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Historical decarbonization of global commercial building operations in the 21st century

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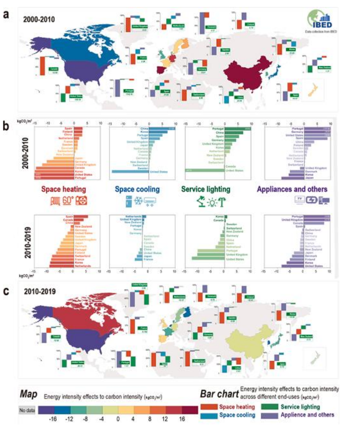
HIGHLIGHTS

- The carbon intensity of commercial building operations in 16 economies declined 1.9 % yr^{-1} in 2000–2019.
- Emission factors and industrial structure were the key to decarbonizing the building operations.
- Energy intensity (e.g., heating: −14.3 $kgCO_2/m^2/yr$) has pushed global decarbonization since the 2010 s.
- Decarbonization level in 16 economies was 230.3 $MtCO_2/yr$ with a decarbonization efficiency of 10.1%;
- Electricity decarbonization will be critical to achieving global carbon neutrality in commercial buildings.

GRAPHICAL ABSTRACT



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ABSTRACT

Building operations will be the most critical step in completing the "last mile" of global carbon neutrality. To seek the best practical path to decarbonize commercial building operations, this study assesses the decarbonization progress of commercial building operations in 16 countries over the last two decades considering socioeconomic, technical, climatic and end-use factors through the decomposing structural decomposition method. The results reveal that (1) the average carbon intensity of commercial building operations in 16 countries has maintained an annual decline of 1.94% throughout the period 2000–2019, and emission factors and industrial structures were generally the key to decarbonizing commercial building operations; (2) energy intensity effects have started to promote global decarbonization in commercial building operations since 2010, with

Abbreviations: DSD, Decomposing structural decomposition; GDIM, Generalized Divisia index method; GDP, Gross domestic product; HVAC, Heating, ventilation, and air conditioning; IBED, International Building Emission Dataset; IDA, Index decomposition analysis; LMDI, Log-mean Divisia index; SDA, Structure decomposition analysis.

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contributions from space heating [-14.33 kg of carbon dioxide per square meter per year ($kgCO_2/m^2/yr$)], service lighting (-5.29 $kgCO_2/m^2/yr$), appliances and others (-2.85 $kgCO_2/m^2/yr$), and space cooling (-1.24 $kgCO_2/m^2/yr$); and (3) the total decarbonization of commercial building operations worldwide was 230.28 mega-tons of carbon dioxide per yr, with a decarbonization efficiency of 10.05% in 2001–2019. Moreover, the robustness of this decarbonization assessment is tested using the typical index decomposition analysis and the decarbonization strategies of global commercial building operations are reviewed. Overall, this study assesses the global historical progress in decarbonizing commercial building operations and closes the relevant gap, and it helps plan the stepwise carbon neutral pathway of future global buildings by the mid-century.

Nomenclature

C	Carbon emissions
$C_j(j = 1, 2, 3, 4)$	Carbon emissions released by space heating, space cooling, service lighting, or appliances and others
c	Carbon intensity
ΔDC	Total decarbonization
ΔDC_i	Decarbonization intensity
E	Energy consumption
$E_j(j = 1, 2, 3, 4)$	Energy consumption by space heating, space cooling, service lighting, or appliances and others
e	Energy intensity
F	Floor space
G	Gross domestic product
G_s	Service industry added value
g	Gross domestic product per capita
i	Economic efficiency
K	Emission factor
$kgCO_2$	Kilograms of carbon dioxide
$MtCO_2$	Mega-tons of carbon dioxide
P	Population size
p	Population density
s	Industrial structure

1. Introduction

Achieving net-zero emissions by mid-century is an important guarantee to meet the Paris Agreement's goal of limiting global warming well below 2℃ and pursuing efforts toward 1.5℃ [1]. The building sector is considered the "last mile" of the roadmap toward the carbon neutrality century, with commercial buildings being among the more energy-consuming sectors and presenting the fastest growing demand worldwide [2]. Global carbon emissions from commercial building operations have been reported to account for over 10% of the total global greenhouse gas emissions and consume 8% of the global energy use [3]. Meanwhile, there is solid evidence that the decarbonization potential in commercial buildings is much more important than previously believed [4]. In addition, the long operational life of buildings accounts for more than 80% of buildings' full life cycle, resulting in significant lock-in and impeding decarbonization of commercial building operations [5]. Therefore, decarbonization in commercial building operations will become the last and most critical step toward addressing the "last mile" of carbon neutrality.

On the other hand, identifying the drivers of decarbonization in commercial buildings and quantifying their contributions are essential for breaking the carbon lock-in effect [6]. Carbon emissions from commercial building operations are primarily released from several end-uses (e.g., heating, cooling, and lighting) [7], which are directly influenced by technology and user behavior [8]. In addition, current literature has proven that the demand for end-use activities, which is driven by global climate change and economic development, changes significantly in different countries [9]. **However, few studies have considered the impact of end-use activities on decarbonizing global commercial buildings.** To seek the best practical path to decarbonize the operational carbon in commercial buildings, three issues should be addressed for the global commercial building sector:

- How has the global operational carbon changed over the last decades?
- How do end-use activities affect the decarbonization of commercial buildings?
- What is the operational decarbonization level and how can its process be accelerated?

To address the questions raised above, this study assesses the decarbonization progress of global commercial building operation during 2000–2019 considering the technical, socioeconomic, climatic and end-use factors using the decomposing structural decomposition (DSD) method. Specifically, the changes in operational carbon intensity of the 16 selected countries are decomposed into 6 factor contributions. In addition, the impacts of end-use activities on decarbonizing commercial building operations are investigated. Thereafter, the historical decarbonization of global commercial building operations across three different emission scales is assessed. Regarding the reliability of the DSD result, the log-mean Divisia index (LMDI) method is used for the robustness test. Moreover, the decarbonization strategies of global commercial building operations are reviewed to seek the best practical path for future building decarbonization.

As for the most important contributions, and in response to the call for building carbon neutrality, this work is the first to evaluate the evolution of carbon emission intensity released by commercial building operation and to assess its historical decarbonization at a global scale. To achieve this goal, the technical, socioeconomic, climatic, and end-use drivers that affect carbon intensity are investigated. In particular, the impacts of end-use characteristics on decarbonizing commercial building operations are also analyzed. To date, there has not been in-depth research on such a topic and it has rarely been discussed in global commercial building operations.

The remainder of the study is organized as follows: Section 2 provides a brief overview of the literature. Section 3 presents the materials and methods, including the commercial building emission model, DSD methods, and data collection. Section 4 shows the change in operational carbon intensity with its drivers' contributions and the impacts of end-use activities on decarbonizing commercial building operations. Section 5 covers three parts: Section 5.1 presents the historical decarbonization progress of global commercial building operations, Section 5.2 tests the robustness of the DSD results, and Section 5.3 discusses the decarbonization strategies of global commercial building operation. Section 6 highlights the conclusions, including key findings and upcoming works.

2. Literature review

The latest evidence shows that the energy-related carbon intensity of commercial building operations was 1.62 times that of residential building operations in 2020 [3] (see Fig. 1), reflecting that the potential situation of high carbon lock-in in commercial buildings is more

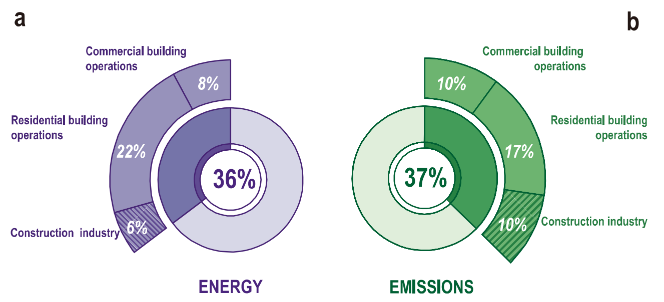

Fig. 1. Share of global building operations in the (a) final energy use and (b) carbon dioxide (CO_2) emissions in 2020.

significant [10]. Currently, many studies (e.g., Wang et al. [11], Xiang et al. [12]) have successfully assessed or forecasted the operational carbon changes in the building sector but have rarely discussed the impact of end-use activities [13]. However, the decarbonization of end-uses [especially the Heating, Ventilation, and Air Conditioning (HVAC) system] does affect buildings toward the net-zero emission status [14]. Evidence shows that HVAC in developed countries account for 50% of building energy consumption and 20% of the national energy consumption demand [15]. In the United States, nearly 40% of energy is consumed by building operations, 38.4% of which is consumed by HVAC systems [16]. It is also reported that space heating in the United Kingdom accounts for approximately 40% of the final energy demand and 20% of the nationwide carbon emissions [17].

Decomposition analysis is applied to identify the key drivers that affect carbon emissions and to further assess carbon reduction, thereby laying a historical decarbonization benchmark for formulating energy and climate policies [18]. Currently, typical decomposition analysis methods mainly include structure decomposition analysis (SDA) and index decomposition analysis (IDA) [19]. SDA decomposes the impact of driving factors affecting carbon emissions based on the input–output model [20]. Considering the limitation of the input–output model, the application of SDA can hardly solve all issues in decomposition analysis [21]. Compared with SDA, IDA has been widely applied due to its simple operation and flexible structure, attracting a large number of scholars to study it and improve it [22]. In 1997, Ang et al. [23] proposed a new LMDI approach, which effectively made up for the defect of decomposition residuals. Later, Ang [24] compared the popular index decomposition analysis methods and concluded that LMDI is a preferred method. However, the latest evidence shows that LMDI may produce unreasonable results because these index decomposition analyses are overly dependent on the interrelationships between variables [25]. To address this issue, Vaninsky [26] developed a generalized Divisia index method (GDIM) in 2014, which not only overcame these deficiencies but also more comprehensively quantified the level of drivers' contributions [27]. Given these advantages, GDIM has been adopted by a few scholars to identify the drivers of major emission sectors, such as industry [28], transportation [29], and buildings [30]. In 2021, Jakub Boratyński [31] devised a simpler and more intuitive decomposition formula (i.e., the DSD, which is mentioned in Section 1), which is based on the abovementioned decomposition analysis framework, and aims to reveal the impact of individual shares on structural changes. Furthermore, reliable cases verified the robustness of the method, and the proposed DSD was used to decompose the changes in the electricity demand of the European Union from 2000 to 2014.

Given the current state of research on carbon emissions from the abovementioned building operations, two gaps should be noted:

Regarding the end-use activity affecting building decarbonization, although classic studies have reported the impact of end-use behavior on carbon emissions from building operation [32], in practice, these efforts have focused on residential buildings. For example, Schipper et al. [33] and Greening et al. [34] analyzed the impact of end-use activities on the carbon intensity of residential buildings in 10 countries. For the main emitters, Fan et al. [35] conducted an in-depth study on the carbon emissions of residential buildings in China, and their study investigated the impact of five end-use energy sources on operational carbon emissions. In addition, some scholars have also analyzed one or two end-use characteristics in residential building operations (such as heating [36] and cooling [37]). To date, few studies have assessed the carbon emission change (especially the decarbonization progress) of commercial buildings considering the end-use activities at a global scale. Therefore, an exhaustive investigation of such a topic for commercial building operations is valuable.

Regarding the decomposition analysis tool for assessing building decarbonization, DSD, as an advanced decomposition analysis method, excels in explaining structural change effects and is mathematically proven to degrade to existing decomposition methods under specific conditions [31]. Clearly, DSD is the preferred method for assessing the decarbonization of different emission sectors (especially in commercial building operations). Furthermore, there are no further reports on DSD's application, and its role in characterizing energy and emissions is not yet clear at all, and is awaiting intensive study.

Therefore, to fill the above gaps, this study applied the DSD method to investigate the change in operational carbon intensity from commercial buildings considering the end-use activities in 16 countries over the last two decades and to further evaluate the decarbonization level of commercial building operations. The primary contributions are as follows:

- This work is the first to investigate the carbon emission intensity of global commercial building operations considering the impact of end-use activities. Only a few studies have reported the impact of end-use activities on the change in building carbon emissions, and these cases only focused on residential buildings. Therefore, this study used DSD to decompose the carbon intensity of global commercial building operations, identifying the factors which include socioeconomic, technical, climatic, and end-use characteristics. In particular, this study further investigated the impact of four types of end-use activities (heating, cooling, lighting, and appliances) on decarbonizing commercial building operations. In addition, the DSD method with its robustness test was also the first to be utilized in the field of carbon emissions, especially in building carbon emissions.
- The historical decarbonization level at different emission scales of global commercial building operations is assessed for the first time. To examine the gap between the decarbonization of building operations and the established targets in each country, this study tracked the historical decarbonization process of commercial building operations in 16 countries from 2000 to 2019 at three emission scales: total decarbonization, decarbonization intensity (i.e., decarbonization per floor space), and decarbonization per capita. In addition, the decarbonization efficiency in commercial building operations was evaluated for each emitter. To seek the best practical path to decarbonize operational carbon, strategies to accelerate the decarbonization process of global commercial buildings were also discussed.

3. Methods and materials

This study mainly adopted the DSD method to analyze the carbon emission intensity of global commercial building operations. First, the commercial building emission model with end-use characteristics is established in Section 3.1. Then the DSD method to identify the drivers affecting building decarbonization is introduced in Section 3.2. Finally, Section 3.3 presents the dataset used in this study.

3.1. Building emission model with end-use characteristics

Considering the comparability of end-use energy across different countries and better analyzing the impact of end-use activities on the decarbonization of commercial building operations [38], the end-uses of commercial building operations in this study were decomposed into space heating, space cooling, service lighting, and appliances and others [39]. In other words, the end-uses other than space heating, space cooling and service lighting were uniformly summarized as appliances and others in this study. Thus, the carbon emissions released by commercial building operations can be expressed as:

$$C = C_{\text{Space heating}} + C_{\text{Space cooling}} + C_{\text{Service lighting}} + C_{\text{Appliances and others}} \tag{1}$$

Refined as $C = \sum_{j=1}^{4} C_j$

where $C_j (j = 1, 2, 3, 4)$ denotes the carbon emissions released by four different end-uses in commercial building operations. Accordingly, the carbon intensity (i.e., carbon emissions per floor space) is defined as $c_j = \frac{C_j}{F}$.

Guided by previous studies, the carbon emission intensity of commercial building operation was driven by six factors [40], as illustrated in Fig. 2 (see the details in the Nomenclature). In view of this, the carbon intensity from the end-use of commercial buildings can be characterized as follows:

$$c_j = \frac{C_j}{F} \equiv \frac{P}{F} \bullet \frac{GDP}{P} \bullet \frac{Gs}{GDP} \bullet \frac{F}{Gs} \bullet \frac{E_j}{F} \bullet \frac{C_j}{E_j} \tag{2}$$

For convenience, let $p = \frac{P}{F}, g = \frac{GDP}{P}, s = \frac{G_s}{GDP}, i = \frac{F}{Gs}, e_j = \frac{E_j}{F}, k_j = \frac{C_j}{E_j}$; then, Eq. (2) can be further simplified as:

$$c_j \equiv p \cdot g \cdot s \cdot i \cdot e_j \cdot k_j \tag{3}$$

Combining Eqs. (1) and (3), the operational carbon intensity is defined as:

$$c = \sum_{j=1}^{4} p \cdot g \cdot s \cdot i \cdot e_j \cdot k_j \tag{4}$$

3.2. Decomposing structural decomposition method

Based on the abovementioned emission model and considering the limitations of existing methods mentioned in the Literature Review, the DSD method was adopted in this section to decompose the carbon intensity of global commercial building operations from 2000 to 2019 to investigate the contributions of each driver to the change in carbon intensity.

Based on the fundamentals of the DSD, let K represent the total carbon emission factor and let it be defined as $K = \sum_{j=1}^{4} k_j$, and Eq. (4) can be rewritten as:

$$c = \sum_{j=1}^{4} K \cdot p \cdot g \cdot s \cdot i \cdot e_j \cdot w_j \tag{5}$$

where $w_j = \frac{k_j}{K}$ denotes the share ratio of the emission factor of end-use j in the total carbon emission factor. Deriving the full differentiation of Eq. (5), one obtains:

$$\mathrm{d}c = \sum_{i=1}^{4} \left(\frac{\partial c_j}{\partial p} \mathrm{d}p + \frac{\partial c_j}{\partial g} \mathrm{d}g + \frac{\partial c_j}{\partial s} \mathrm{d}s + \frac{\partial c_j}{\partial i} \mathrm{d}i + \frac{\partial c_j}{\partial K} \mathrm{d}K + \frac{\partial c_j}{\partial e_j} \mathrm{d}e_j + \frac{\partial c_j}{\partial w_j} \mathrm{d}w_j \right) \tag{6}$$

Then, by introducing the relaxation component $\mathrm{d}F_i$ and the displacement component $\mathrm{d}F$, Eq. (6) can be further expanded into the following linear equations:

$$\begin{cases} \mathrm{d}c = \sum_{i=1}^{4} \left(\frac{\partial c_j}{\partial p} \mathrm{d}p + \frac{\partial c_j}{\partial g} \mathrm{d}g + \frac{\partial c_j}{\partial s} \mathrm{d}s + \frac{\partial c_j}{\partial i} \mathrm{d}i + \frac{\partial c_j}{\partial K} \mathrm{d}K + \frac{\partial c_j}{\partial e_j} \mathrm{d}e_j + \frac{\partial c_j}{\partial w_j} \mathrm{d}w_j \right) \\ \mathrm{d}w_j = \mathrm{d}F_i + \mathrm{d}F \\ \sum_{j=1}^{4} \mathrm{d}w_j = 0 \end{cases} \tag{7}$$

Furthermore, the linear system Eq. (7) can be represented more compactly in matrix notation:

$$\mathbf{A} \cdot \mathrm{d}\mathbf{y} = \mathbf{B} \cdot \mathrm{d}\mathbf{z} \tag{8}$$

where $\mathrm{d}\mathbf{y}$ is the endogenous variable and $\mathrm{d}\mathbf{y} = [\mathrm{d}c, \mathrm{d}w_1, \mathrm{d}w_2, \mathrm{d}w_3, \mathrm{d}w_4, \mathrm{d}F]^{\mathrm{T}}$, $\mathrm{d}\mathbf{z}$ is the exogenous variable and $\mathrm{d}\mathbf{z} = [\mathrm{d}K, \mathrm{d}p, \mathrm{d}g, \mathrm{d}s, \mathrm{d}i, \mathrm{d}e_1, \mathrm{d}e_2, \mathrm{d}e_3, \mathrm{d}e_4, \mathrm{d}F_1, \mathrm{d}F_2, \mathrm{d}F_3, \mathrm{d}F_4]^{\mathrm{T}}$. **A** and **B** represent

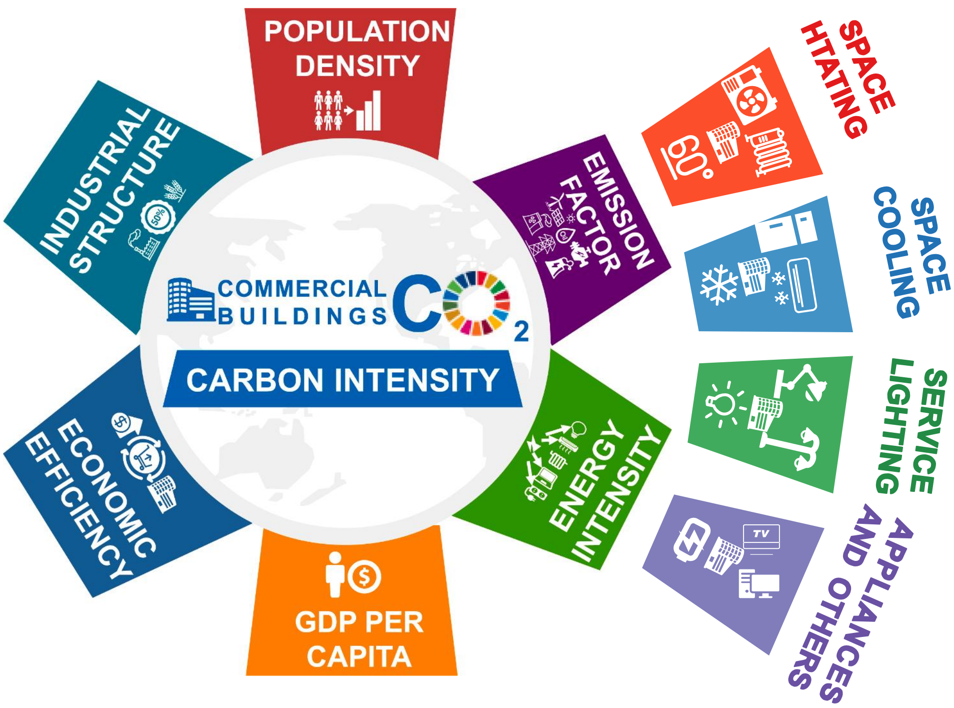

Fig. 2. Drivers affecting the carbon emission intensity of commercial building operation.

the coefficient matrix and are only related to endogenous variables and exogenous variables, so let $\mathbf{A} = f(\mathbf{z}, \mathbf{y})$, $\mathbf{B} = g(\mathbf{z}, \mathbf{y})$, and satisfy:

$$\mathbf{A} = \begin{bmatrix} 1 & -\frac{\partial c_1}{\partial w_2} & -\frac{\partial c_2}{\partial w_2} & -\frac{\partial c_3}{\partial w_3} & -\frac{\partial c_4}{\partial w_4} & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \sum\frac{\partial c_j}{\partial K}\mathrm{d}K & \sum\frac{\partial c_j}{\partial K}\mathrm{d}K & \sum\frac{\partial c_j}{\partial K}\mathrm{d}K & \sum\frac{\partial c_j}{\partial K}\mathrm{d}K & \sum\frac{\partial c_j}{\partial K}\mathrm{d}K & \frac{\partial c_j}{\partial K}\mathrm{d}K & \frac{\partial c_j}{\partial K}\mathrm{d}K & \frac{\partial c_j}{\partial K}\mathrm{d}K & \frac{\partial c_j}{\partial K}\mathrm{d}K & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

Expanding Eq. (8), one obtains:

$$\mathbf{A}\cdot\mathrm{d}\mathbf{y} = \mathbf{B}\cdot\mathrm{diag}(\mathrm{d}\mathbf{z})\cdot\mathbf{j} \tag{10}$$

where $\mathrm{diag}(\mathrm{d}\mathbf{z})$ is a diagonal matrix consisting of the elements of vector $\mathbf{z}$, and $\mathbf{j}$ is a vector of ones. $\mathrm{d}\mathbf{y}$ can be easily solved by:

$$\mathrm{d}\mathbf{y} = \mathbf{A}^{-1}\cdot\mathbf{B}\cdot\mathrm{diag}(\mathrm{d}\mathbf{z})\cdot\mathbf{j} \tag{11}$$

The derivation of the exact differential equation above provides a natural decomposition scheme, but the equation was strictly valid only for infinitesimal changes in variables. In other words, the cumulative effect of exogenous variables on endogenous variables can be approximated by full differentiation with sufficient precision as long as the actual change in exogenous variables (exogenous shocks) was divided into enough stages [41]. In this study, the actual changes in exogenous variables were evenly divided into K stages (Guided by [31], K was set to 16000). Further applying Euler's method in numerical integration [42], the effect of each stage $\mathbf{D}^{(k)}$ can be mathematically expressed as:

$$\begin{cases} \mathbf{D}^{(k)} = \left(\mathbf{A}^{(k-1)}\right)^{-1}\cdot\mathbf{B}^{(k-1)}\cdot\mathrm{diag}(\mathrm{d}\mathbf{z}) \\ \mathrm{d}\mathbf{y}^{(k)} = \mathbf{D}^{(k)}\cdot\mathbf{j} \\ \mathbf{z}^{(k)} = \mathbf{z}^{(k-1)} + \mathrm{d}\mathbf{z} \\ \mathbf{y}^{(k)} = \mathbf{y}^{(k-1)} + \mathrm{d}\mathbf{y}^{(k)} \\ \mathbf{A}^{(k)} = f\left(\mathbf{z}^{(k)}, \mathbf{y}^{(k)}\right) \\ \mathbf{B}^{(k)} = g\left(\mathbf{z}^{(k)}, \mathbf{y}^{(k)}\right) \end{cases} \tag{12}$$

where $\mathrm{d}\mathbf{z} = \frac{\Delta z}{K}$ and $k = 1, 2, \cdots, K$. When $k = 0$, the coefficient matrices $\mathbf{A}$ and $\mathbf{B}$ are initialized using the base period data by $\begin{cases} \mathbf{A}^{(0)} = f\left(\mathbf{z}^{(0)}, \mathbf{y}^{(0)}\right) \\ \mathbf{B}^{(0)} = g\left(\mathbf{z}^{(0)}, \mathbf{y}^{(0)}\right) \end{cases}$. The contribution of each installment was then repeatedly accumulated to obtain the required decomposition:

$$\mathbf{D} = \sum\nolimits_{k=1}^{K}\mathbf{D}^{(k)} \tag{13}$$

The element d_{ij} of the $\mathbf{D}$ matrix was interpreted as the contribution of the change in the j-th exogenous variable $\Delta\mathbf{z}_j$ to the change in the i-th endogenous variable $\Delta\mathbf{y}_i$. Obviously, this study is more concerned with the effect of drivers (i.e., exogenous variables) on carbon intensity, and therefore, carbon intensity change can be decomposed by DSD as:

$$\Delta c|_{0\to T} = \Delta K_{\mathrm{DSD}} + \Delta p_{\mathrm{DSD}} + \Delta g_{\mathrm{DSD}} + \Delta s_{\mathrm{DSD}} + \Delta i_{\mathrm{DSD}} + \Delta e_{\mathrm{DSD}} \tag{14}$$

where $\Delta K_{\mathrm{DSD}} = \Delta K + \sum_{i=1}^{4}F_i$ denotes the contribution of changes in carbon emission factors and their shares to carbon intensity, which is interpreted generically by the DSD as the contribution caused by the carbon emission factors. It is noteworthy that Δe_{DSD} in Eq. (14) was further decomposed by:

$$\Delta e_{\mathrm{DSD}} = \sum\nolimits_{i=1}^{4}e_i \tag{15}$$

$$= \Delta e_{\text{Space heating}} + \Delta e_{\text{Space cooling}} + \Delta e_{\text{Service lighting}} + \Delta e_{\text{Appliances and others}}$$

Eq. (15) reveals the effect of energy intensity on carbon intensity across different end-use activities.

3.3. Dataset

Based on the availability of data and the consistency of statistical measures, this study collected data from 16 countries from 2000 to 2019 to serve the carbon emission model of global commercial building operations. Fig. 3 summarizes the descriptive statistics of the collected raw data, covering service industry added value (Gs), population size (P), gross domestic product (GDP, refined as G), floor space (F), energy consumption (E), and carbon emissions (C) of commercial buildings. In addition, energy and emissions from commercial building operations were further subdivided by end-use activities into space heating, space cooling, service lighting, and appliances and others (see Fig. 3 b and c). Data related to commercial building operations were taken from the International Building Emission Dataset (IBED, https://www.researchgate.net/project/International-Building-Emission-Dataset-IBED). The data for population and economic indicators were accessed from the World Bank database (data.worldbank.org).

4. Results

4.1. Changes in operational carbon intensity of global commercial buildings

Fig. 4 reveals the change in operational carbon intensity of commercial buildings in the 16 selected countries from 2000 to 2019 based on the assessment of the DSD method. This shows that from 2000 to 2019, the carbon intensity of commercial building operations in all countries except China decreased significantly to varying degrees, with an average decline of −1.94% per yr. Of these, the most pronounced decline occurred in the United States [-181.62 kg of carbon dioxide per square meter ($kgCO_2/m^2$) during 2000–2019], with an average decline of −3.55% per yr. In terms of phase changes in carbon intensity, most countries have consistently maintained a steady decline, while the remaining countries (Sweden, Netherlands, Finland, Korea, and China) have shown an inverted U-shape in the carbon intensity dynamics of

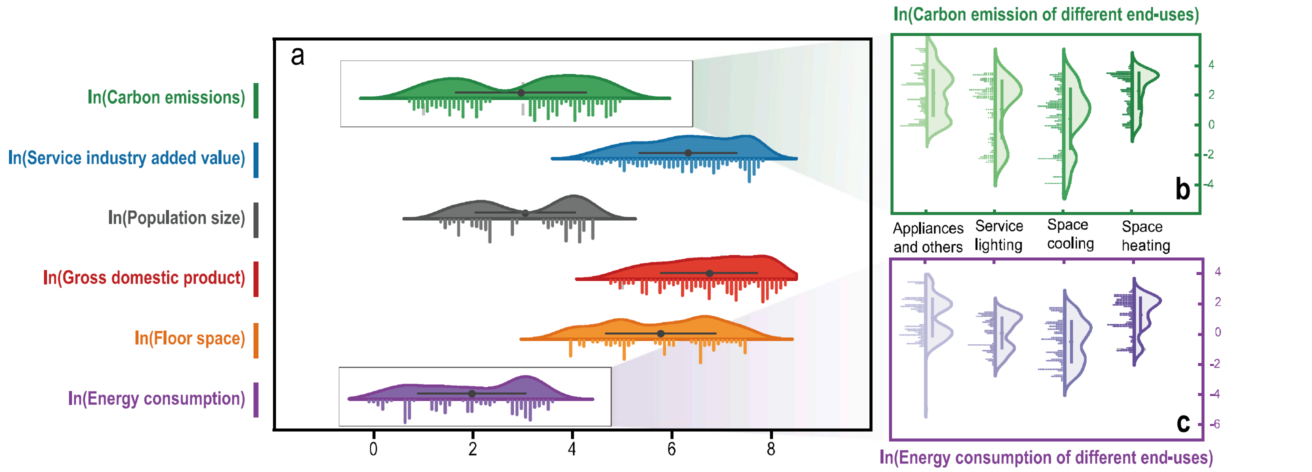

Fig. 3. Descriptive statistics of raw data for 16 countries from 2000 to 2019: (a) carbon emissions, service industry added value, population size, GDP, floor space, and energy consumption; (b) energy consumption of different end-uses; (c) carbon emissions of different end-uses. Note: the points in the scatter plot represent the samples, and the dots and horizontal lines in the density plot represent the mean values and standard deviation intervals, respectively.

commercial buildings, that is, a gradual decline after reaching a peak. At the same time, it should be noted that the carbon intensity of commercial building operations decreased more significantly after 2010 because the change in carbon intensity in the first stage (2000–2010) was −1.42% per yr, while in the second stage (2010–2019), it was −2.93% per yr. In addition, according to the Climatic Data for Building Design [43], Fig. 4 reflects that the average carbon intensity in the hot humid zone (31.83 $kgCO_2/m^2$) and the cold zone (55.04 $kgCO_2/m^2$) was obviously lower than that in the temperate zone (74.74 $kgCO_2/m^2$) since the demand for space heating and cooling in the temperate zone was stronger than that in other climate zones.

For the drivers affecting the carbon intensity change, during the period of 2000–2019, the GDP per capita (average contribution in 16 countries: 32.22%) was the most positive driver to increase the carbon intensity of commercial building operations for all countries, especially in developing economies (e.g., China: 93.51%). Another positive driver was economic efficiency, with an average contribution of 6.36% in 16 countries. With regard to the drivers that reduce carbon intensity, emission factors (average contribution in 16 countries: −75.44%) were the most important in most countries, especially in Portugal (-805.14%), followed by Denmark (-65.60%), Spain (-48.68%), Finland (-48.26%) and the United Kingdom (-41.66%). However, Japan (16.36%) was the only emitter with an increase in carbon intensity due to emission factors. Meanwhile, the industrial structure (average contribution in 16 countries: −20.95%) was another driver to decrease the carbon intensity in most countries [excluding the United States (37.09%) and Finland (9.51%)]. Furthermore, the impacts of population density and energy intensity on the changes in operational carbon intensity were not stable. For example, population density exerted a positive effect on carbon intensity in Korea, Finland, the United States, and China, while population density in the United Kingdom persistently suppressed the increase in carbon intensity. In addition, energy intensity was more likely to drive the carbon intensity increase before 2010, while this driver promoted the decarbonization of commercial building operations in most countries after 2010.

Overall, the decomposition of the changes in the carbon intensity of global commercial building operations answers Issue 1 posed in Section 1.

4.2. *Impacts of end-use activities on decarbonizing commercial building operations*

To elucidate the impact of different end-use activities on the change in operational carbon intensity, the energy intensity effects (see the purple bars in Fig. 4) of 16 countries were further decomposed into the contributions of four end-uses. Fig. 5 presents the contribution levels of different end-use activities to carbon intensity changes in global commercial building operations in 2000–2019. In Fig. 5 a and c, the color of each country on the map indicates the effect of the energy intensity on the evolution of its corresponding carbon intensity, and the waterfall on the map shows the decomposition of the energy intensity effect covering end-use characteristics. Furthermore, Fig. 5 b further reveals the impacts of four types of end-use activity on decarbonizing the operational carbon intensity across different countries.

Specifically, in the first stage (2000–2010, see Fig. 5 a), the end-use decomposition results of the energy intensity effects show a ladder-like pattern in most countries, which reveals that the changes in energy intensity caused by the four different end-use activities all played positive roles in the energy intensity effects of commercial building operations. Generally, the largest contributors were appliances and others (41.74%) and space heating (41.43%), followed by service lighting (10.85%) and space cooling (5.79%). That is, the impact of energy intensity on carbon intensity in the first stage was primarily attributed to the appliances and others and space heating. Taking Sweden as an example, from 2000 to 2010, energy intensity was the crucial factor driving the increase in operational carbon intensity and led to an increase of 12.69% (2.96 $kgCO_2/m^2$) in operational carbon intensity. Specifically, space heating, appliances and others contributed 47.54% (1.41 $kgCO_2/m^2$) and 50.18% (1.49 $kgCO_2/m^2$), respectively. As illustrated in Fig. 5 b, for space heating, in Japan (-0.78 $kgCO_2/m^2/yr$), Germany (-1.04 $kgCO_2/m^2/yr$), the United Kingdom (-1.20 $kgCO_2/m^2/yr$), Canada (-1.45 $kgCO_2/m^2/yr$), Korea (-1.49 $kgCO_2/m^2/yr$), the United States (-4.96 $kgCO_2/m^2/yr$) and Portugal (-9.30 $kgCO_2/m^2/yr$), changes in energy intensity caused by space heating severely curbed the growth in carbon intensity while playing a smaller but still important role in the increased emissions for the remaining countries (ranging from 0.01 $kgCO_2/m^2/yr$ to 0.32 $kgCO_2/m^2/yr$). Meanwhile, in most countries, service lighting (1.04 $kgCO_2/m^2/yr$) and space cooling (2.02 $kgCO_2/m^2/yr$) have contributed to increases in carbon intensity to varying degrees. However, in the United States, the energy intensity caused by service lighting and space cooling decreased the carbon intensity by 7.08 $kgCO_2/m^2/yr$, accounting for 64.61% of the energy intensity effect. In addition, appliances and others drove the increase in carbon intensity in most countries. In contrast, for Japan, Korea, Denmark, and the United Kingdom, the change in energy intensity caused by appliances and others resulted in a decrease in the carbon intensity of −0.87, −0.59, −0.55, and −0.16 $kgCO_2/m^2/yr$, respectively, accounting for 57.95%, 51.39%, 131.16%, and 18.35% of the respective total energy intensity

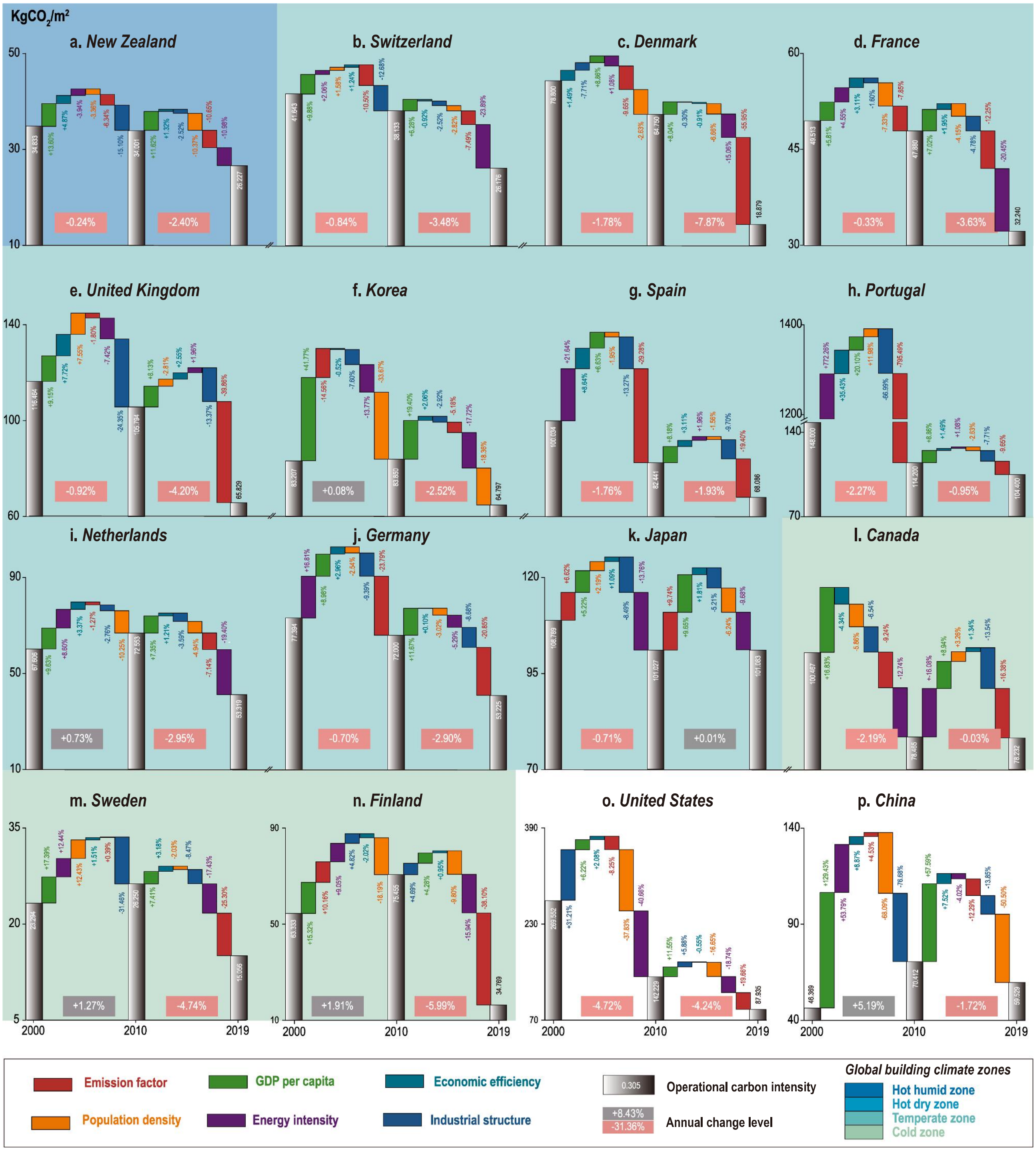

Fig. 4. Changes in the operational carbon intensity of global commercial buildings (2000–2019). Note: change in carbon intensity was divided into two phases: 2000–2010 and 2010–2019, and the change in carbon intensity within each phase was decomposed into six drivers' impacts. Countries were separated by building climate zones, with China and the United States not being divided due to the coverage of multiple climate zones.

effects. Therefore, the changes in energy intensity caused by appliances and others were the main reason for decreasing the energy intensity in the above countries.

Regarding the second stage (2010–2019, see Fig. 5 c), space heating, appliances and others remained the major contributors to decreasing the energy intensity effect, especially in developed countries located in Europe and North America. The impact of service lighting on the energy intensity effect was more significant overall than in the first phase, and the effect was bidirectional. For instance, for the United Kingdom (-499.35%), Portugal (-835.73%), and Spain (-151.51%), the energy intensity effect related to service lighting had a significant negative effect and even offset the increase in carbon intensity caused by other end-use activities, while for the United Kingdom, Germany, China, the Netherlands, and New Zealand, the energy intensity effect had a significant positive effect. Additionally, compared to other end-uses, the role of space cooling in energy intensity effects was not significant. However, in China (before 2010: 44.24%, after 2010: 87.71%), the energy intensity effect caused by space cooling played a critical role. From

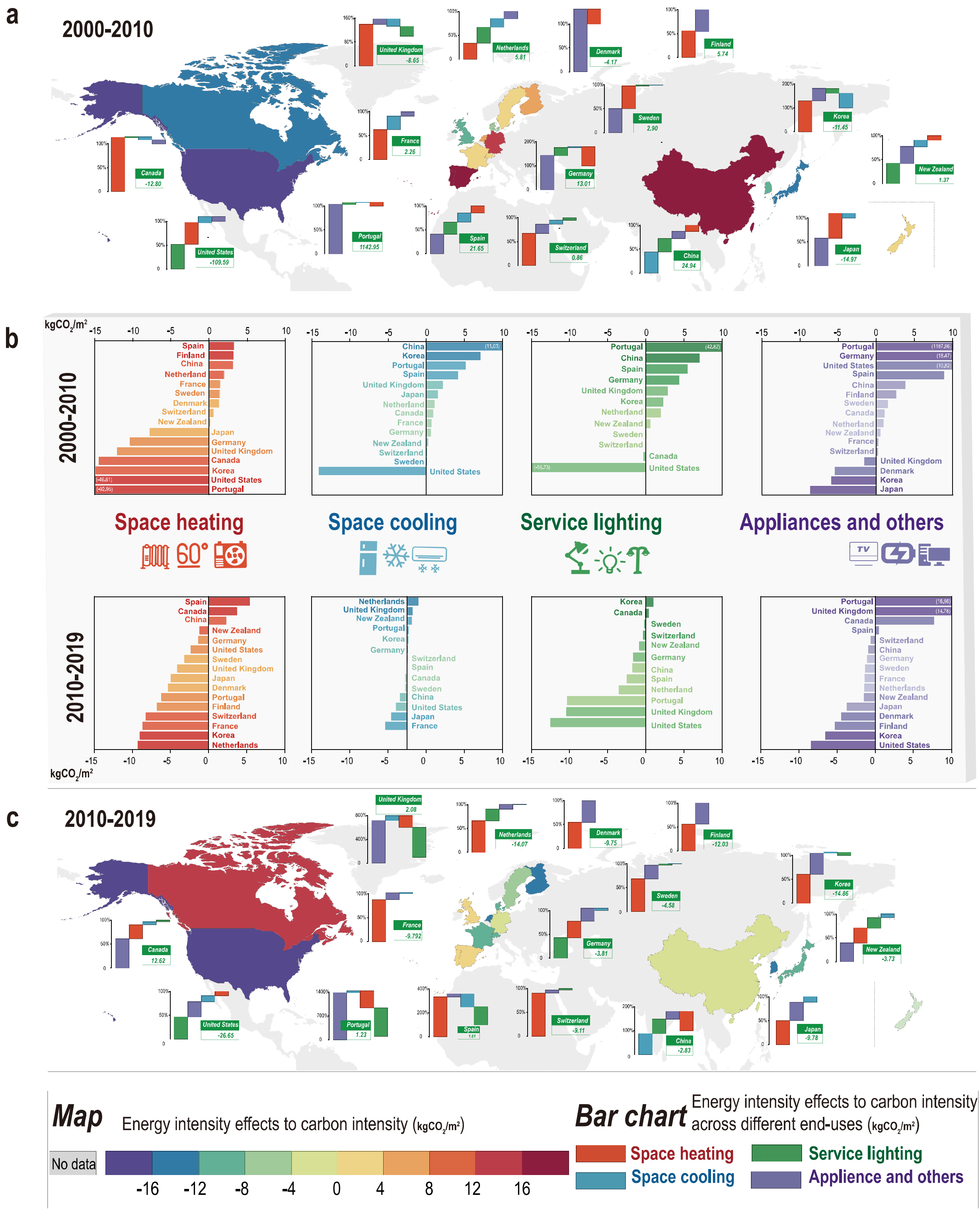

Fig. 5. Contributions of different end-use activities to the carbon intensity change of global commercial building operation in (a) 2000–2010 and (c) 2010–2019; (b) impacts of different end-use activities on decarbonizing the operational carbon intensity across different countries (2000–2019). Note: due to data availability, service lighting was not considered in Japan and France, and service lighting and space cooling were not considered in Denmark and Finland.

the measurement shown in Fig. 5 b, space heating led to the reduction of carbon emissions from commercial building operations in a growing number of countries (ranging from −1.03 $kgCO_2/m^2/yr$ to −0.13 $kgCO_2/m^2/yr$), excluding Spain (0.60 $kgCO_2/m^2/yr$), Canada (0.41 $kgCO_2/m^2/yr$), and China (0.25 $kgCO_2/m^2/yr$). Similar trends can be observed in the appliances and others: after 2010, the effect of service lighting on carbon intensity reversed significantly in almost all countries (excluding Korea and the United States), and the results show that the impact of energy intensity caused by service lighting on carbon intensity was 1.04 $kgCO_2/m^2/yr$ and −4.69 $kgCO_2/m^2/yr$ before and after 2010, respectively, with the most pronounced changes in the United Kingdom (before 2010: 0.29 $kgCO_2/m^2/yr$, after 2010: -1.15 $kgCO_2/m^2/yr$) and Portugal (before 2010: 4.28 $kgCO_2/m^2/yr$, after 2010: -1.14 $kgCO_2/m^2/yr$). For space cooling, the contribution of energy intensity from space cooling to carbon intensity gradually decreased or even showed signs of reversal (before 2010: 2.02 $kgCO_2/m^2/yr$, after 2010: -0.64 $kgCO_2/m^2/yr$), while it should be noted that the suppressive effect of space cooling on carbon intensity in the United States was also significantly decreasing, with France (-0.38 $kgCO_2/m^2/yr$) replacing the United States (-0.19 $kgCO_2/m^2/yr$) as the top emitter affected by space cooling.

Overall, throughout the study period, the impact of energy intensity on carbon intensity changed from positive to negative in most countries, such as China and most European countries, while the opposite was true for Canada and the United Kingdom. The reason for this phenomenon is the rapid change in the structure of the energy effect in each country around the 2010 s. More specifically, space heating, appliances and others were observed to inhibit carbon intensity in an increasing number of countries, while space cooling and service lighting have gradually shifted from increasing to decreasing carbon intensity, with service lighting having the most significant reversal effect. In another word, the energy intensity effect gradually contributed to decarbonizing global commercial building operations from 2000 to 2019, with space heating (-14.33 $kgCO_2/m^2/yr$) being the key end-use to decarbonize the operation, followed by service lighting (-5.29 $kgCO_2/m^2/yr$), appliances and others (-2.85 $kgCO_2/m^2/yr$), and space cooling (-1.24 $kgCO_2/m^2/yr$).

In summary, the above results reveal the role of end-use activities in the decarbonization of global commercial building operations, addressing Issue 2 posed in Section 1.

5. Discussion

After investigating the evolution of the carbon intensity of global commercial building operations over the last decades, a timely assessment of historical decarbonization can help each country confront and improve the gap between current carbon reduction efforts and established targets. For this purpose, Section 5.1 evaluates the historical decarbonization progress of global commercial building operation. The typical IDA method (i.e., LMDI) was used to test the robustness of the DSD result shown in Section 4 to prove the reliability of the historical decarbonization result in Section 5.2. Finally, Section 5.3 discusses the strategies to accelerate the decarbonization process of global commercial buildings.

5.1. Historical decarbonization in global commercial building operations

On the basis of the decomposition of the operational carbon intensity of global commercial buildings, the decarbonization intensity ($\Delta DC_i|_{0\rightarrow T}$) can be obtained by the negative contributions of drivers that affect the carbon intensity and is expressed as follows [44]:

$$\Delta DC_i|_{0\rightarrow T} = \sum |\Delta c_i|_{0\rightarrow T}| \tag{16}$$

where $\Delta c_i \in \{\Delta p_{DSD}, \Delta g_{DSD}, \Delta s_{DSD}, \Delta i_{DSD}, \Delta e_{DSD}, \Delta K_{DSD}\}$ and satisfies $\Delta c_i|_{0\rightarrow T} \leq 0$ Accordingly, the total decarbonization ($\Delta DC|_{0\rightarrow T}$) from the commercial building operations can be expressed as:

$$\Delta DC|_{0\rightarrow T} = F|_{0\rightarrow T} \times (\Delta DC_i|_{0\rightarrow T}) \tag{17}$$

Thereafter, this study traced the historical decarbonization process of commercial building operations in 16countries during 2001–2019 from three scales: total decarbonization, decarbonization per capita, and decarbonization per floor space (decarbonization intensity). Fig. 6 a and b reflects the trend of total decarbonization. The results show that in the past 20 years (2001–2019), the total cumulative decarbonization in commercial building operations of 16countries was 4375.39 mega-tons of carbon dioxide ($MtCO_2$), which was 10.05% of the total cumulative emissions. Of these, the cumulative decarbonization levels of China (1159.90 $MtCO_2$) and the United States (2244.39 $MtCO_2$) were far ahead of other countries in the same period, followed by Germany (236.98 $MtCO_2$), the United Kingdom (161.08 $MtCO_2$) and Korea (159.25 $MtCO_2$), while the cumulative decarbonization of the remaining countries was less than 100 $MtCO_2$ (ranging from 6.91 $MtCO_2$ to 83.84 $MtCO_2$). Specifically, the total decarbonization of commercial building operations in China has been steadily increasing overall, with an average growth of 14.76% per yr. The opposite is true for the United States, with an average decrease of -3.25% per yr. In the rest of the world, the annual decarbonization from commercial building operations evolved dynamically over time and generally peaked approximately in 2010. For example, Canada (8.01 $MtCO_2$) and Japan (1.30 $MtCO_2$) peaked in 2009, and France (9.66 $MtCO_2$), the Netherlands (5.16 $MtCO_2$), Finland (2.96 $MtCO_2$), and Sweden (0.96 $MtCO_2$) peaked in 2011. In terms of the phased decarbonization process shown in Fig. 6 c, the average share of the total cumulative decarbonization over the four periods was 29.08% (2001–2005), 26.71% (2006–2010), 26.81% (2011–2015), and 17.40%

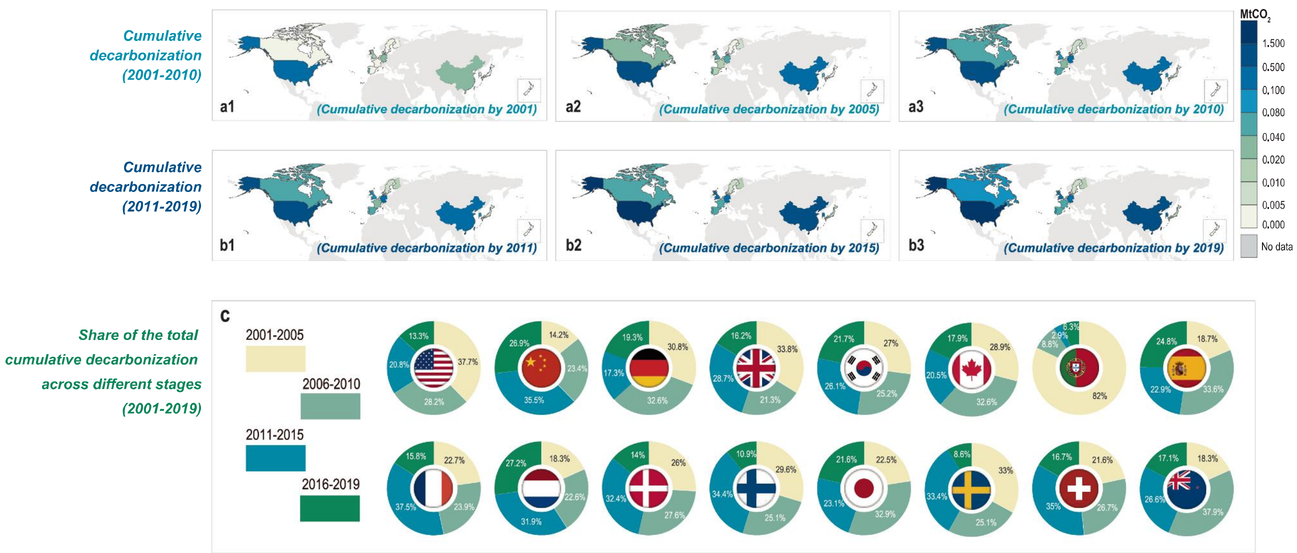

Fig. 6. Total cumulative decarbonization of global commercial building operations in (a1-a3) 2001–2010 and (b1-b3) 2011–2019; (c) share of the total cumulative decarbonization across different stages.

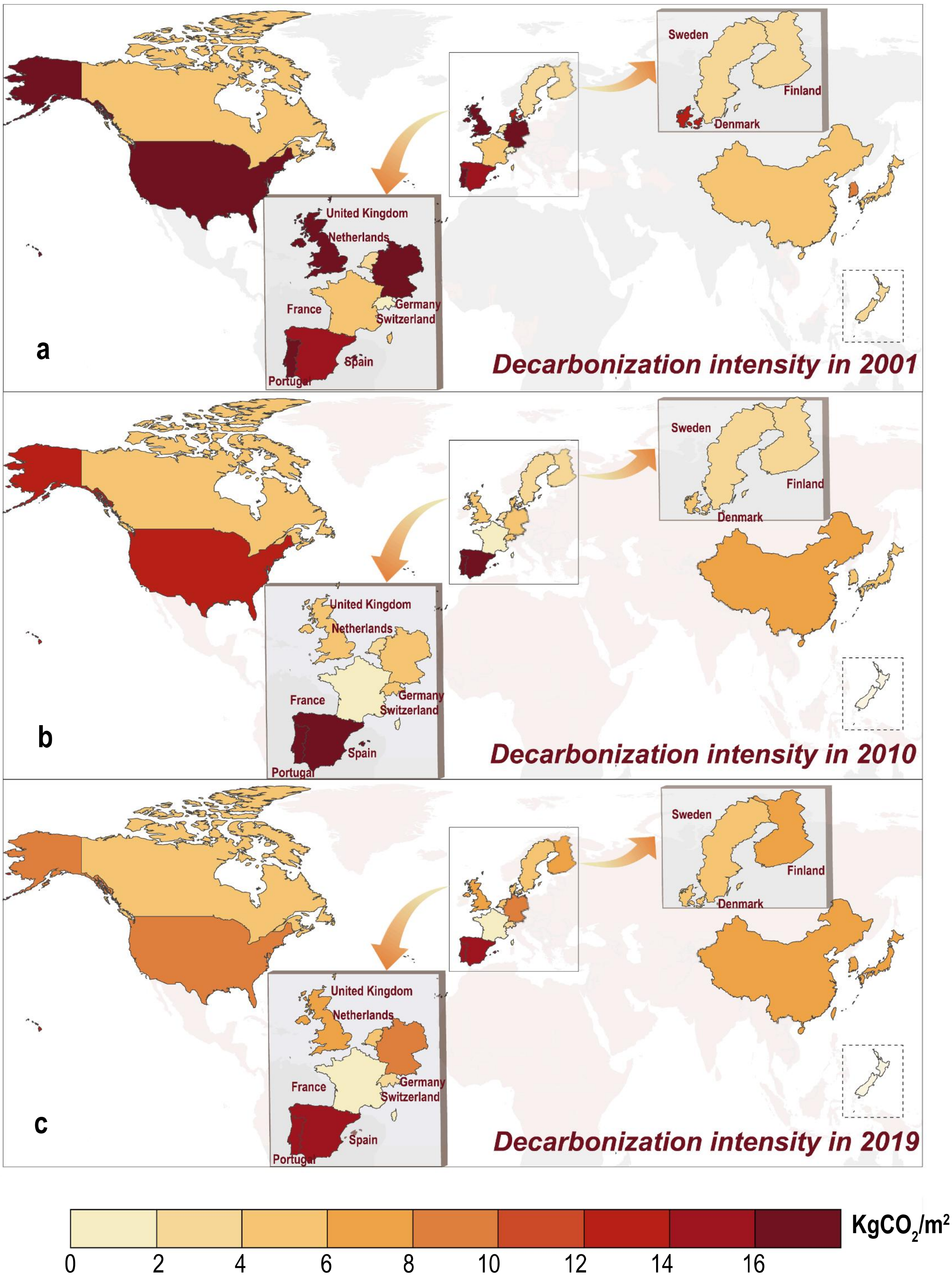

Fig. 7. Decarbonization intensity of global commercial building operations in 2001, 2010, and 2019.

(2016–2019). In other words, the global pace of decarbonization of commercial building operations was gradually slowing down, which warns that the potential effect of high carbon lock-in in commercial building operations may hinder deep decarbonization in the short term and up to the upcoming decades.

Moreover, the change in decarbonization intensity of global commercial operations is shown in Fig. 7. This shows that the change in decarbonization intensity varied widely across countries. In the United States, the United Kingdom, France, Germany, and Denmark, the decarbonization intensity generally decreased, with average decreases of −4.50%, −3.72%, −3.71%, −3.16%, and −2.13% per yr, respectively. However, the decarbonization intensity increased slightly in China (1.58% per yr) and Finland (6.23% per yr). The remaining countries showed relatively stable changes in decarbonization intensity, and it is noteworthy that the decarbonization intensity of commercial buildings in Portugal and Spain consistently remained over 14 $kgCO_2/m^2/yr$ during the study period, and the intensity was much higher than that in other countries in 2019. Overall, from 2000 to 2019, the gap between the decarbonization intensities of countries gradually narrowed, with an average decarbonization intensity of 6.86 $kgCO_2/m^2$ of

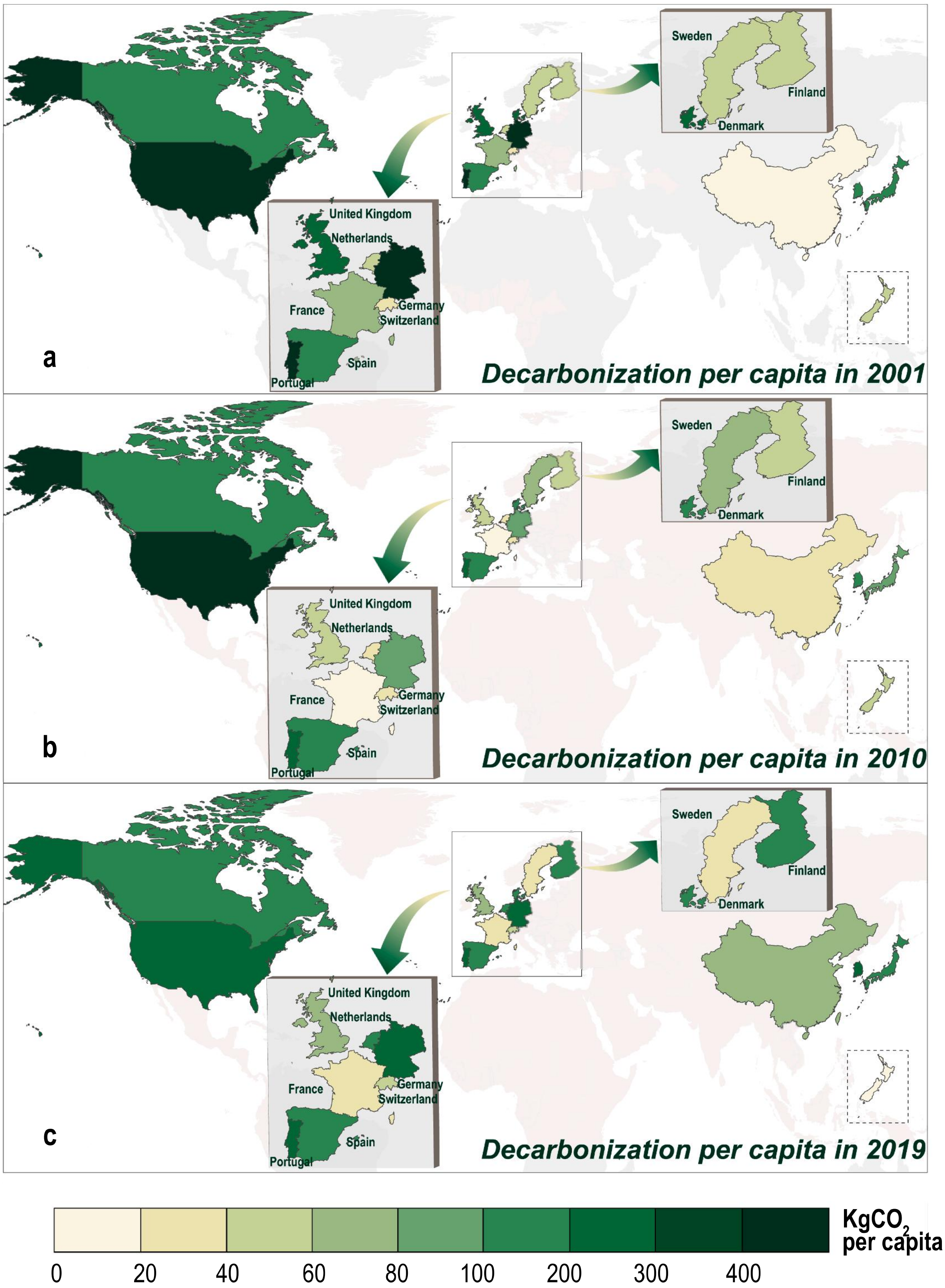

Fig. 8. Decarbonization per capita of global commercial building operations in 2001, 2010, and 2019.

commercial building operations in 2019.

Fig. 8 shows the result of the global decarbonization per capita, which is similar to the decarbonization intensity of global commercial building operations. Countries located in North America (the United States and Canada) and Europe (the United Kingdom, Netherlands, France, Germany, Switzerland, Spain, and Portugal) normally had high levels of decarbonization per capita, and most of their decarbonization per capita showed a downward trend. China and Finland have gradually increased from 18.39 $kgCO_2$ per capita and 43.47 $kgCO_2$ per capita in 2000 to 44.98 $kgCO_2$ per capita and 179.44 $kgCO_2$ per capita in 2019, respectively. In 2019, the average decarbonization per capita of commercial building operations was 97.42 $kgCO_2$ per capita, of which the highest was the United States (247.61 $kgCO_2$ per capita), followed by Korea (235.23 $kgCO_2$ per capita), Portugal (208.19 $kgCO_2$ per capita), and Germany (206.14 $kgCO_2$ per capita). It should be noted that despite the total decarbonization level between the United States and China was similar, a significant gap exists in the decarbonization per capita, which was not only affected by the large gap in population size, but also related to the difference in user behavior during the building operation. Compared with China, the decarbonization effect caused by user activities in commercial building operations of the United States was more pronounced, especially in the end-uses of service lighting and space heating. As a result, the decarbonization per capita associated with the service lighting and space heating in the United States was higher than that in China [45].

Overall, the above discussion reviews the historical decarbonization levels of global commercial building operations across three scales: total decarbonization, decarbonization intensity, and decarbonization per capita, responding to Issue 3 raised in Section 1.

5.2. Robustness of the decomposing structural decomposition method

This study identified the drivers of carbon intensity and further evaluated the historical decarbonization from commercial building operations using the DSD method. Although DSD is an advanced technical tool for carbon intensity decomposition, there is still a lack of strong practical evidence to support the reliability of the results. In contrast, LMDI [46], a classical index decomposition analysis, has been extensively accepted by existing efforts [47]. Therefore, this study adopted LMDI to test the robustness of the DSD results.

To deploy the robustness test, the building emission model proposed in Section 3.1 [see Eq. (4)] was rewritten as follows:

$$c = \sum_{j=1}^{4} p \cdot g \cdot s \cdot i \cdot e_j \cdot k_j = p \cdot g \cdot s \cdot i \cdot e \cdot K \tag{18}$$

Then, guided by the LMDI application handbook [48], the change in the carbon intensity of commercial buildings was decomposed again as follows:

$$\Delta c|_{0 \to T} = \Delta K_{\mathrm{LMDI}} + \Delta p_{\mathrm{LMDI}} + \Delta g_{\mathrm{LMDI}} + \Delta s_{\mathrm{LMDI}} + \Delta i_{\mathrm{LMDI}} + \Delta e_{\mathrm{LMDI}} \tag{19}$$

Specifically, each term (e.g., ΔK_{LMDI}) [49] on the right-hand side of the above equation is further expressed as:

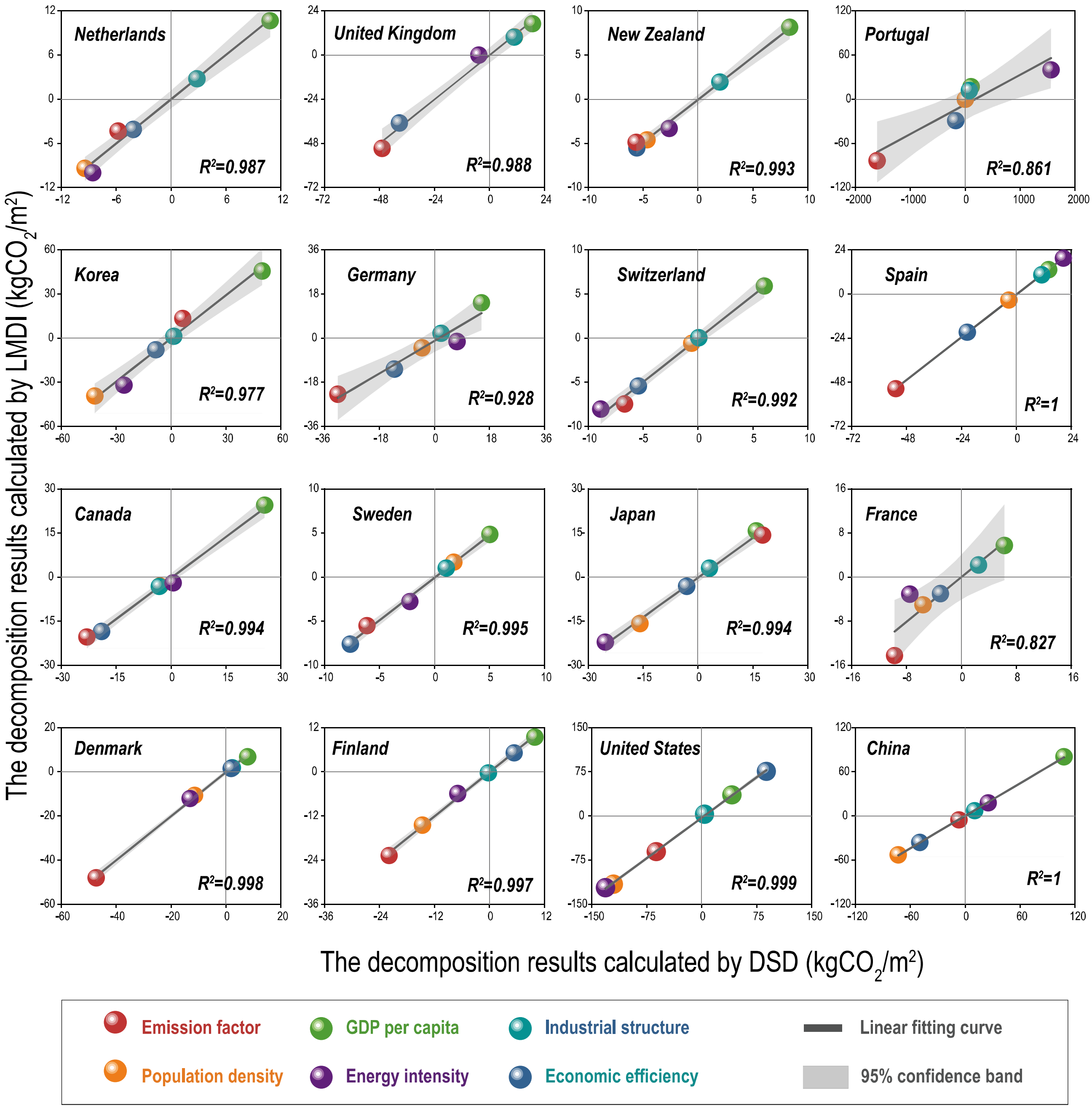

Fig. 9. Comparison of the DSD and LMDI results by regression analysis.

$$\Delta K_{\mathrm{LMDI}} = \frac{c|_T - c|_0}{\ln c|_T - \ln c|_0} \cdot \ln\left(\frac{K|_T}{K|_0}\right) \tag{20}$$

Thereafter, the results generated based on DSD [Eq. (14)] and LMDI [Eq. (19)] were compared by regression analysis (see Fig. 9). It can be clearly observed that all drivers are distributed in the first or third quadrants of the coordinate system, indicating that the two decomposition methods agree on whether the contribution of each driver is positive or negative. For instance, GDP per capita (see green points in Fig. 9) is in the first quadrant in all cases because both DSD and LMDI methods state that GDP per capita in 16 countries contributes positively to the growth of carbon intensity from commercial building operations. As shown in Fig. 9, the average goodness-of-fit (R^2) for the 16 countries is 0.97, which means that the results generated by the two decomposition techniques are essentially identical, and the 95% confidence interval also corroborates that the test results are reliable. In other words, the DSD method is sufficient to output convincing decomposition results in the carbon intensity analysis and historical decarbonization assessment of global commercial building operations.

Overall, the robustness test verifies that the DSD results are reliable for assessing the decarbonization of global commercial building operations, and this examination is the final step in fully answering Issues 1 and 2 raised in Section 1.

5.3. Strategies to accelerate the decarbonization process of global commercial buildings

Electricity decarbonization is expected to be a key approach to break the carbon lock-in effect [50]. For building operations, improving the electrification of end-use by deploying zero-carbon electricity is becoming an attractive approach to decarbonize buildings [51]. Even in the absence of policy interventions, the electrification level in the building sector shows strong performance [52]. To completely answer Issue 3 in Section 1, this study investigated the current state of global commercial building electrification development and proposed recommendations for the deep decarbonization of commercial building operations [53].

Fig. 10 shows the commercial building electrification level in 16 countries in 2000, 2010, and 2019. All annulus sectors were divided into two categories (red block: electrification level over 50%, blue block: electrification level below 50%). It can be clearly observed that the share of red blocks gradually increases, with 9 of the 16 countries having electrification coverage by 2019. The highest level of electrification was found in Portugal, followed by Korea, New Zealand, Spain, Japan, Sweden, the United Kingdom, France, and Finland. In contrast, China was by far the country with the lowest level of electrification. Overall, the electrification level of end-uses in global commercial buildings has steadily grown, from 46.96% in 2000 to 53.65% in 2019. At the same time, the end-use energy efficiency of commercial building operations was advancing the process of decarbonizing commercial buildings. However, the pace of decarbonization was noted to have slowed based on the results observed in Section 5.1.

Based on the analysis above, the following recommendations are proposed to accelerate the decarbonization process of global commercial building operations. In terms of electrification of end-use, for space heating and cooling, areas with high heat density need to adopt more district heat network technologies and maximize the district heat supply [54]. At the same time, the proportion of combined heat and power production (or industrial waste heat [55]) technologies used is upgraded to reduce the decarbonization costs of heating and cooling [56]. Areas with lower heat density use geothermal source heat pumps or other low-carbon alternatives [57](e.g., fuel cells and hydrogen-based technologies [58]). In addition, to relieve pressure on the demand for electricity infrastructure [59], a dual-source system using new heat pumps to maintain existing fossil-fueled equipment is an optional transition option [60]. For service lighting, the application of light-emitting diodes needs to be vigorously promoted to replace incandescent lamps as soon as possible and then gradually replace fluorescent lamps [61]. In terms of the building decarbonization, monitoring and regulation of energy use in commercial buildings worldwide should be strengthened [62]. For instance, the commercial buildings energy consumption survey in the United States provides an in-depth look at the building stock, end-use activity, and energy structure in building operations. In China, commercial building energy monitoring platforms have been deployed in dozens of provinces and cities (e.g., Shanghai) to collect hourly/daily energy data of different end-uses in building operations [63]. In terms of building structure design, ultralow energy buildings, near-zero energy buildings, and zero-carbon buildings need to be promoted [64]. High-performance building envelopes (e.g., colored low-emissivity films [65] and variable conductivity materials [66]) should be designed to enhance building energy efficiency and reduce emissions. In terms of technical measures, the governments are suggested to increase the use of economic instruments such as carbon markets [67], carbon taxes [68], and digital technology to guide the development of low-carbon technologies [69]. vigorously develop carbon capture, utilization and storage technologies suitable for buildings [70], and strengthen ecosystem carbon sequestration [71]. In summary, this study combined the historical decarbonization assessment and the electrification development retrospection in commercial building operations worldwide and proposed corresponding policy recommendations, thus completely responding to Issue 3 raised in Section 1.

6. Conclusion

This study assessed the decarbonization progress of global commercial building operations over the last two decades via the DSD method. First, the building emission model with end-use characteristics was established to characterize the operational carbon intensity and its changes in the 16 selected countries were investigated. In addition, the impacts of end-use activities on decarbonizing commercial building operations were evaluated. Based on the DSD result, the historical decarbonization level across different emitters' commercial buildings was assessed. Furthermore, the LMDI approach was applied to examine

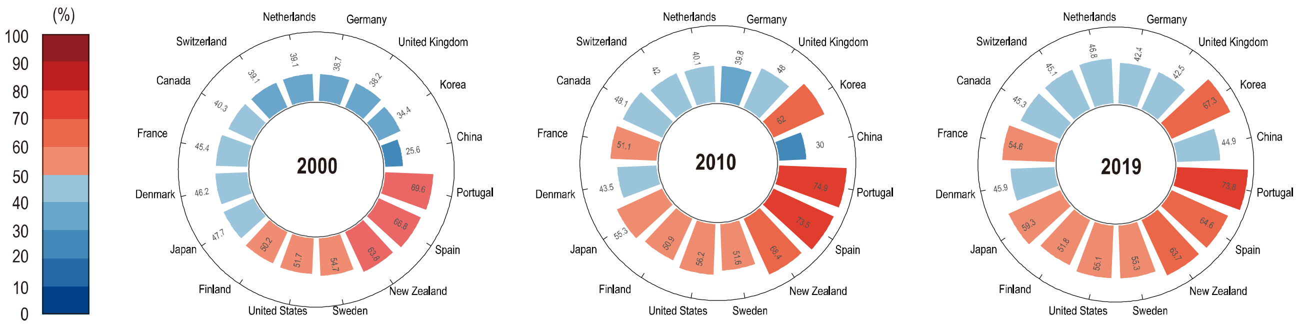

Fig. 10. Electrification levels in global commercial building operations (2000–2019).

the robustness of DSD. Finally, the decarbonization strategies of global commercial building operations were reviewed to seek the best practical path for future building decarbonization. The key findings are summarized as follows.

6.1. Key findings

- **The carbon intensity of global commercial building operations continued to decline from 2000 to 2019, and the trend was more significant.** The carbon emission intensity in 16 countries decreased by an average of 1.42% and 2.93% per year in the periods of 2000–2010 and 2010–2019, respectively. GDP per capita as a factor was the most positive factor hindering the decrease in carbon intensity, followed by economic efficiency. On the other hand, the emission factor and industrial structure were key to decarbonizing the commercial building operations.
- **Energy intensity covering different end-uses contributed to decarbonizing commercial buildings, with the largest contributions from space heating (-14.33 $kgCO_2/m^2/yr$) and service lighting (-5.29 $kgCO_2/m^2/yr$), followed by appliances and others (-2.85 $kgCO_2/m^2/yr$), and space cooling (-1.24 $kgCO_2/m^2/yr$).** Regarding the energy intensity, space heating was the main way to decarbonize commercial building operations (-20.21 $kgCO_2/m^2/yr$) during 2000–2010, while the decarbonization effect of other end-uses was not obvious. From 2010 to 2019, the positive effect of space heating, appliances and others on the decarbonization was observed in an increasing number of countries (space heating: −7.80 $kgCO_2/m^2/yr$, appliances and others: −3.62 $kgCO_2/m^2/yr$). Furthermore, the contributions of service lighting (before 2010: 1.04 $kgCO_2/m^2/yr$, after 2010: −4.69 $kgCO_2/m^2/yr$) and space cooling (before 2010: 2.02 $kgCO_2/m^2/yr$, after 2010: −0.64 $kgCO_2/m^2/yr$) to decarbonization started to change from positive to negative.
- **The pace of decarbonization of global commercial building operations was slowing. By 2019, the decarbonization intensity of commercial buildings in 16 countries was 6.86 $kgCO_2/m^2$ or 97.42 $kgCO_2$ per capita.** This study evaluated the progress of decarbonization of global commercial buildings. From 2000 to 2019, the cumulative decarbonization level of 16 countries was 4375.39 $MtCO_2$, equivalent to 10.05% of the total cumulative emissions, of which 77.81% of decarbonization came from China and the United States. The cumulative decarbonization of the remaining countries was generally less than 100 $MtCO_2$ per emitter. The share of decarbonization of commercial buildings in 16 countries during the four periods was 29.08% (2001–2005), 26.71% (2006–2010), 26.81% (2011–2015), and 17.40% (2016–2019).

6.2. Upcoming works

To further reinforce the theme of decarbonizing commercial buildings, tools for assessing the decarbonization of future building operations should continue to be developed to determine a deep decarbonization roadmap for the global commercial building sector, leading to the 1.5 ℃ goal set out in the Paris climate agreement. In addition, the shared socioeconomic pathway provides climate and socioeconomic trajectories under different scenarios, which can also be employed to forecast the future trajectory of emissions from the building sector and the cost effectiveness of deep decarbonization. Second, although this is the first study to decompose the operational carbon intensity of commercial buildings considering the end-use activities with the robustness of the results being examined, the impact of other end-uses (e.g., cooking and special building equipment) on decarbonizing commercial buildings is worthy for further investigation. More than that, residential buildings with high emissions are also worth studying using the method proposed in this study. In addition, the decarbonization assessment at the near-real-time level should become the next knowledge gap to be covered, which will be more effective to identify the change of operational decarbonization during extreme events such as the COVID-19 pandemic. Finally, since population size, climate conditions, and economic growth vary greatly across different regions, climate adaptation policies need to provide more details to be implemented effectively. Therefore, analyzing the decarbonization of commercial buildings at the city level will be beneficial in realizing deep decarbonization in the era of carbon neutrality.

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.

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Author Contributions

MD Ma conceptualized the framework of this study. XW Xiang, X Ma, and MD Ma contributed to the methodology, data collection, data calculation, and results analysis. WG Cai, W Feng, and ZL Ma helped to polish the original manuscript. All authors read, revised and approved the final version of the original manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2022.119401.

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