comparison of building decarbonization scenarios by 2050 towards 1.5–2 °C targets. Nat Commun 2022;13:3077.
[18] Jing R, Zhou Y, Wu J. Electrification with flexibility towards local energy decarbonization. Adv Appl Energy 2022;5:100088.
[19] You K, Yu Y, Li Y, Cai W, Shi Q. Spatiotemporal decomposition analysis of carbon emissions on Chinese residential central heating. Energy Build 2021;253:111485.
[20] Schipper L, Ting M, Khrushch M, Golove W. The evolution of carbon dioxide emissions from energy use in industrialized countries: an end-use analysis. Energy Policy 1997;25:651–72.
[21] Greening LA, Ting M, Krackler TJ. Effects of changes in residential end-uses and behavior on aggregate carbon intensity: comparison of 10 OECD countries for the period 1970 through 1993. Energy Econ 2001;23:153–78.
[22] Fan JL, Liao H, Liang QM, Tatano H, Liu CF, Wei YM. Residential carbon emission evolutions in urban–rural divided China: an end-use and behavior analysis. Appl Energy 2013;101:323–32.
[23] Berrill P, Gillingham KT, Hertwich EG. Drivers of change in US residential energy consumption and greenhouse gas emissions, 1990–2015. Environ Res Lett 2021;16 034045.
[24] Shimoda Y, Sugiyama M, Nishimoto R, Momonoki T. Evaluating decarbonization scenarios and energy management requirement for the residential sector in Japan through bottom-up simulations of energy end-use demand in 2050. Appl Energy 2021;303:117510.
[25] Xu XY, Ang BW. Analysing residential energy consumption using index decomposition analysis. Appl Energy 2014;113:342–51.
[26] Waite M, Modi V. Electricity load implications of space heating decarbonization pathways. Joule 2020;4:376–94.
[27] Mastrucci A, Byers E, Pachauri S, Rao ND. Improving the SDG energy poverty targets: residential cooling needs in the Global South. Energy Build 2019;186:405–15.
[28] Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. Renew Sustain Energy Rev 2009;13:1819–35.
[29] Reyna JL, Chester MV. Energy efficiency to reduce residential electricity and natural gas use under climate change. Nat Commun 2017;8:14916.
[30] Khanna N, Fridley D, Zhou N, Karali N, Zhang J, Feng W. Energy and CO2 implications of decarbonization strategies for China beyond efficiency: modeling 2050 maximum renewable resources and accelerated electrification impacts. Appl Energy 2019;242:12–26.
[31] Chung W, Kam MS, Ip CY. A study of residential energy use in Hong Kong by decomposition analysis, 1990–2007. Appl Energy 2011;88:5180–7.
[32] Vaninsky A. Factorial decomposition of CO_2 emissions: a generalized Divisia index approach. Energy Econ 2014;45:389–400.
[33] Ma M, Feng W, Huo J, Xiang X. Operational carbon transition in the megalopolises' commercial buildings. Build Environ 2022;226:109705.
[34] Boratyński J. Decomposing structural decomposition: the role of changes in individual industry shares. Energy Econ 2021;103:105587.
[35] Li H, Wang Z, Hong T, Piette MA. Energy flexibility of residential buildings: a systematic review of characterization and quantification methods and applications. Adv Appl Energy 2021;3:100054.
[36] Nie H, Kemp R. Index decomposition analysis of residential energy consumption in China: 2002–2010. Appl Energy 2014;121:10–19.
[37] Xiang X, Ma M, Ma X, Chen L, Cai W, Feng W, et al. Historical decarbonization of global commercial building operations in the 21st century. Appl Energy 2022;322:119401.
[38] Zhou N, Khanna N, Feng W, Ke J, Levine M. Scenarios of energy efficiency and CO_2 emissions reduction potential in the buildings sector in China to year 2050. Nat Energy 2018;3:978–84.
[39] Langevin J, Harris CB, Reyna JL. Assessing the potential to reduce U.S. building CO_2 emissions 80% by 2050. Joule 2019;3:2403–24.
[40] Wang R, Feng W, Wang L, Lu S. A comprehensive evaluation of zero energy buildings in cold regions: actual performance and key technologies of cases from China, the US, and the European Union. Energy 2021;215:118992.
[41] Fujimori S, Kainuma M, Masui T, Hasegawa T, Dai H. The effectiveness of energy service demand reduction: a scenario analysis of global climate change mitigation. Energy Policy 2014;75:379–91.
[42] Luderer G, Vrontisi Z, Bertram C, Edelenbosch OY, Pietzcker RC, Rogelj J, et al. Residual fossil CO_2 emissions in 1.5–2 °C pathways. Nat Clim Chang 2018;8:626–33.
[43] Levesque A, Pietzcker RC, Baumstark L, Luderer G. Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5°C scenario. Environ Res Lett 2021;16 054071.
[44] Li K, Ma M, Xiang X, Feng W, Ma Z, Cai W, et al. Carbon reduction in commercial building operations: a provincial retrospection in China. Appl Energy 2022;306:118098.
[45] Li H, Hong T. A semantic ontology for representing and quantifying energy flexibility of buildings. Adv Appl Energy 2022;8:100113.
[46] Zou C, Ma M, Zhou N, Feng W, You K, Zhang S. Toward carbon free by 2060: a decarbonization roadmap of operational residential buildings in China. Energy 2023;277:127689.
[47] Zhang Q, Zhang L, Nie J, Li Y. Techno-economic analysis of air source heat pump applied for space heating in northern China. Appl Energy 2017;207:533–42.
[48] Mehmood S, Lizana J, Núñez-Peiró M, Maximov SA, Friedrich D. Resilient cooling pathway for extremely hot climates in Southern Asia. Appl Energy 2022;325:119811.
[49] Pavanello F, De Cian E, Davide M, Mistry M, Cruz T, Bezerra P, et al. Air-conditioning and the adaptation cooling deficit in emerging economies. Nat Commun 2021;12:6460.
[50] Zhang S, Ma M, Xiang X, Cai W, Feng W, Ma Z. Potential to decarbonize the commercial building operation of the top two emitters by 2060. Resour Conserv Recycl 2022;185:106481.
[51] Yan R, Xiang X, Cai W, Ma M. Decarbonizing residential buildings in the developing world: historical cases from China. Sci Total Environ 2022;847:157679.
[52] Chen L, Ma M, Xiang X. Decarbonizing or illusion? How carbon emissions of commercial building operations change worldwide. Sustain Cities Soc 2023;96:104654.
[53] Ang BW. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 2005;33:867–71.
[54] Xiang X, Ma X, Ma Z, Ma M, Cai W. Python-LMDI: a tool for index decomposition analysis of building carbon emissions. Buildings 2022;12:83.
[55] Liu Z, Deng Z, Zhu B, Ciais P, Davis SJ, Tan J, et al. Global patterns of daily CO_2 emissions reductions in the first year of COVID-19. Nat Geosci 2022;15:615–20.
[56] Davis SJ, Liu Z, Deng Z, Zhu B, Ke P, Sun T, et al. Emissions rebound from the COVID-19 pandemic. Nat Clim Chang 2022;12:412–14.
[57] Chua KJ, Chou SK, Yang WM. Advances in heat pump systems: a review. Appl Energy 2010;87:3611–24.
[58] Wirtz M, Neumaier L, Remmen P, Müller D. Temperature control in 5th generation district heating and cooling networks: an MILP-based operation optimization. Appl Energy 2021;288:116608.
[59] Tang BJ, Guo YY, Yu B, Harvey LDD. Pathways for decarbonizing China's building sector under global warming thresholds. Appl Energy 2021;298:117213.
[60] Ma X, Lu H, Ma M, Wu L, Cai Y. Urban natural gas consumption forecasting by novel wavelet-kernelized grey system model. Eng Appl Artif Intell 2023;119:105773.
[61] Zhang K, Prakash A, Paul L, Blum D, Alstone P, Zoellick J, et al. Model predictive control for demand flexibility: real-world operation of a commercial building with photovoltaic and battery systems. Adv Appl Energy 2022;7:100099.
[62] Johnson SC, Papageorgiou DJ, Harper MR, Rhodes JD, Hanson K, Webber ME. The economic and reliability impacts of grid-scale storage in a high penetration renewable energy system. Adv Appl Energy 2021;3:100052.
[63] Skandalos N, Karamanis D. An optimization approach to photovoltaic building integration towards low energy buildings in different climate zones. Appl Energy 2021;295:117017.
[64] Jing R, Wang J, Shah N, Guo M. Emerging supply chain of utilising electrical vehicle retired batteries in distributed energy systems. Adv Appl Energy 2021;1:100002.

[65] Von Wald G, Sundar K, Sherwin E, Zlotnik A, Brandt A. Optimal gas-electric energy system decarbonization planning. Adv Appl Energy 2022;6:100086.
[66] Zhang S, Zhou N, Feng W, Ma M, Xiang X, You K. Pathway for decarbonizing residential building operations in the US and China beyond the mid-century. Appl Energy 2023;342:121164.
[67] Jing R, Wang X, Zhao Y, Zhou Y, Wu J, Lin J. Planning urban energy systems adapting to extreme weather. Adv Appl Energy 2021;3:100053.
[68] You K, Yu Y, Cai W, Liu Z. The change in temporal trend and spatial distribution of CO2 emissions of China's public and commercial buildings. Build Environ 2023;229:109956.
[69] Henry A, Prasher R, Majumdar A. Five thermal energy grand challenges for decarbonization. Nat Energy 2020;5:635–7.
[70] Safari A, Saidur R, Sulaiman FA, Xu Y, Dong J. A review on supercooling of Phase Change Materials in thermal energy storage systems. Renew Sustain Energy Rev 2017;70:905–19.
[71] Wei M, Lee SH, Hong T, Conlon B, McKenzie L, Hendron B, et al. Approaches to cost-effective near-net zero energy new homes with time-of-use value of energy and battery storage. Adv Appl Energy 2021;2:100018.
[72] Chen WY. The role of urban green infrastructure in offsetting carbon emissions in 35 major Chinese cities: a nationwide estimate. Cities 2015;44:112–20.
[73] Berardi U, GhaffarianHoseini A, GhaffarianHoseini A. State-of-the-art analysis of the environmental benefits of green roofs. Appl Energy 2014;115:411–28.
[74] Pérez G, Rincón L, Vila A, González JM, Cabeza LF. Green vertical systems for buildings as passive systems for energy savings. Appl Energy 2011;88:4854–9.
[75] Oh DY, Noguchi T, Kitagaki R, Park WJ. CO_2 emission reduction by reuse of building material waste in the Japanese cement industry. Renew Sustain Energy Rev 2014;38:796–810.
[76] Scrivener KL, John VM, Gartner EM. Eco-efficient cements: potential economically viable solutions for a low-CO_2 cement-based materials industry. Cem Concr Res 2018;114:2–26.