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Original Paper

What decarbonized the residential building operation worldwide since the 2000s

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ABSTRACT

Decarbonization in operational residential buildings worldwide has become critical in achieving the carbon neutral target due to the growing household energy demand. To accelerate the pace of global carbon neutrality, this study explores the operational carbon change in global residential buildings through the generalized Divisia index method and decoupling analysis, considering the decarbonization levels of residential buildings at different scales. The results show that (1) most of the samples showed a decrease in the total emissions from 2000 to 2019. Except for China and the United States (US), the carbon emissions in global residential building operations decreased by 7.95 million tons of carbon dioxide ($MtCO_2$) per year over the study period. Emissions per gross domestic product (GDP) was the most positive driver causing the decarbonization of residential buildings, while GDP was the most negative driver. (2) Carbon intensity was essential to achieving a strong decoupling of economic development and carbon emissions. The US almost consistently presented strong decoupling, while China showed weak decoupling over the last two decades. (3) The pace of decarbonization in global residential building operations is gradually slowing down. From 2000 to 2019, decarbonization from residential buildings across 30 countries was 2094.3 $MtCO_2$, with a decarbonization efficiency of 3.4%. Overall, this study addresses gaps in evaluating global decarbonization from operational residential buildings and provides a reference for evaluating building decarbonization by other emitters.

1. Introduction

Carbon emissions from human activities have posed a significant existential threat to modern civilization (Zhang et al., 2020a). The Intergovernmental Panel on Climate Change indicated that the global level of carbon emissions over the past decade has reached the highest level on record (IPCC, 2022). Without immediately deep decarbonization in all sectors, the goal of limiting global warming to 1.5 °C by mid-century will likely not be achieved (Ren et al., 2022a). Buildings, which play a critical role towards the global carbon neutral status, accounted for one-third of energy use and two-fifths of carbon emissions worldwide in 2020 (UNEP, 2021). Carbon emissions from the operational phase of buildings have an essential place in carbon mitigation due to the long lifespans, with 8.7 gigatons of carbon dioxide worldwide in 2020 (Zhang et al., 2022b). Evidence shows that carbon mitigation in residential buildings has a decisive contribution to the limitation of global warming (Panagiotidou et al., 2021). In 2020, global residential buildings accounted for 22% of all energy consumption, roughly three times that of commercial buildings (IEA, 2021; Zhang et al., 2021c). Compared to commercial buildings, residential buildings have been proven to possess lower decarbonization efficiency and more significant carbon lock-in effects, and to be cost effective in decarbonization (Jing et al., 2022b; Li et al., 2022). There is no doubt that if buildings are the “last kilometer” sector of global carbon neutrality, residential buildings can be considered the “last one hundred meters” of the sector (You et al., 2021, 2023). Therefore, it is necessary to evaluate the historical decarbonization level of global residential building operations to achieve deep decarbonization and achieve carbon neutrality.

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Abbreviations

GDIM	Generalized Divisia index method
HCE	Household consumption expenditure
IBED	International Building Emissions Database
$kgCO_2$	Kilograms of carbon dioxide
kgoe	Kilograms of oil equivalent
LMDI	Log-mean Divisia index
$MtCO_2$	Million tons of carbon dioxide
NDCs	Nationally Determined Contributions
OECD	Organization for Economic Co-operation and Development
USD	the United States dollars

Symbols

C	The total carbon emissions
c	Emissions per floor space
$c_{\langle ce}$	Emissions per household consumption expenditure
c_{gdp}	Emissions per GDP
c_p	Emissions per capita
E	The total energy consumption
e	Energy consumption per floor space
$e_{\langle ce}$	Energy consumption per household consumption expenditure
F	Gross floor space
g	GDP per capita
GDP	Gross domestic product
HCE	Household consumption expenditure
K	Household consumption expenditure
P	Population
s	Expenditure-to-value ratio
φ	Decoupling elasticity index
$\Delta C_{0\rightarrow T}$	Carbon emission changes during ΔT
$\Delta HCE_{0\rightarrow T}$	Household consumption expenditure per capita changes during ΔT

Limiting global warming to well below 1.5 °C will require a significant reduction in global carbon emissions by the mid-century, followed by negative emissions (Zhang et al., 2020a). To this end, 136 countries have mentioned the building emission reductions in their nationally determined contributions (NDCs) under the Paris Agreement (Jiang et al., 2022c), although these vary in their ambition (Li and Duan, 2020). It can be noted that although many countries have proposed NDCs for global carbon neutrality, a review of historical decarbonization and a baseline determination for decarbonization potential from residential buildings are not yet been conducted. To fill the above research gaps, several pending issues can be proposed for global residential buildings as follows:

- How the operational carbon changes worldwide in this century?
- How does the decoupling status in economy and emissions perform among different emitters?
- What is the decarbonization level, and how can we perform in depth decarbonize to achieve net-zero emissions?

To tackle the above issues, this study focuses on establishing a decomposition model for carbon emissions in operational residential buildings to identify the main drivers of carbon emission changes and assess the historical decarbonization level. Meanwhile, a decoupling analysis model is developed to examine the decoupling status of emissions and the economy via year-by-year and two-phase approaches, as well as to explore the impact of different subdivision decoupling elasticities. To deeply evaluate decarbonization efforts, this study explores historical decarbonization levels based on decomposition models from four scales, decarbonization per floor space, per household, per capita, and total decarbonization, and further discusses decarbonization efficiency. In addition, this study reviews building decarbonization strategies based on the development of electrification levels in different countries and proposes policy recommendations for achieving global carbon neutrality goals in the future.

Regarding the most significant contribution, this study makes the first attempt to investigate the changes in carbon emissions from global residential building operations using the extended generalized Divisia index method (GDIM), an improved index decomposition analysis model, and to explore the decoupling status of the economy and emissions. To the best of our knowledge, there have been relatively few studies using GDIM for buildings and almost none for residential buildings from a global perspective. Additionally, this study provides an empirical global case for deep decarbonization by assessing the historical decarbonization level and determining the baseline of decarbonization potential.

The rest of this study is structured as follows: a review of the literature is presented in Section 2. Section 3 introduces the model and data sources. Section 4.1 proposes an assessment of drivers influencing decarbonization, and the decoupling effect of the economy and carbon emissions is presented in Section 4.2. Sections 5.1 and 5.2 investigate the historical carbon mitigation level through four scales, and Section 5.3 covers the decarbonization strategies in residential buildings by exploring the development of the electrification level. Section 6 concludes the key findings and suggests future study directions.

2. Literature review

With the continuous attention to climate change issues, the study of carbon emission drivers has become an area of heavy discussion among different fields (Su and Ang, 2012). Currently, the approach of decomposition analysis in carbon emissions mainly includes index decomposition analysis and structural decomposition analysis (Liu et al., 2019). Since structural decomposition analysis needs to be supported by a large amount of data in input-output tables, it is difficult to widely implement this method (Lin and Raza, 2021). However, the log-mean Divisia index (LMDI) proposed by Ang (2005) as one of the index decomposition approaches is widely used in carbon emission driver decomposition analysis due to its simplicity of calculation and absence of residuals (Zhang et al., 2022a). The deficiencies of the LMDI approach have gradually emerged with the intensive investigation of the index decomposition analysis. Evidence shows that the LMDI approach on the basis of Kaya identity is unreliable due to the interdependence among its drivers, and the selection of drivers largely affects the decomposition results. To address this limitation, Vaninsky (2014) proposed GDIM, which more comprehensively and accurately quantified the contribution of drivers, distinguished the relevance of drivers and solved the issues of double calculations. It is worth noting that GDIM has gained much attention despite its short history of application. GDIM has been applied to analyze the changes in energy-related greenhouse gases in the agricultural sector in European Union countries (Yan et al., 2017a), changes in carbon emissions from residential buildings in developing countries (Yan et al., 2022), and the impact of information and communication technologies on changes in carbon emissions in the Organization for Economic Cooperation and Development (OECD) countries (Wang et al., 2021b). GDIM has also been applied to investigate the carbon emission changes in different industries. Shao et al. (2016) explored the changes in carbon emissions from China's mining sector and revealed that carbon intensity and output scale are two primary factors. Liu et al. (2022) employed GDIM to investigate the drivers affecting carbon emissions in the manufacturing sector and found that the carbon intensity of innovation inputs and output are key factors. Meanwhile, GDIM has contributed significantly to the evolution of new energy development (Pan and Dong, 2022), PM 2.5 control (Yu and Fang, 2021), non-fossil energy development (Zhang et al., 2020b), and electricity consumption analysis (Fang et al., 2020). As mentioned above, it can be seen that from the global perspective, there is almost no research on GDIM in building operations.

The challenge of how to effectively balance carbon emissions and economic development has been explored for many years (Zhao et al., 2016; Yang et al., 2021). The OECD was the first to introduce the concept of "decoupling" and to develop a basic theory of the relationship between economic growth and environmental pollution (OECD, 2001). Tapio applied elasticity theory to decoupling indicators and classified them into eight categories (Tapio, 2005). Compared to the OECD decoupling model, the Tapio decoupling elasticity index is widely used in existing studies due to its computational simplicity and provides a clear definition of decoupling states (Wang et al., 2020). Decoupling analysis is increasingly applied by scholars in different industries, such as energy (Kan et al., 2019), electricity (Wang et al., 2022a), buildings (Chen et al., 2022b), and manufacturing (Hang et al., 2019). The decoupling analysis approach accurately describes the dynamic relationship between economic growth and environmental changes, and the combination of decoupling analysis and decomposition analysis can effectively identify the critical decarbonization factors and provide a reference for decarbonization policies.

A review of the literature reveals that although there have been some studies on the decomposition of carbon emission changes, research gaps remain. The drivers that cause changes in carbon emissions from buildings have been investigated exhaustively in existing studies; however, most of these studies focused on commercial buildings (Ma et al., 2017), specifically mostly on a single country, and ignored the impact of carbon emissions from building operations (Jing et al., 2017). As the world's leading carbon emitter, exploring the historical changes in carbon emissions and identifying the carbon mitigation potential will be of importance for advancing the global carbon neutrality goal (Dong et al., 2021). Compared to commercial buildings, residential buildings have a higher potential for decarbonization, and it has been considered a significant threat on the path to carbon neutrality due to the difficulty of energy efficiency renovation of existing buildings and the increase in household energy consumption demand (Yan et al., 2017b). Nevertheless, studies on changes in carbon emissions from residential building operations in global leading carbon emitters remain scarce. Regarding the research methods, most existing studies used the index decomposition approach, and the examination of the drivers was typically not comprehensive. Therefore, the assessment of historical carbon emission changes in residential buildings can help clarify the decarbonization potential, identify the main drivers and provide effective assistance for decarbonization in residential buildings.

The status quo reveals the urgent need to consider the historical trajectories of carbon emissions from residential buildings and to identify the path of decarbonization and the decoupling relationship between emissions and the economy. To this end, this study endeavors to propose a historical decarbonization assessment framework, which can serve as the primary tool for evaluating the development of decarbonization in operational residential buildings in different economies around the world. Accordingly, this study strives to make the following contributions.

- **This study is the first to investigate the historical carbon emission changes and drivers in operational residential buildings across 30 countries from 2000 to 2019.** This study is the first to employ an extended GDIM approach to explore the historical carbon emissions of global residential buildings. Using this approach, 14 drivers, including technological and socioeconomic factors are identified, which are not available within other existing index decomposition approaches; additionally, the impact on carbon emission changes is quantified. Meanwhile, this study further explores the decoupling nexus between emissions and the economy and investigates the contribution of different decoupling subcomponents in it, which forms a contrast and complementary explanation with the decomposition results.
- **This study makes the first attempt to build a global framework for assessing historical decarbonization in residential building operations based on decarbonization intensity, total decarbonization and decarbonization efficiency.** This study investigates the annual decarbonization and explores the decarbonization intensity from decarbonization per floor space, per household, per capita and total decarbonization, then further evaluates the historical decarbonization efficiency. On this basis, the development of the electrification level is reviewed to further discuss decarbonization strategies for achieving global carbon neutrality. This study strives to form a relatively complete decarbonization assessment framework and serve as a primary reference tool for policy-makers on the path to achieving carbon neutrality.

3. Method and data sources

Section 3 introduces a framework to assess the carbon emissions changes in operational residential buildings worldwide. In Section 3.1, the GDIM approach is developed to identify the impact of different drivers on carbon emissions. Then, based on the GDIM decomposition model, the Tapio decoupling model is introduced to further explore the decoupling effect of carbon indicators and economic indicators (Section 3.2). In addition, the research area and data sources are introduced in Section 3.3.

3.1. Decomposition model

After considering the limitations of existing decomposition methods, the extended GDIM was proposed to refine the deficiencies. The extended GDIM approach mainly constructed a multidimensional driver decomposition model including absolute and relative indicators, which revealed the motives of changes in environmental target variables (carbon emissions in this study). The approach compensated for the deficiency of formal dependence among factors in the existing decomposition methods, in which the decomposition results distinguish the correlations among all factors to avoid the problem of double calculations (Boratyński, 2021). According to the fundamental theory of GDIM, emission sources and characteristics of residential buildings, carbon emissions can be considered with different carbon intensities to build the decomposition analysis model. According to the examination of Chen et al. (2022a) for the change in carbon emissions of the operational residential buildings, five carbon intensities can be considered (as shown in Eq. (1)), including emissions per household consumption expenditure (HCE), emissions per energy consumption (i.e., emission factor), emissions per capita, emissions per gross domestic product (GDP), and emissions per floor space. According to the analysis above, the expression of the influencing factors for carbon emissions from residential buildings can be presented as follows.

$$C_i = \frac{C_i}{HCE_i} HCE_i = \frac{C_i}{E_i} E_i = \frac{C_i}{GDP_i} GDP_i = \frac{C_i}{P_i} P_i = \frac{C_i}{F_i} F_i \tag{1}$$

$$\frac{E_i}{HCE_i} = \left(\frac{C_i}{HCE_i}\right) \Big/ \left(\frac{C_i}{E_i}\right) \tag{2}$$

$$\frac{HCE_i}{GDP_i} = \left(\frac{C_i}{GDP_i}\right) \Big/ \left(\frac{C_i}{HCE_i}\right) \tag{3}$$

$$\frac{GDP_i}{P_i} = \left(\frac{C_i}{P_i}\right) \Big/ \left(\frac{C_i}{GDP_i}\right) \tag{4}$$

$$\frac{P_i}{F_i} = \left(\frac{C_i}{F_i}\right) \Big/ \left(\frac{C_i}{P_i}\right) \tag{5}$$

where i indicates different country samples ($i = 1, 2, 3 \ldots 30$). As shown in Eq. (1), C represents the total carbon emissions in residential building operations, HCE represents the household consumption expenditure, E is the total energy consumption from residential buildings, GDP represents the gross domestic product, P indicates the population size and F is the gross floor space of residential buildings. The five variables mentioned above are absolute indicators for the decomposition method. For simplicity of representation, the relative indicators are defined as follows: $K = C/\ E$ indicates the emission factor, $c_{\langle ce} = C/HCE$ indicates the emissions per HCE, $c_{gdp} = C/GDP$ indicates emissions per GDP, $c_p = C/\ P$ indicates emissions per capita, $e_{\langle ce} = E/HCE$ is energy consumption per HCE, $s = HCE/GDP$ represents the expenditure-to-value ratio, $g = GDP/P$ represents GDP per capita, $c = C/F$ indicates emissions per floor space, and $e = E/F$ represents energy consumption per floor space (e.g., energy intensity). Eqs. (1)–(5) can be further converted into the following equations.

$$C_i = HCE_i \bullet c_{\langle ce,i} \tag{6}$$

$$HCE_i \cdot c_{\langle ce,i} - E_i \bullet K_i = 0 \tag{7}$$

$$\mathrm{HCE}_i \cdot c_{\langle ce,i} - GDP_i \bullet c_{gdp,i} = 0 \tag{8}$$

$$\mathrm{HCE}_i \cdot c_{\langle ce,i} - P_i \bullet c_{p,i} = 0 \tag{9}$$

$$\mathrm{HCE}_i \cdot c_{\langle ce,i} - F_i \bullet c_i = 0 \tag{10}$$

$$\mathrm{HCE}_i - GDP_i \bullet s_i = 0 \tag{11}$$

$$E_i - \mathrm{HCE}_i \bullet e_{\langle ce,i} = 0 \tag{12}$$

$$GDP_i - P_i \bullet g_i = 0 \tag{13}$$

$$E_i - F_i \bullet e_i = 0 \tag{14}$$

Assuming that the contribution of different drivers $X = [HCE, c_{\langle ce}, E, K, GDP, c_{gdp}, s, e_{\langle ce}, P, c_p, g, F, c, e]$ to the change in carbon emissions is $C_i(X)$, a Jacobian matrix Φ_X consisting of different drivers can be constructed from Eqs. (6)–(14).

$$\Phi_X = \begin{pmatrix} c_{\langle ce,i} & HCE_i & -K_i & -E_i & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ c_{\langle ce,i} & HCE_i & 0 & 0 & -c_{gdp,i} & -GDP_i & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ c_{\langle ce,i} & HCE_i & 0 & 0 & 0 & 0 & 0 & 0 & -c_{p,i} & -P_i & 0 & 0 & 0 & 0 \\ c_{\langle ce,i} & HCE_i & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -c_i & -F_i & 0 \\ 1 & 0 & 0 & 0 & -s & 0 & -GDP_i & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -e_{\langle ce,i} & 0 & 1 & 0 & 0 & 0 & 0 & -HCE_i & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -g_i & 0 & -P_i & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -e_i & 0 & -F_i \end{pmatrix}^{\mathrm{T}} \tag{15}$$

It can be noted that the Jacobian matrix Φ_X consists of all first-order partial derivatives of the drivers from Eqs. (7)–(14), which quantified the impact of each driver change on carbon emissions. Therefore, according to the GDIM principle, the changes in carbon emissions can be decomposed into the summing up of the contributions from different drivers, as presented in Eq. (16).

$$\Delta C_i[X|\Phi]^T = \int_L \nabla C_i^T \left(I - \Phi_X \Phi_X^+\right) dX \tag{16}$$

where L represents the time span, I indicates the identity matrix and $\nabla C_i = \begin{pmatrix} c_{\langle ce,i} & HCE_i & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T$. The superscript "+ " indicates the generalized inverse matrix, and $\Phi_X^+ = \left(\Phi_X^T \Phi_X\right)^{-1} \Phi_X^T$ occurs when the columns in the Jacobian matrix Φ_X are linearly independent. As mentioned above, the changes in carbon emissions of each sample can be decomposed into 14 drivers, which can be obtained as follows:

$$\Delta C_i = \sum_{j=1}^{14} \Delta C_i(X_j) \tag{17}$$

where j indicates the different drivers $j = (1, 2, \ldots 14)$. Hence, the contributions of absolute indicators and relative indicators causing the change in carbon emissions can be quantified by the above equations. For a more detailed description of the different drivers, Table 1 provides the relevant interpretations and the units used, in which the United States dollars (USD) are measured with 2010 US dollars.

Table 1
Variable interpretations and the units used.

Symbol	Meaning	Units	Expression
C	The total carbon emissions	Million tons of carbon dioxide ($MtCO_2$)	–
E	The total energy consumption	Million tons of oil equivalent (Mtoe)	–
HCE	Household consumption expenditure	Billion USD	–
GDP	Gross domestic product (GDP)	Billion USD	–
P	Population	Million persons	–
F	Gross floor space	Million square meters (m^2)	–
K	Emission factor	Kilograms of carbon dioxide ($kgCO_2$)/Kilograms of oil equivalent (kgoe)	$K=\frac{C}{E}$
c_{hce}	Emissions per HCE	$kgCO_2$/USD	$c_{hce}=\frac{C}{HCE}$
c_{gdp}	Emissions per GDP	$kgCO_2$/USD	$c_{gdp}=\frac{C}{GDP}$
c_p	Emissions per capita	$kgCO_2$/person	$c_p=\frac{C}{P}$
e_{hce}	Energy consumption per HCE	kgoe/USD	$e_{hce}=\frac{E}{HCE}$
s	Expenditure-to-value ratio	%	$s=\frac{HCE}{GDP}$
g	GDP per capita	USD/person	$g=\frac{GDP}{P}$
c	Emissions per floor space	$kgCO_2/m^2$	$c=\frac{C}{F}$
e	Energy consumption per floor space	$kgoe/m^2$	$e=\frac{E}{F}$

3.2. Decoupling analysis

As mentioned above, the Tapio decoupling model has been widely used in existing studies due to its clear judgment criteria and simple calculation. Therefore, this study employed the Tapio decoupling model to build the judgment for decoupling the carbon indicator (e.g., the total carbon emissions) from the economic indicator (e.g., HCE). According to the definition, the expression can be illustrated as follows:

$$\varphi=\frac{\Delta C_{|0\rightarrow T}/C_{|0}}{\Delta HCE_{|0\rightarrow T}/HCE_{|0}} \tag{18}$$

where i indicates the country sample ($i=1,2,3\ldots 30$), $\Delta C_{i|0\rightarrow T}$ denotes the change in the total carbon emissions in residential building operations during the study period [0, T], and $\Delta HCE_{|0\rightarrow T}$ denotes the change in HCE. $C_{i|0}$ and $HCE_{|0}$ represent the carbon emissions and HCE in the base year chosen from the study period, respectively.

As defined in Eq. (17), the total decoupling elasticity φ_i can be further decomposed into the summing up of a series sub-decoupling elasticity as follows:

$$\varphi=\frac{\sum_{j=1}^{14}\Delta C(X_j)_{|0\rightarrow T}/C_{|0}}{\Delta HCE_{|0\rightarrow T}\Big/HCE_{|0}} \tag{19}$$

$$\varphi=\varphi_{HCE}+\varphi_{c_{hce}}+\varphi_E+\varphi_K+\varphi_{GDP}+\varphi\ c_{gdp}+\varphi_s+\varphi_{e_{hce}}+\varphi_P+\varphi_{c_p}+\varphi_g+\varphi_F+\varphi_c+\varphi_e \tag{20}$$

3.3. Data sources

Due to data validity and accessibility, the research samples of this study are 30 countries' residential building operations. The historical data, including energy consumption, total carbon emissions, and gross floor space, were obtained from the International Building Emissions Database (IBED) (Xiang et al., 2022). The data on population size, HCE and GDP were accessed from the World Bank, and all the economy-related indicators are measured with 2010 USD. To better observe the data distribution, Fig. 1a presents carbon emissions and five absolute indicators of the total carbon emissions changes using scatter plots, normal distribution overlays and box charts. Such data descriptions are commonly seen in the existing studies. The small year-to-year variation and the high density of data within the same value range leads to a visual bias of sparse data. To tackle the problem mentioned, Fig. 1b and c shows the density distribution of the axial whisker distribution map of population and residential floor space.

4. Results

4.1. Identification of drivers influencing residential building decarbonization

As mentioned in Section 3, the impact of 14 drivers on carbon emissions changes in operational residential buildings across 30 countries from 2000 to 2019 based on the GDIM approach is illustrated in Fig. 2. A total of 86.7% of the samples showed a decrease in the total carbon emissions from 2000 to 2019. Among all the samples, China and the United States (US) showed the most significant change in emissions. With the exception of China and the US, the rest of the samples decreased 7.9 $MtCO_2$ per year over the study period. From 2000 to 2019, the largest carbon emissions drop was in the US, which fell to 256.2 $MtCO_2$, with an average decrease of 1.1% per yr, while China's carbon emissions had the highest growth to 787.9 $MtCO_2$, with an average increase of 10.1% per yr. For the phasing of the change in the total carbon emissions, more than half (17/30) of the samples showed a decline in both phases. Notably, of the remaining 13 countries, 11 samples showed an inverted U-shaped change in the total emissions, reflecting a gradual decoupling between the economy and carbon emissions, except for China and South Korea, which showed sustained growth.

For the positive factors of decarbonization, emissions per GDP (average contribution level: 12.8%) was the most significant factor that caused a reduction in carbon emissions during the whole study period (2000-2019). Specifically, the most significant effects could be found in China (−25.7%), Lithuania (−23.3%) and the Slovak

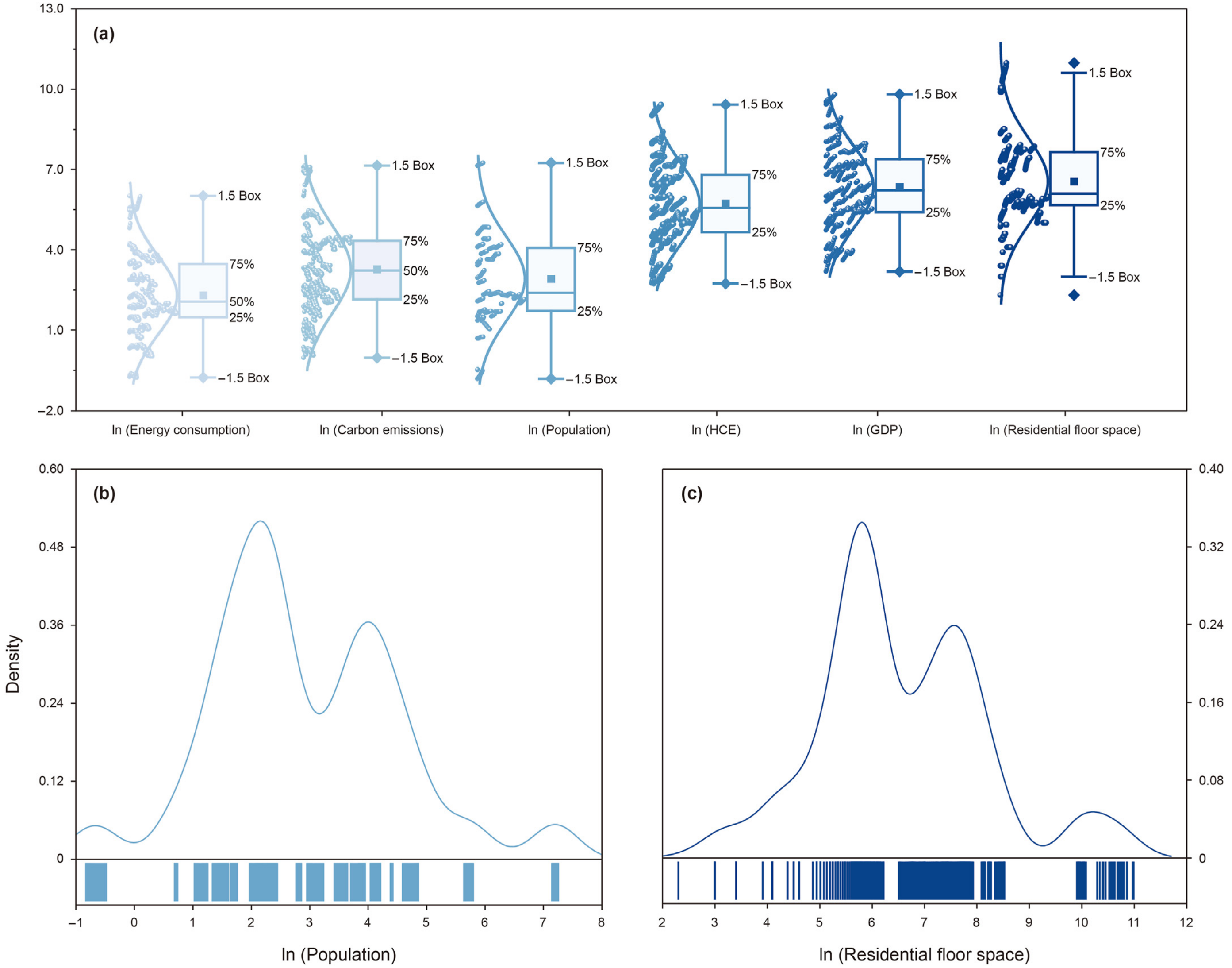

Fig. 1. (**a**) Normal curve and box superimposed plots for six variables and (**b-c**) population and residential floor space numerical density distribution across 30 countries from 2000 to 2019. Note: (a) The scatter denotes the samples, the diamond represents the maximum and minimum values, the square denotes the mean, the horizontal line in the center of the cabinet indicates the median value, and the boxes' sides reflect the 75% and 25% distribution levels, respectively, and (b-c) the vertical line in the bottom represents the samples.

Republic (−19.3%). Another positive factor for decarbonization was emissions per HCE (average contribution level: 11.7%), followed by emissions per floor space (average contribution level: 9.9%), emissions per capita (average contribution level: 5.5%) and emission factor (average contribution level: 5.4%). However, China (10.2%) was the only emitter with a growth in carbon emissions caused by emissions per floor space. Regarding the negative drivers of decarbonization, GDP (average contribution level: 9.8%) showed the most significant performance, especially in developing countries (e.g., China: 65.8%). Another negative factor for decarbonization was HCE (average contribution level: 8.6%), followed by residential floor space and population, with average contribution levels of 6.9% and 2.1%, respectively. Obviously, it can be intuitively observed that energy consumption, energy consumption per floor space, GDP per capita and the expenditure-to-value ratio had no significant effect on decarbonization in residential buildings. In addition, the impact of energy consumption on decarbonization did not appear unique, with the average contribution level changing from 2.9% before 2010 to −1.4% after 2010. Compared to the study period from 2000 to 2010, the absolute contribution level of different drivers decreased from 2010 to 2019, which is consistent with the continued declining trend in the total carbon emissions.

Overall, the analysis of the drivers' influences on the changes in the total carbon emissions from the operational residential buildings worldwide addresses question 1 in Section 1.

4.2. *Decoupling effect of residential buildings in representative emitters*

The results of the GDIM model in Section 4.1 show that economic indicators were the main negative drivers for decarbonization, implying a significant driving effect of economic growth on the growth of carbon emissions, and an obvious coupling relationship between these two can be found. To quantify the coupling relationship between the total emissions and economic indicators, this study established a Tapio decoupling index model based on GDIM and then explored whether a decoupling effect exists between emissions and the economy from 2000 to 2019.

Due to space limitations, four representative emitters were selected in this study based on a comprehensive consideration of the total carbon emissions and geographical location: the US, China, Australia, and Japan. As shown in Fig. 3, this study focused on the

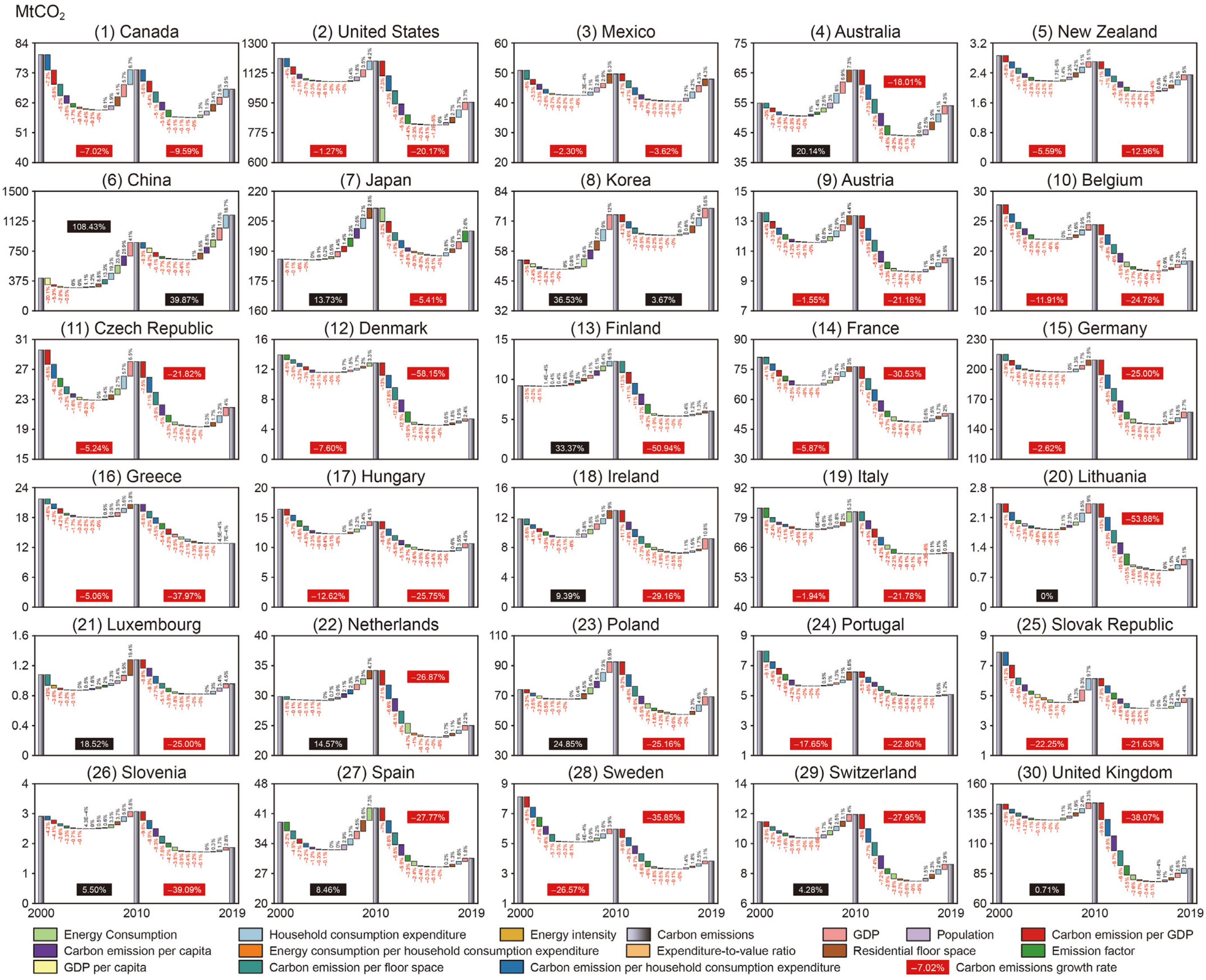

Fig. 2. Drivers' effects on changes in the operational carbon emissions of global residential buildings from 2000 to 2019.

decoupling effect on a year-by-year basis and in two phases. For the decoupling effect of two stages (radar plot in Fig. 3), it can be observed that the decoupling subsections with the most significant contribution to the strong decoupling status (i.e., carbon emission mitigation) and the weak decoupling status (i.e., carbon emission growth) can basically correspond to the results presented in Fig. 2 through GDIM approach. For example, from 2000 to 2010, the decoupling subsections that contributed most to the strong decoupling status in the US were emissions per HCE, while for China, Australia, and Japan, they were GDP per capita, emissions per floor space, and energy consumption per floor space, respectively. It is worth noting that almost all of the prominent contributions to the strong decoupling status were from relative indicators, while the weak decoupling status was from absolute indicators, indicating that carbon intensity will peak earlier in the decarbonization pathway compared to the total emissions. Specifically, the decoupling subsections with the most significant contributions to the strong and weak decoupling status from 2010 to 2019 were emissions per GDP and GDP for the US and Australia, and emissions per HCE and HCE for China.

Regarding the year-by-year decoupling effect (see Fig. 3 a-1), it can be observed that the proportion of years with a total decoupling elasticity index less than 0 (i.e., strong decoupling) in the US was 10/19, reaching a minimum value of −6.6 in 2012. Furthermore, the proportion of years with strong decoupling in the year-by-year analysis was 7/19, 6/19, and 2/19 for Australia, Japan and China, respectively. For the subsections of the annual peak decoupling elasticity index on a year-by-year basis, the prominent contributions to the strong decoupling results in 2012 for the US were emissions per GDP, emissions per HCE, emissions per floor space and emissions per capita. A similar situation also occurred in Japan, where the annual decoupling elasticity index peaked in 2018. For China, the decoupling elasticity index in the year-by-year analysis all showed weak decoupling except for 2004 and 2014, which presented strong decoupling, while 2001, 2002, and 2003 presented expansive negative decoupling. However, the decoupling subsections that contributed prominently to the expansive negative decoupling in 2003 were almost identical to those that contributed to the strong decoupling in the US in 2012, indicating that carbon emissions from residential buildings in China were still in the developing stage, while the US was already in the stage of decoupling carbon emissions from the economy.

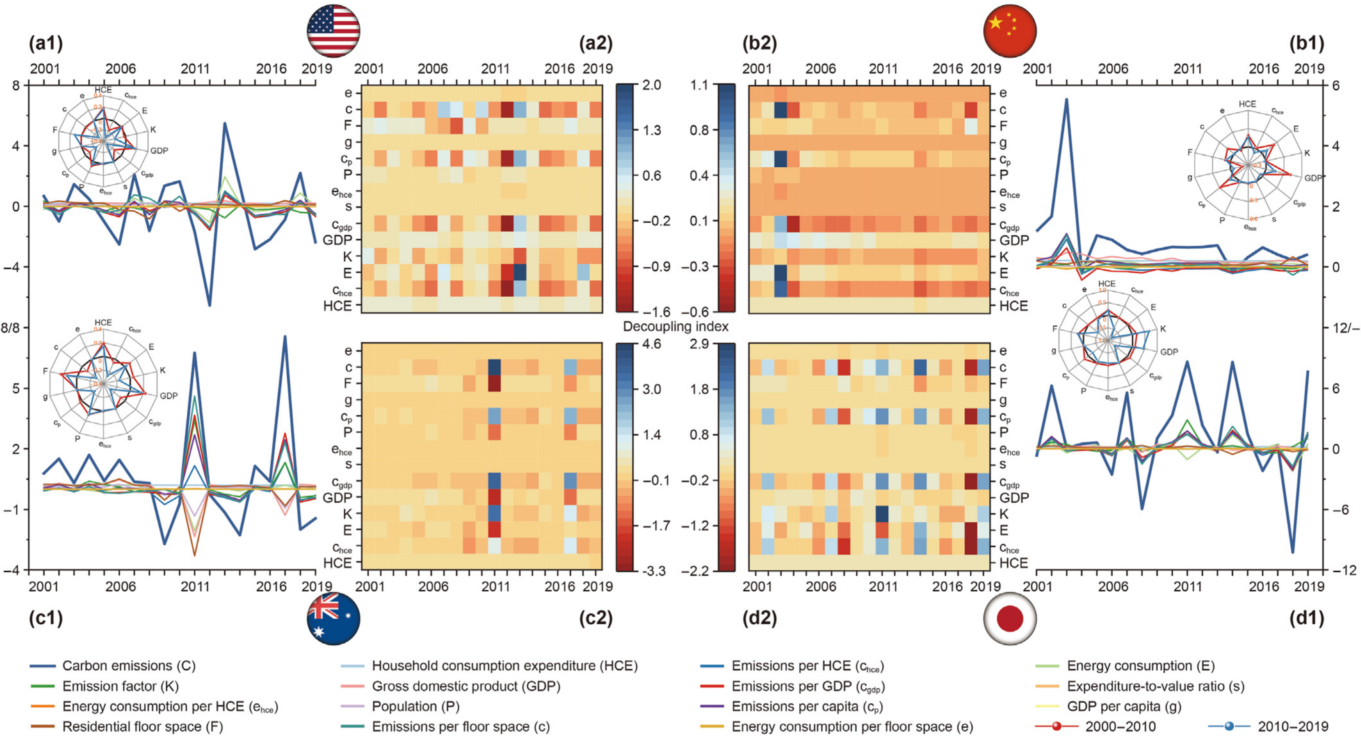

Fig. 3. Decoupling effect of different drivers affecting operational carbon in representative emitters' residential buildings.

Australia's sub decoupling elasticity index appeared to cancel each other out in 2011 (emissions per HCE and population, emission factor and residential floor space, GDP and emissions per capita), indicating that the total decoupling elasticity index in this year was largely influenced by the changes in emissions per floor space, energy consumption and emissions per GDP. Obviously, energy consumption, GDP per capita, the expenditure-to-value ratio, emissions per floor space, and HCE had a small and almost constant impact on the total decoupling elasticity index in the year-by-year analysis.

Overall, the investigation of decoupling status between economy and emissions from residential buildings in representative emitters addresses issue 2 in Section 1.

5. Discussion

As illustrated in Section 4, the decomposition and decoupling approaches thoroughly investigated the changes in historical carbon emissions and the status of coupling in emissions and economy. However, an accurate assessment of the historical decarbonization level can help different emitters directly close the gap with the proposed NDCs. Thus, Section 5.1 illustrates the changes in annual decarbonization, the total accumulated decarbonization, and decarbonization intensity across three scales from residential building operations to classify historical decarbonization. Section 5.2 proposes decarbonization efficiency to further assess the historical decarbonization level. Finally, through a review of decarbonization strategies based on the development of the electrification level in operational residential buildings worldwide, Section 5.3 proposes measures for deep decarbonization in residential buildings.

5.1. Decarbonization of global residential buildings

Based on the decomposition in carbon emissions from the operational residential buildings worldwide through GDIM in Section 4.1, decarbonization can be derived by summing up the negative contributions to the total emissions. Therefore, this study explores the decarbonization intensity in operational residential buildings across 30 countries on four scales: decarbonization per floor space, decarbonization per household, decarbonization per capita and total decarbonization. Fig. 4 presents the trend in annual decarbonization for 30 countries over the study period.

Although the total accumulated decarbonization continuously increased, the decarbonization in different years showed a fluctuation. As shown in Fig. 4, it can be intuitively observed that there are significant differences in annual decarbonization from residential building operations in different countries. Specifically, the US, as an economically developed country, decoupled carbon emission growth from economic development, with the highest average annual decarbonization of 44.3 $MtCO_2$, while China, as a developing country, had a similarly high average annual decarbonization (18.1 $MtCO_2$), although it was still in a weak decoupling status. Ranking by average annual decarbonization, the next highest were Germany and the United Kingdom (UK), with average annual carbon reductions of 8.1 $MtCO_2$ and 6.3 $MtCO_2$, respectively. It is worth noting that the rest of the countries had an annual average decarbonization of less than 5 $MtCO_2$, and 13 of them had an annual average decarbonization of less than 1 $MtCO_2$. This result indicates that China and the US have made essential contributions to the promotion of global decarbonization in residential building operations. The trends in the annual decarbonization curves showed that for different countries' annual decarbonization peak cases from 2000 to 2019, some countries peaked before 2010 (e.g., Mexico 3.7 $MtCO_2$ in 2004 and New Zealand 0.7 $MtCO_2$ in 2007) and after 2015 (e.g., Japan 16.5 $MtCO_2$ in 2018 and Portugal 2.4 $MtCO_2$ in 2019). The vast majority of the remaining countries (74.0%) peaked between 2011 and 2014, such as the UK in 2011 (23.8 $MtCO_2$), the US in 2012 (123.8 $MtCO_2$), and China in 2014 (68.2 $MtCO_2$).

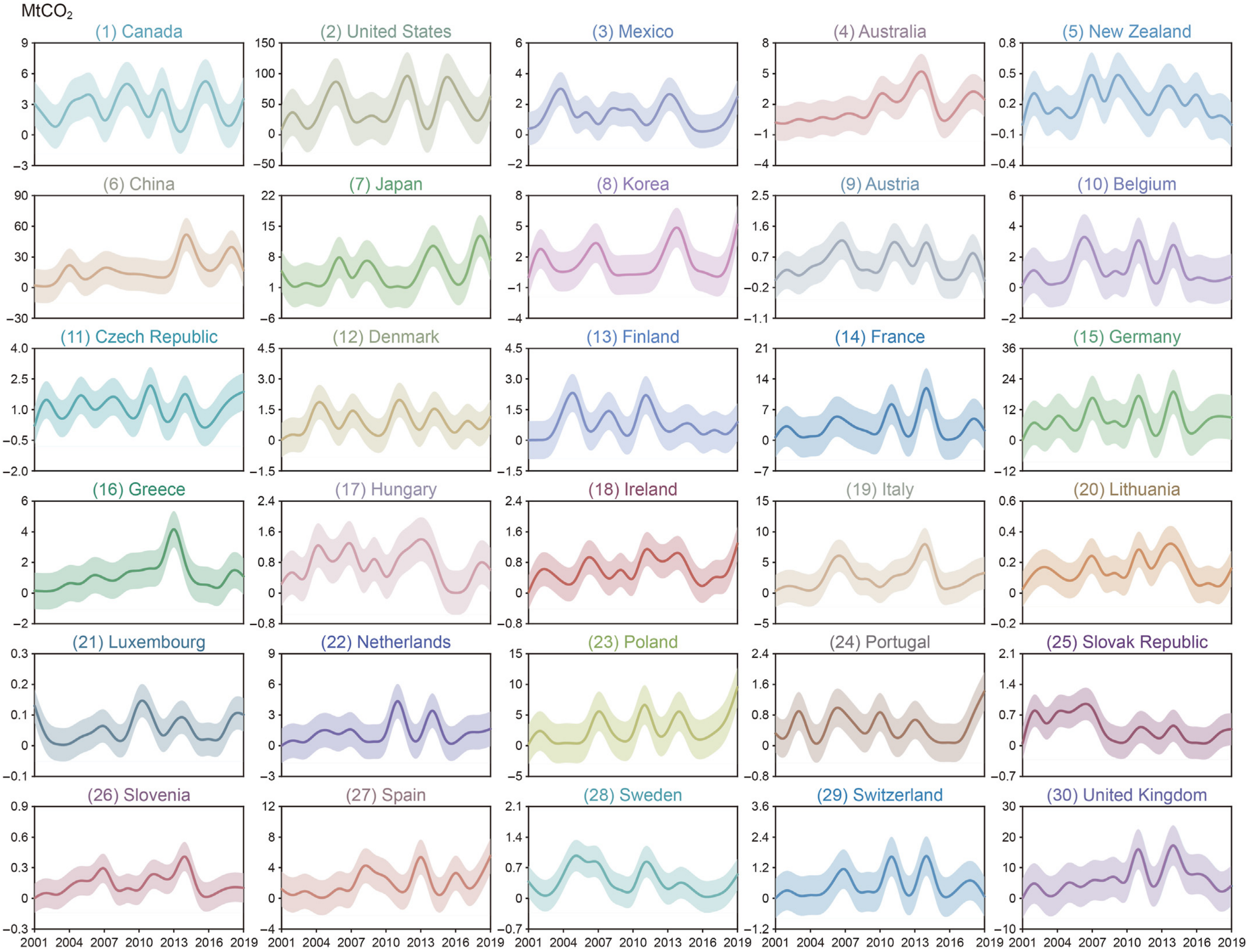

Fig. 4. Changes in annual decarbonization of global residential building operations (2001-2019).

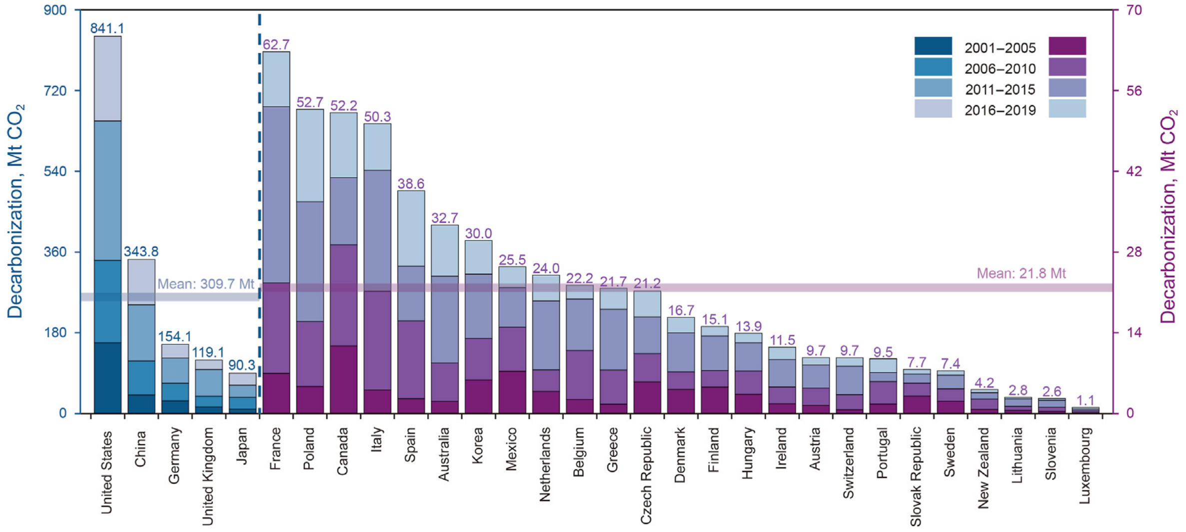

Fig. 5. Accumulated decarbonization in global residential building operations from 2000 to 2019.

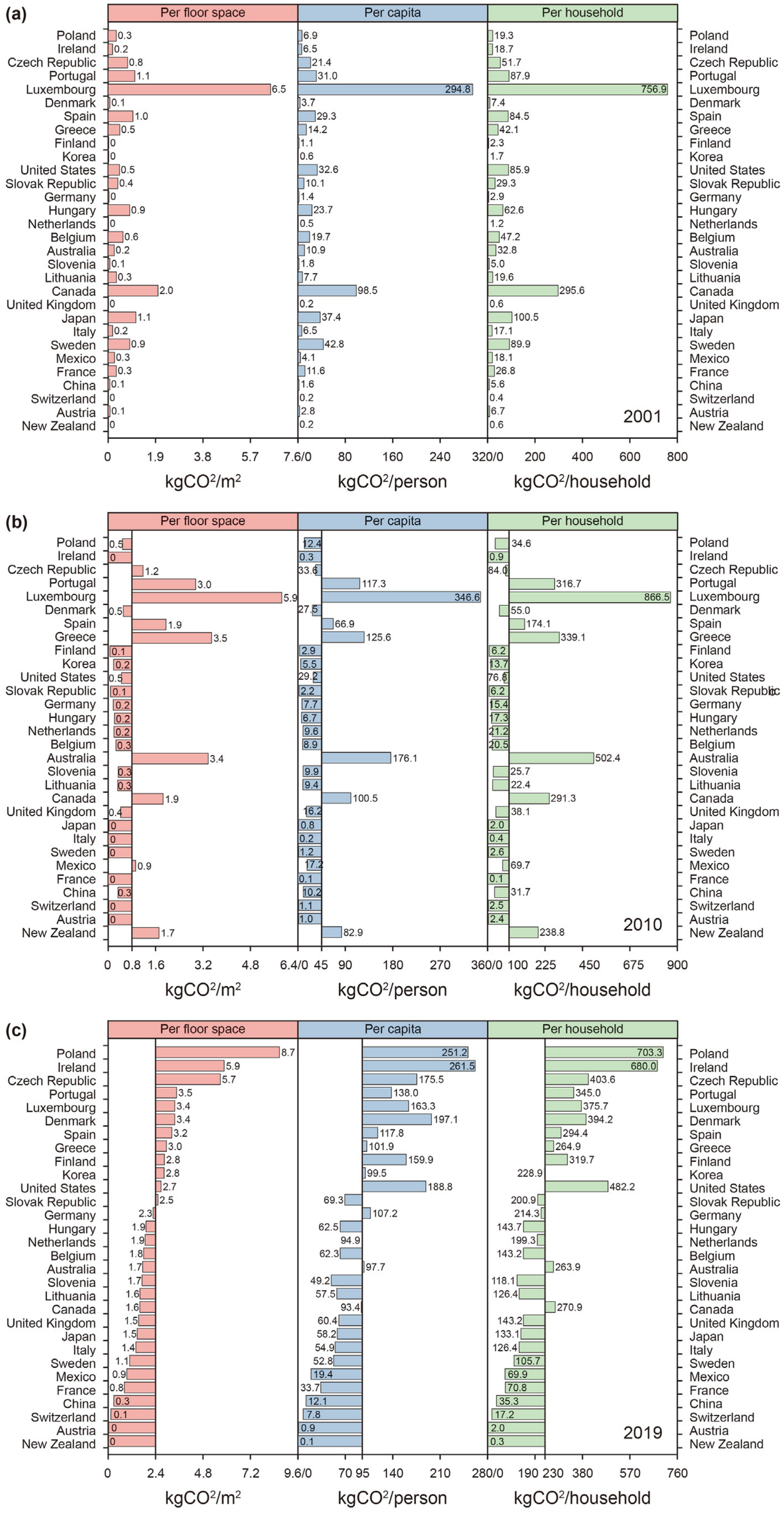

Fig. 6. Decarbonization intensity of the operational residential buildings worldwide at three scales (2001, 2010 and 2019).

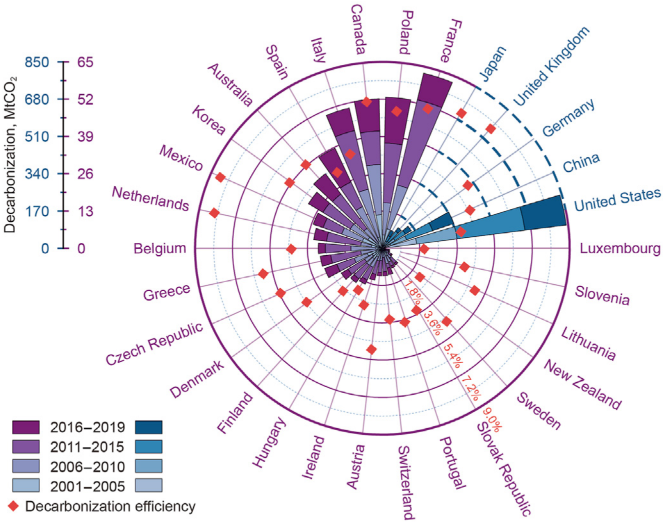

Fig. 7. Total decarbonization and its decarbonization efficiency in operational residential buildings worldwide during 2001-2019.

Fig. 5 presents the trend of the total accumulated decarbonization in global residential building operations from 2000 to 2019. The results indicate that the total accumulated decarbonization in the operational global residential buildings across 30 countries was 2094.3 $MtCO_2$ from 2000 to 2019, which accounted for 3.4% of the total accumulated carbon emissions. Among them, the total accumulated decarbonization of the US (841.1 $MtCO_2$) and China (343.8 $MtCO_2$) were much higher than those in other countries, followed by Germany (154.1 $MtCO_2$) and the UK (119.1 $MtCO_2$), whereas the total accumulated decarbonization of the rest of the samples was below 100 $MtCO_2$ (the largest is 90.4 $MtCO_2$ for Japan, and the smallest is 1.1 $MtCO_2$ for Luxembourg). It is worth noting that compared to the annual average decarbonization from 2001 to 2013, 60% of the samples saw a decrease in the annual average decarbonization from 2013 to 2019, indicating a gradual slowdown in the pace of decarbonization and a progressive carbon lock-in effect.

Fig. 6 shows the change in decarbonization intensities in the operational global residential buildings on three scales: decarbonization per floor space, per household and per capita. Regarding decarbonization per floor space, from 2000 to 2019, the average decarbonization per floor space of residential buildings in 30 countries was 1.9 $kgCO_2/m^2/yr$. Specifically, the Czech Republic (3.7 $kgCO_2/m^2/yr$), Belgium (3.2 $kgCO_2/m^2/yr$), and Ireland (3.2 $kgCO_2/m^2/yr$) were the top three emitters. Although the decarbonization per floor space from residential buildings in different countries fluctuated from year to year, most countries reached their annual decarbonization per floor space peak between 2011 and 2014, which resembled the changes in annual total decarbonization mentioned before. It can be clearly observed from Fig. 6 that there are significant differences in the changes in decarbonization intensities across the three scales for 30 countries in the study period. Taking decarbonization per capita as an example, from 2000 to 2019, decarbonization per capita generally declined in Canada, New Zealand, Austria and Luxembourg, with average annual declines of −0.3%, −2.7%, −3.7% and −2.5%, respectively. It is worth noting that all but these four countries showed increases, and even one-third of the samples grew by more than 100% per year during the study period. Overall, the global decarbonization of residential buildings under the three scales showed an upward trend over the study period. For example, the decarbonization per household of global residential building operations increased from 64.0 $kgCO_2/household$ in 2000 to 229.2 $kgCO_2/household$ in 2019. In particular, Luxembourg remained above 300 $kgCO_2/household$ throughout the study period, much higher than other countries.

5.2. Decarbonization efficiency of global residential buildings

To obtain deeper insight into the future decarbonization potential of global residential buildings and provide a benchmark for national determined contributions targets, decarbonization efficiency was introduced into the decarbonization assessment framework as a ratio of total decarbonization to total carbon emissions.

Fig. 7 presents the total decarbonization of different stages and the decarbonization efficiency during the study period. As mentioned above, the total decarbonization of different countries varied considerably from 2000 to 2019. The total decarbonization of the 30 countries during the study period amounted to 2094.3 $MtCO_2$, with the decarbonization of China, the US, Germany, the UK and Japan (sum of 1548.5 $MtCO_2$), far exceeding the remaining countries (sum of 545.8 $MtCO_2$). The decarbonization efficiency in global residential buildings was 3.4%, with Finland having the highest decarbonization efficiency of 8.3%. However, Finland's total decarbonization was 15.0 $MtCO_2$ during the study period, which was lower than the 63.3% of countries. In contrast, China, which ranked second in the total carbon emissions, had the lowest decarbonization efficiency among all countries at 2.1%, which means that there is still a significant resistance to the road of decarbonization for residential buildings in China. The global decarbonization from residential buildings peaked at 783.6 $MtCO_2$ during the third stage (from 2011 to 2015). The analysis of carbon emission reductions at different stages showed that the total decarbonization in most countries showed an inverted U-shaped trend of increasing and then decreasing. For instance, the average decarbonization from residential buildings in the US peaked at 62.1 $MtCO_2/yr$ from 2011 to 2015 and rapidly shrunk to 47.2 $MtCO_2/yr$ from 2016 to 2019. A few countries, such as Denmark, had an average decarbonization of 0.8 $MtCO_2/yr$, 0.6 $MtCO_2/yr$, 1.3 $MtCO_2/yr$, and 0.7 $MtCO_2/yr$ in the four stages, showing an inverted N-shaped trend of decreasing, increasing, and then decreasing. In any case, the changes in decarbonization from different countries indicate that the pace of decarbonization is gradually slowing down and that the carbon lock-in effect becomes obvious.

5.3. Development strategies for deep decarbonization in residential building operations

At present, 61 of the 137 countries worldwide that have committed to attaining carbon neutrality have put their pledges in writing form through legal provisions, draft laws, and policy declarations (Wei et al., 2022b). Finland ranks at a distant second among the major countries that have committed to carbon neutrality, with plans to achieve carbon neutrality by 2035. Austria has a carbon neutrality target of 2040, while Germany and Sweden have a carbon neutrality target of 2045. Most countries with climate commitments have 2050 as a target (e.g., the US), but China has a target of 2060 (Jiang et al., 2022a). For the building sector, 136 countries have now included actions to improve energy efficiency and address building-related carbon emissions in their NDCs, and more than 80 countries have building energy codes in place, alongside the efforts of local governments. It is worth noting that a timely review of decarbonization strategies can help different industries formulate precise goals for achieving carbon neutrality.

As shown in Section 4.1 and Section 5.2, China and the US have high carbon emissions from residential building operations; however, China has the lowest decarbonization efficiency, which means

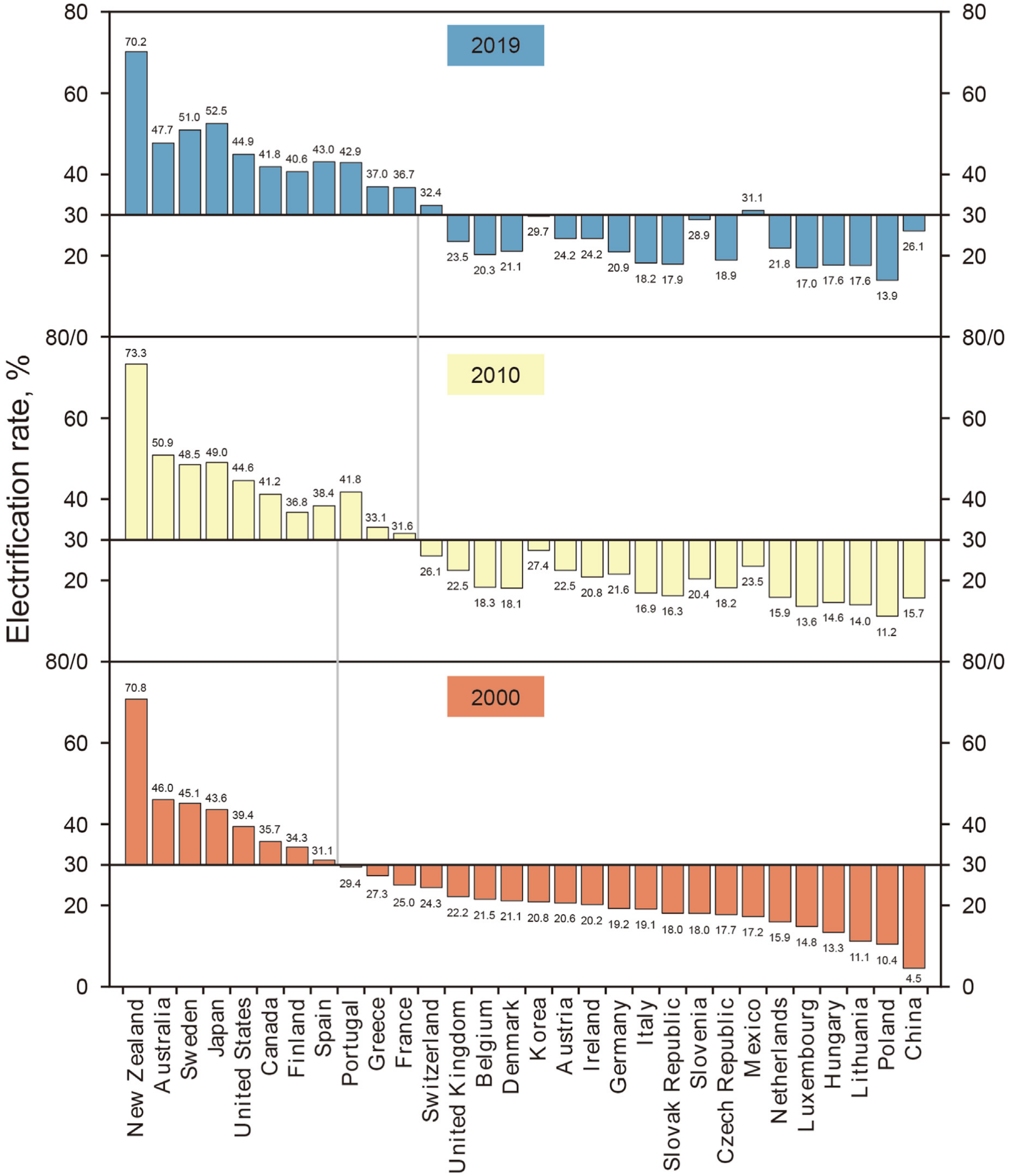

Fig. 8. Electrification levels for global residential building operations in 2000, 2010 and 2019.

that actions to hasten the decarbonization level of residential buildings in developing countries are necessary (Tang et al., 2021). In the context of combating climate change and decarbonization, different emitters are conducting energy transformation, with electrification in the building sector is considered a pivotal path to achieve deep decarbonization (Binsted, 2022). Electricity, as a clean and high-quality energy source, has high end-use efficiency and low pollution (Chen et al., 2022c; Wang et al., 2022b). At present, it has become a powerful means to reduce emissions for upgrading electrification to improve carbon emissions in residential building operations.

To intuitively investigate the electrification level for different countries, Fig. 8 illustrates the electrification rates of residential buildings for 30 countries in 2000, 2010 and 2019. Using 30% as the boundary, a gradual increase in the electrification level of residential buildings worldwide can be observed. The global average electrification rate increased from 25.2% in 2000 to 28.2% in 2010, reaching 31.1% in 2019. New Zealand had the highest steady electrification rate of approximately 70%, which is believed to be related to New Zealanders' lifestyle habits of using electricity primarily for domestic living and through the use of government incentives (Jack et al., 2021). The electrification rate of residential buildings in Sweden, Japan, the US and Canada have historically been at a high level, exceeding 35% starting at the beginning of the 21st century, and still maintaining a steady growth trend (Jiang et al., 2022b). Portugal and Mexico developed rapidly during the study period, improving by approximately 14% from 2000 to 2019, with an average annual increase of 0.7%. The growth in the urbanization rate and the middle class changes the economic consumption structure and increases the degree of household intelligence, indirectly enhancing the electrification level in residential buildings (Zhang et al., 2021b). Taking China as an example, due to the booming economy, the change in peoples' consumption consciousness and living habits has indirectly led to the rapid growth of the electrification level in residential buildings (Lin and Liu, 2015). From 2000 to 2019, the electrification rate of residential buildings in China increased approximately five times.

Based on the above analysis, residential buildings possess more space for decarbonization due to their high total carbon emissions. Thus, the following recommendations can be made for energy efficiency and decarbonization in residential buildings. (a) Develop building energy decarbonization systems represented by zero-carbon electricity (Jing et al., 2022a). In new buildings, the construction of new buildings that integrate photovoltaic power generation, energy storage, direct current power distribution and flexible power consumption should be promoted (Koskela et al., 2019; Puranen et al., 2021; Zhang and Yan, 2021a). For existing buildings, electric cooking and heat pump technologies to supplement heating can be encouraged in building renovation in conjunction with urban renewal (Vivian et al., 2020; Wei et al., 2022a). (b) Make the development of near-zero energy buildings a top priority for carbon neutrality. Increase the proportion of near-zero energy buildings in new buildings and renovate existing buildings to make them meet ultralow energy standards (Ohene et al., 2022b). Relevant regions can vigorously introduce mandatory policies and supporting standards to promote near-zero energy buildings (Ohene et al., 2022a). (c) Replace coal with low-grade heat sources mainly from industrial waste heat to achieve near-zero carbon heating and no longer build centralized heat supply infrastructure with natural gas as the heat source (Lubner and Prasher, 2022; Ren et al., 2023). (d) Improve energy use efficiency, promptly revise the energy efficiency standards (Kairies-Alvarado et al., 2021), raise the market access threshold (Ren et al., 2022b), and give full play to energy efficiency labels and green energy certification (Wang et al., 2021a). (e) Regarding technical measures, it is necessary to vigorously develop carbon capture, utilization and sequestration techniques applicable to buildings (Chen et al., 2020; Wilberforce et al., 2021), develop negative carbon emission technologies (Pires, 2019; Jing et al., 2020), and enhance carbon sinks in ecosystems (Ye and Chuai, 2022).

Overall, by reviewing the decarbonization strategies based on the development of electrification levels, this section makes recommendations for future decarbonization in residential building operations and answers issue 3 in Section 1.

6. Conclusion

This study investigated the changes in carbon emissions from residential building operations and the primary drivers through the GDIM approach. The decoupling status of the economy and emissions in major emitters was further discussed through the decoupling elasticity index. In addition, this study assessed the decarbonization level at different scales, introduced decarbonization efficiency to determine the potential for future decarbonization, and laid the groundwork for achieving global carbon neutrality. Finally, this study reviewed the global decarbonization strategies for residential building operations in response to the call for global carbon neutrality and provided a reference for the quest to speed up the decarbonization of operational residential buildings worldwide.

6.1. Key findings

- Most of the samples showed a decrease in total carbon emissions during 2000-2019, with the US falling the most to 256.2 $MtCO_2$ and China rising the most to 787.9 $MtCO_2$ in 2019. Except for China and the US, the carbon emissions in global residential building operations decreased 7.9 $MtCO_2$ per year over the study period. From 2000 to 2019, carbon emissions in the US fell the most, with an annual decrease of 1.1%; in China, they rose the most, with an annual increase of 10.1%. Emissions per GDP was the most positive driver causing decarbonization of residential buildings, followed by emissions per HCE. GDP represents the most positive driver impeding decarbonization in residential buildings, followed by HCE.
- **Carbon intensity was essential to achieve a strong decoupling of economic development and carbon emissions.** For the year-by-year decoupling effect, the US reached a minimum decoupling elasticity index of -6.6 in 2012 (strong decoupling), where emissions per capita had the most significant contribution of 24.1%. China, from 2000 to 2019, showed a weak decoupling except for 2004 and 2014, where HCE had the most significant contribution of 20.7% on average. Whether the decoupling status was discussed on a year-by-year or two-stage basis, almost all of the prominent contributions to the strong decoupling status came from relative indicators (such as emissions per GDP and emissions per HCE). In contrast, the contributions to the weak decoupling status came from absolute indicators (such as GDP and HCE), suggesting that carbon intensity peaks earlier in the decoupling pathway relative to the total carbon emissions.
- **The pace of decarbonization in global operating residential buildings is gradually decelerating. By 2019, decarbonization from residential buildings across 30 countries was 2094.3 $MtCO_2$, with a decarbonization efficiency of 3.4%.** The US and China, as the strong decoupling and weak decoupling representative countries, respectively, possessed the highest average annual decarbonization of 44.3 and 18.1 $MtCO_2$ per year. From 2000 to 2019, the decarbonization per floor space, per capita, and per household of global residential buildings were 1.9 $kgCO_2/m^2/yr$, 76.3 $kgCO_2/person/yr$, and 186.9 $kgCO_2/household/yr$, respectively.

6.2. Upcoming study

Although historical carbon mitigation has been exhaustively investigated in this study, some efforts can still be made in future studies. First, we will expand the database and establish a global near-real-time building carbon emissions database. Currently, most studies in the IBED database are on an annual basis. Therefore, it is essential to expand the time series to investigate the characteristics and drivers of near real-time building carbon emissions and to assess the decarbonization potential of near real-time building end-use operations. Then, studies on future carbon emissions changes from buildings should be strengthened. Scenario analysis can be employed to explore the pathway to achieving the mid-century building carbon neutrality target under the deep decarbonization scenario. Furthermore, deep decarbonization pathways should be identified for global buildings under the carbon neutrality target and contribute to the Paris Agreement's global 1.5 °C climate target. Finally, the extension of the study scope needs to be considered. Although this study extended the sample to 30 countries, it mainly focused on high-income countries due to data availability. The remaining countries with significant changes in carbon emissions also deserve to be considered to complete the sample to achieve global carbon neutrality.

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References

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Pol. 33, 867–871. https://doi.org/10.1016/j.enpol.2003.10.010.

Binsted, M., 2022. An electrified road to climate goals. Nat. Energy 7, 9–10. https://doi.org/10.1038/s41560-021-00974-8.

Boratyński, J., 2021. Decomposing structural decomposition: the role of changes in individual industry shares. Energy Econ. 103, 105587. https://doi.org/10.1016/j.eneco.2021.105587.

Chen, J., Fan, W., Li, D., Liu, X., Song, M., 2020. Driving factors of global carbon footprint pressure: based on vegetation carbon sequestration. Appl. Energy 267, 114914. https://doi.org/10.1016/j.apenergy.2020.114914.

Chen, M., Lei, J., Xiang, X., Ma, M., 2022a. Carbon mitigation in the operation of Chinese residential buildings: an empirical analysis at the provincial scale. Buildings 12. https://doi.org/10.3390/buildings12081128.

Chen, M., Ma, M., Lin, Y., Ma, Z., Li, K., 2022b. Carbon Kuznets curve in China's building operations: retrospective and prospective trajectories. Sci. Total Environ. 803, 150104. https://doi.org/10.1016/j.scitotenv.2021.150104.

Chen, Q., Kuang, Z., Liu, X., Zhang, T., 2022c. Energy storage to solve the diurnal, weekly, and seasonal mismatch and achieve zero-carbon electricity consumption in buildings. Appl. Energy 312, 118744. https://doi.org/10.1016/j.apenergy.2022.118744.

Dong, K., Dong, X., Jiang, Q., Zhao, J., 2021. Assessing energy resilience and its greenhouse effect: a global perspective. Energy Econ. 104, 105659. https://doi.org/10.1016/j.eneco.2021.105659.

Fang, D., Hao, P., Yu, Q., Wang, J., 2020. The impacts of electricity consumption in China's key economic regions. Appl. Energy 267, 115078. https://doi.org/10.1016/j.apenergy.2020.115078.

Hang, Y., Wang, Q., Zhou, D., Zhang, L., 2019. Factors influencing the progress in decoupling economic growth from carbon dioxide emissions in China's manufacturing industry. Resour. Conserv. Recycl. 146, 77–88. https://doi.org/10.1016/j.resconrec.2019.03.034.

IEA, 2021. World Energy Outlook 2021. https://www.iea.org/reports/world-energy-outlook-2021.

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. https://www.ipcc.ch/report/ar6/wg3/.

Jack, M.W., Mirfin, A., Anderson, B., 2021. The role of highly energy-efficient dwellings in enabling 100% renewable electricity. Energy Pol. 158, 112565. https://doi.org/10.1016/j.enpol.2021.112565.

Jiang, H.-D., Liu, L.-J., Dong, K., Fu, Y.-W., 2022a. How will sectoral coverage in the carbon trading system affect the total oil consumption in China? A CGE-based analysis. Energy Econ. 110, 105996. https://doi.org/10.1016/j.eneco.2022.105996.

Jiang, H.-D., Xue, M.-M., Liang, Q.-M., Masui, T., Ren, Z.-Y., 2022b. How do demand-side policies contribute to the electrification and decarburization of private transportation in China? A CGE-based analysis. Technol. Forecast. Soc. Change 175, 121322. https://doi.org/10.1016/j.techfore.2021.121322.

Jiang, H.-D., Purohit, P., Liang, Q.-M., Dong, K., Liu, L.-J., 2022c. The cost-benefit comparisons of China's and India's NDCs based on carbon marginal abatement cost curves. Energy Econ. 109, 105946. https://doi.org/10.1016/j.eneco.2022.105946.

Jing, R., Zhou, Y., Wu, J., 2022a. Electrification with flexibility towards local energy decarbonization. Advances in Applied Energy 5, 100088. https://doi.org/10.1016/j.adapen.2022.100088.

Jing, R., Xie, M.N., Wang, F.X., Chen, L.X., 2020. Fair P2P energy trading between residential and commercial multi-energy systems enabling integrated demand-side management. Appl. Energy 262, 114551. https://doi.org/10.1016/j.apenergy.2020.114551.

Jing, R., Wang, M., Zhang, R., Li, N., Zhao, Y., 2017. A study on energy performance of 30 commercial office buildings in Hong Kong. Energy Build. 144, 117–128. https://doi.org/10.1016/j.enbuild.2017.03.042.

Jing, R., Hua, W., Lin, J., Lin, J., Zhao, Y., Zhou, Y., Wu, J., 2022b. Cost-efficient decarbonization of local energy systems by whole-system based design optimization. Appl. Energy 326, 119921. https://doi.org/10.1016/j.apenergy.2022.119921.

Kairies-Alvarado, D., Muñoz-Sanguinetti, C., Martínez-Rocamora, A., 2021. Contribution of energy efficiency standards to life-cycle carbon footprint reduction in public buildings in Chile. Energy Build. 236, 110797. https://doi.org/10.1016/j.enbuild.2021.110797.

Kan, S., Chen, B., Chen, G., 2019. Worldwide energy use across global supply chains: decoupled from economic growth? Appl. Energy 250, 1235–1245. https://doi.org/10.1016/j.apenergy.2019.05.104.

Koskela, J., Rautiainen, A., Järventausta, P., 2019. Using electrical energy storage in residential buildingsSizing of battery and photovoltaic panels based on electricity cost optimization. Appl. Energy 239, 1175–1189. https://doi.org/10.1016/j.apenergy.2019.02.021.

Li, K., Ma, M., Xiang, X., Feng, W., Ma, Z., Cai, W., Ma, X., 2022. Carbon reduction in commercial building operations: a provincial retrospection in China. Appl. Energy 306, 118098. https://doi.org/10.1016/j.apenergy.2021.118098.

Li, M., Duan, M., 2020. Efforts-sharing to achieve the Paris goals: ratcheting-up of NDCs and taking full advantage of international carbon market. Appl. Energy 280, 115864. https://doi.org/10.1016/j.apenergy.2020.115864.

Lin, B., Liu, H., 2015. China's building energy efficiency and urbanization. Energy Build. 86, 356–365. https://doi.org/10.1016/j.enbuild.2014.09.069.

Lin, B., Raza, M.Y., 2021. Analysis of electricity consumption in Pakistan using index decomposition and decoupling approach. Energy 214, 118888. https://doi.org/10.1016/j.energy.2020.118888.

Liu, B., Shi, J., Wang, H., Su, X., Zhou, P., 2019. Driving factors of carbon emissions in China: a joint decomposition approach based on meta-frontier. Appl. Energy 256, 113986. https://doi.org/10.1016/j.apenergy.2019.113986.

Liu, J., Yang, Q., Ou, S., Liu, J., 2022. Factor decomposition and the decoupling effect of carbon emissions in China's manufacturing high-emission subsectors. Energy 248, 123568. https://doi.org/10.1016/j.energy.2022.123568.

Lubner, S.D., Prasher, R.S., 2022. Combined heat and electricity using thermal storage to decarbonize buildings and industries. One Earth 5, 230–231. https://doi.org/10.1016/j.oneear.2022.03.001.

Ma, M., Pan, T., Ma, Z., 2017. Examining the driving factors of Chinese commercial building energy consumption from 2000 to 2015: a STIRPAT model approach. J. ENG. SCI. TECHNOL. REV. 10, 28–38. https://doi.org/10.25103/jestr.103.05.

OECD, 2001. OECD Environmental Strategy for the First Decade of the 21st Century: Adopted by OECD Environmental Ministers. OECD. https://www.oecd.org/environment/indicators-modelling-outlooks/1863539.pdf.

Ohene, E., Chan, A.P.C., Darko, A., 2022a. Review of global research advances towards net-zero emissions buildings. Energy Build. 266, 112142. https://doi.org/10.1016/j.enbuild.2022.112142.

Ohene, E., Chan, A.P.C., Darko, A., 2022b. Prioritizing barriers and developing mitigation strategies toward net-zero carbon building sector. Build. Environ. 223, 109437. https://doi.org/10.1016/j.buildenv.2022.109437.

Pan, Y., Dong, F., 2022. Dynamic evolution and driving factors of new energy development: fresh evidence from China. Technol. Forecast. Soc. Change 176, 121475. https://doi.org/10.1016/j.techfore.2022.121475.

Panagiotidou, M., Aye, L., Rismanchi, B., 2021. Optimisation of multi-residential building retrofit, cost-optimal and net-zero emission targets. Energy Build. 252, 111385. https://doi.org/10.1016/j.enbuild.2021.111385.

Pires, J.C.M., 2019. Negative emissions technologies: a complementary solution for climate change mitigation. Sci. Total Environ. 672, 502–514. https://doi.org/10.1016/j.scitotenv.2019.04.004.

Programme, U.N.E., 2021. 2021 Global Status Report for Buildings and Construction: towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector. https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction.

Puranen, P., Kosonen, A., Ahola, J., 2021. Techno-economic viability of energy storage concepts combined with a residential solar photovoltaic system: a case study from Finland. Appl. Energy 298, 117199. https://doi.org/10.1016/j.apenergy.2021.117199.

Ren, X., Zhang, X., Yan, C., Gozgor, G., 2022a. Climate policy uncertainty and firm-level total factor productivity: evidence from China. Energy Econ. 113, 106209. https://doi.org/10.1016/j.eneco.2022.106209.

Ren, X., liu, Z., Jin, C., Lin, R., 2023. Oil price uncertainty and enterprise total factor productivity: evidence from China. Int. Rev. Econ. Finance 83, 201–218. https://doi.org/10.1016/j.iref.2022.08.024.

Ren, X., Li, Y., yan, C., Wen, F., Lu, Z., 2022b. The interrelationship between the carbon market and the green bonds market: evidence from wavelet quantile-on-quantile method. Technol. Forecast. Soc. Change 179, 121611. https://doi.org/10.1016/j.techfore.2022.121611.

Shao, S., Liu, J., Geng, Y., Miao, Z., Yang, Y., 2016. Uncovering driving factors of carbon emissions from China's mining sector. Appl. Energy 166, 220–238. https://doi.org/10.1016/j.apenergy.2016.01.047.

Su, B., Ang, B.W., 2012. Structural decomposition analysis applied to energy and emissions: some methodological developments. Energy Econ. 34, 177–188. https://doi.org/10.1016/j.eneco.2011.10.009.

Tang, B.-J., Guo, Y.-Y., Yu, B., Harvey, L.D.D., 2021. Pathways for decarbonizing China's building sector under global warming thresholds. Appl. Energy 298, 117213. https://doi.org/10.1016/j.apenergy.2021.117213.

Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transport Pol. 12, 137–151. https://doi.org/10.1016/j.tranpol.2005.01.001.

Vaninsky, A., 2014. Factorial decomposition of CO_2 emissions: a generalized Divisia index approach. Energy Econ. 45, 389–400. https://doi.org/10.1016/j.eneco.2014.07.008.

Vivian, J., Prataviera, E., Cunsolo, F., Pau, M., 2020. Demand Side Management of a pool of air source heat pumps for space heating and domestic hot water production in a residential district. Energy Convers. Manag. 225, 113457. https://doi.org/10.1016/j.enconman.2020.113457.

Wang, B., Deng, N., Liu, X., Sun, Q., Wang, Z., 2021a. Effect of energy efficiency labels on household appliance choice in China: sustainable consumption or irrational intertemporal choice? Resour. Conserv. Recycl. 169, 105458. https://doi.org/10.1016/j.resconrec.2021.105458.

Wang, J., Jiang, Q., Dong, X., Dong, K., 2021b. Decoupling and decomposition analysis of investments and CO_2 emissions in information and communication technology sector. Appl. Energy 302, 117618. https://doi.org/10.1016/j.apenergy.2021.117618.

Wang, X., Wei, Y., Shao, Q., 2020. Decomposing the decoupling of CO_2 emissions and economic growth in China's iron and steel industry. Resour. Conserv. Recycl. 152, 104509. https://doi.org/10.1016/j.resconrec.2019.104509.

Wang, Y., Liu, Y., Huang, L., Zhang, Q., Gao, W., Sun, Q., Li, X., 2022a. Decomposition the driving force of regional electricity consumption in Japan from 2001 to 2015. Appl. Energy 308, 118365. https://doi.org/10.1016/j.apenergy.2021.118365.

Wang, Z., Fu, H., Ren, X., 2022b. The impact of political connections on firm pollution: new evidence based on heterogeneous environmental regulation. Petrol. Sci.

Wei, H., Zhang, Y., Wang, Y., Hua, W., Jing, R., Zhou, Y., 2022a. Planning integrated energy systems coupling V2G as a flexible storage. Energy 239, 122215. https://doi.org/10.1016/j.energy.2021.122215.

Wei, Y.-M., Chen, K., Kang, J.-N., Chen, W., Wang, X.-Y., Zhang, X., 2022b. Policy and Management of Carbon Peaking and Carbon Neutrality: A Literature Review. Engineering. https://doi.org/10.1016/j.eng.2021.12.018.

Wilberforce, T., Olabi, A.G., Sayed, E.T., Elsaid, K., Abdelkareem, M.A., 2021. Progress in carbon capture technologies. Sci. Total Environ. 761, 143203. https://doi.org/10.1016/j.scitotenv.2020.143203.

Xiang, X., Ma, M., Ma, X., Chen, L., Cai, W., Feng, W., Ma, Z., 2022. Historical decarbonization of global commercial building operations in the 21st century. Appl. Energy, 119401. https://doi.org/10.1016/j.apenergy.2022.119401.

Yan, Q., Yin, J., Baležentis, T., Makutėnienė, D., Štreimikienė, D., 2017a. Energy-related GHG emission in agriculture of the European countries: an application of the Generalized Divisia Index. J. Clean. Prod. 164, 686–694. https://doi.org/10.1016/j.jclepro.2017.07.010.

Yan, R., Ma, M., Pan, T., 2017b. Estimating energy savings in Chinese residential buildings from 2001 to 2015: a decomposition analysis. J. Eng. Sci. Technol. Rev. 10, 107–113. https://doi.org/10.25103/jestr.101.15.

Yan, R., Xiang, X., Cai, W., Ma, M., 2022. Decarbonizing residential buildings in the developing world: historical cases from China. Sci. Total Environ. 847, 157679. https://doi.org/10.1016/j.scitotenv.2022.157679.

Yang, J., Hao, Y., Feng, C., 2021. A race between economic growth and carbon emissions: what play important roles towards global low-carbon development? Energy Econ. 100, 105327. https://doi.org/10.1016/j.eneco.2021.105327.

Ye, X., Chuai, X., 2022. Carbon sinks/sources' spatiotemporal evolution in China and its response to built-up land expansion. J. Environ. Manag. 321, 115863. https://doi.org/10.1016/j.jenvman.2022.115863.

You, K., Yu, Y., Li, Y., Cai, W., Shi, Q., 2021. Spatiotemporal decomposition analysis of carbon emissions on Chinese residential central heating. Energy Build. 253, 111485. https://doi.org/10.1016/j.enbuild.2021.111485.

You, K., Ren, H., Cai, W., Huang, R., Li, Y., 2023. Modeling carbon emission trend in China's building sector to year 2060. Resour. Conserv. Recycl. 188, 106679. https://doi.org/10.1016/j.resconrec.2022.106679.

Yu, B., Fang, D., 2021. Decoupling economic growth from energy-related PM2.5 emissions in China: a GDIM-based indicator decomposition. Ecol. Indicat. 127, 107795. https://doi.org/10.1016/j.ecolind.2021.107795.

Zhang, H., Chen, J., Li, W., Song, X., Shibasaki, R., 2020a. Mobile phone GPS data in urban ride-sharing: an assessment method for emission reduction potential. Appl. Energy 269, 115038. https://doi.org/10.1016/j.apenergy.2020.115038.

Zhang, H., Yan, J., et al., 2021a. 1.6 Million transactions replicate distributed PV market slowdown by COVID-19 lockdown. Appl. Energy 283, 116341. https://doi.org/10.1016/j.apenergy.2020.116341.

Zhang, S., Li, Z., Ning, X., Li, L., 2021b. Gauging the impacts of urbanization on CO_2 emissions from the construction industry: evidence from China. J. Environ. Manag. 288, 112440. https://doi.org/10.1016/j.jenvman.2021.112440.

Zhang, S., Xiang, X., Ma, Z., Ma, M., Zou, C., 2021c. Carbon neutral roadmap of commercial building operations by mid-century: lessons from China. Buildings 11, 510. https://doi.org/10.3390/buildings11110510.

Zhang, S., Ma, M., Li, K., Ma, Z., Feng, W., Cai, W., 2022a. Historical carbon abatement in the commercial building operation: China versus the US. Energy Econ. 105, 105712. https://doi.org/10.1016/j.eneco.2021.105712.

Zhang, S., Ma, M., Xiang, X., Cai, W., Feng, W., Ma, Z., 2022b. Potential to decarbonize the commercial building operation of the top two emitters by 2060. Resour. Conserv. Recycl. 185, 106481. https://doi.org/10.1016/j.resconrec.2022.106481.

Zhang, X., Geng, Y., Shao, S., Wilson, J., Song, X., You, W., 2020b. China's non-fossil energy development and its 2030 CO_2 reduction targets: the role of urbanization. Appl. Energy 261, 114353. https://doi.org/10.1016/j.apenergy.2019.114353.

Zhao, X., Zhang, X., Shao, S., 2016. Decoupling CO_2 emissions and industrial growth in China over 1993–2013: the role of investment. Energy Econ. 60, 275–292. https://doi.org/10.1016/j.eneco.2016.10.008.