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Publication Date

2023-10-01

DOI

10.1016/j.apenergy.2023.121441

Applied Energy 347 (2023) 121441

Contents lists available at ScienceDirect

Applied Energy

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

Heterogeneity or illusion? Track the carbon Kuznets curve of global residential building operations

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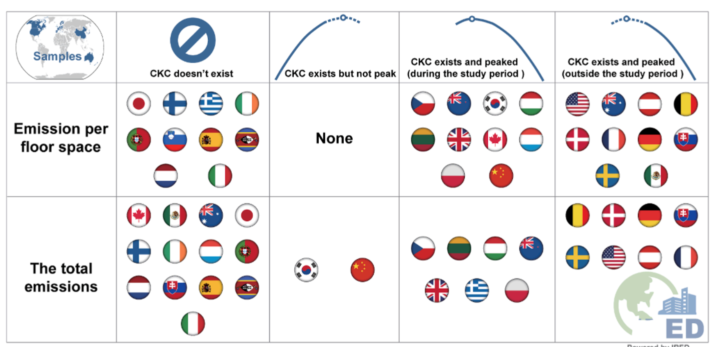
HIGHLIGHTS

- Carbon Kuznets curve (CKC) shows carbon trajectories in global residential building operations.
- At emission per household level, more than 76% of samples represent the inverted U-shape.
- Regardless of any emission scale, over 80% of global residential buildings have peaked.
- Decoupling analysis and threshold regression verify the robustness and heterogeneity of CKCs.
- Development strategies of electrification and energy efficiency in global buildings are reviewed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Residential building
Carbon peak
Environmental Kuznets curve
Decoupling elasticity
Threshold regression

ABSTRACT

Residential buildings, the "last mile" sector in the global decarbonization, have become the most significant uncertain factor hindering carbon neutrality with increasing household energy demand. To track the operational carbon in buildings, this study investigates the carbon Kuznets curve (CKC) and the corresponding decoupling status of residential building operations at four emission scales by using the data of 30 countries from 2000 to 2019. The results show that (1) the CKC model can fit more than half of the samples. Most curves have an inverted U-shape, with 76% of emission per household and 82% of total emissions. (2) In the presence of the CKC, over four-fifths of global residential buildings peak regardless of any emission scale. The analysis denotes that the carbon emissions of developed countries reach their peaks earlier. In the total emissions, the samples' peaking proportion is 20% and 25% with income per capita < 20,000 United States dollars (USD) and 20,000–40,000 USD, respectively. (3) The Tapio decoupling analysis and the threshold regression effectively verify the robustness and the heterogeneity of CKCs, respectively. Strong decoupling effects of CKCs in most countries are demonstrated at the scales of emission per floor space and the total emissions, and the heterogeneity proves the classic inverted U-shaped relationship between economy and emissions doesn't exist in all emitters. Overall, this study tracks the historical carbon emission trajectories of residential building operations at

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https://doi.org/10.1016/j.apenergy.2023.121441
Received 7 August 2022; Received in revised form 11 March 2023; Accepted 10 June 2023
Available online 20 June 2023

a global scale, providing reference for different economies to simulate the dynamic of building carbon emissions along with the economic booming.

Nomenclature

Abbreviations

CKC	Carbon Kuznets curve
EKC	Environmental Kuznets curve
GNI	gross national income
OECD	Organization for Economic Co-operation and Development
USD	United States dollars

Symbols

C_c	The total carbon emissions
C_f	Carbon emission per floor space
C_h	Carbon emission per household
C_p	Carbon emission per capita
i	Gross national income per capita
$kgCO_2$	Kilograms of carbon dioxide
$MtCO_2$	Million tons of carbon dioxide
φ	Decoupling elasticity index
$\Delta c_{0\rightarrow T}$	Carbon emission changes during ΔT
$\Delta i_{0\rightarrow T}$	Income per capita changes during ΔT

1. Introduction

The operational carbon of building sector accounts for 28% of the global energy-related carbon emissions [1]. Residential building, as a key part of the building sector, may become the biggest uncertainty (i.e., the last mile) in the future carbon–neutral transition due to the rapid growth of household energy demand and residential building stocks across different countries, especially in emerging economies [2]. Moreover, the allocation scheme of carbon budget of residential buildings over various economies is not clear in the context of global 1.5-degree target [3]. Thus, to seek the global decarbonization pathway of future residential buildings, it is urgent to review and track the operational carbon changes of residential buildings worldwide.

Climate mitigation ambitions have driven the major economies to declare their carbon neutral goals [4], especially in the building-related sectors [5]. To date, the carbon Kuznets curve (CKC) estimation with decoupling model has become a classical tool to explore the impact of economic growth on carbon emissions and to simulate the future decarbonization potential at a nation-regional scale [6,7]. However, when it comes to a global level, the diversity of national conditions and socio-economy causes the heterogeneity of CKC discovered in existing studies [8]. In residential building sector, Liang, et al. [9] analyzed the different building decarbonization patterns in a few megacities by using the CKC model, and at least four types of CKCs can be confirmed in their samples. However, the reason to explain the above different CKC types (i.e., the heterogeneity) is out of insight. Therefore, in the context of global residential buildings, this study proposes the following three questions to be solved.

- What are the CKCs' features of global residential building operations at various emission scales?
- How to verify the robustness and the heterogeneity of CKCs across different economies?
- How to strengthen the decarbonization effect of future residential building operations?

To address the above issues, this study primarily uses the CKC model to identify the presence, peak states, and features of carbon emissions of residential building operations at different emission scales in 30 countries from 2000 to 2019. Besides, the robustness of the CKCs' results is tested through the decoupling elasticity index, and the decoupling effect is evaluated. Furthermore, the threshold regression model is employed to further check the robustness and to verify the heterogeneity of CKCs among different country groups. Finally, this study discusses the improvement of electrification and energy efficiency in buildings to respond the goal of net-zero world, and offers reference to better achieve the deep decarbonization in future building operations.

As for the most important contribution, this is the first study to fully explore the heterogeneity of CKCs in global residential building operations. Through investigating the CKC and the decoupling effect of operational carbon in global residential buildings, the CKC model can fit more than half of the samples at any emission scale, whether the CKC estimation is grouped by different economic levels or geographical locations. Most curves have an inverted U-shape, and the N-shape or inverted N-shape curves mainly exist in countries with lower income per capita, which reflects the heterogeneity of CKCs. To face the heterogeneity, the threshold regression model is applied to further investigate the heterogeneity of CKCs among different country groups. To date, this topic has been yet discussed in the context of global residential building operations.

The remainder of this study is organized as follows: Section 2 presents the literature review. Section 3 introduces the model and the data source. Section 4 illustrates the main results, including the CKCs' features of global residential building operations at various emission scales, different income levels, and different geographical locations. Section 5 includes three parts. Section 5.1 assesses the Tapio decoupling elasticity index and examines the robustness of the CKC results at different emission scales. Section 5.2 adopts the threshold regression model to further check the robustness and to verify the heterogeneity of CKCs among different country groups. Section 5.3 discusses the strategies to strengthen the decarbonization effect of global residential building operations. Section 6 summarizes the key findings and future studies.

2. Literature review

Because of its simple form and fast judgment, the environmental Kuznets curve (EKC), first established by Kuznets [10], is widely used to depict the relationship between changes in environmental quality and economic growth [11]. As an extended form of EKC, the CKC mainly addresses the impact of carbon dioxide emissions and the typical CKC presents an inverted U-shape on emissions and economy [12]. To date, many academics have already utilized the CKC model to explore the impact of economic development on emissions.

The existing studies can be generally summarized as verification of CKCs' presence and descriptions of CKCs' characteristics. Regarding the verification of the presence of CKC, Dong, et al. [13] tested the validity of the CKC hypothesis in 14 Asia-Pacific countries from 1970 to 2016, and the results indicated that 13 countries supported the hypothesis. At the country level, the presence of CKCs in Turkey [14], Malaysia [15], the United States (US) [6], and China [16] was tested and further explored for carbon changes as economic growth. Many countries have also employed the CKC model to analyze the emission status at the sectoral level. For example, Pablo-Romero, et al. [17] estimated the CKCs for the transport sector with panel data covering European Union countries and indicated that the turning point has not yet emerged. Chen, et al. [18] focused on operational carbon changes in Chinese buildings, illustrating the presence, peaking status and features of CKCs. Regarding the characteristics of CKCs, Park, et al. [19] examined the

CKC hypothesis for 16 metropolitan regions in Korea and found the potential presence of an N-shape curve. Similarly, Özokcu and Özdemir [8] tested two empirical models, including 26 OECD countries and 52 emerging countries, and both models demonstrated N-shape and inverted N-shape curves.

Decoupling models are a well-known method used to examine whether a synergistic nexus between economy and emissions exists [7]. Through a literature review, the current common decoupling analysis methods are mainly divided into two types: the OECD decoupling model [20] and the Tapio decoupling index [21]. The results of the OECD decoupling model evaluation are largely affected by choice of the base period, and different decisions will cause different results. However, compared with the OECD approach, Tapio decoupling elasticity analysis instead aims at the differences between different time, which is conducive to testing the effectiveness of policy implementation [22]. Furthermore, the Tapio model uses the relative value and elastic index to clarify the development process for the different decoupling statuses [23]. Since the Tapio approach has a simple assessment and provides a good benchmark for confirming the decoupling states, it has been applied in current studies widely [24,25]. Through literature combining, the application of decoupling analysis mainly includes the indicator decoupling approach and the comprehensive approach with decoupling and decomposition analysis. Shuai, et al. [26] proposed three carbon indices and identified the decoupling status of 133 countries, which is a typical indicator decoupling approach for exploring the nexus of carbon emissions and economic indicators. Zhang, et al. [27] built an assessment framework of carbon emission reduction of commercial buildings in China and the US in 2001–2018 with decomposition and decoupling analysis, showing that the annual decarbonization intensity in China was 10 Kilograms of carbon dioxide per meter square ($kgCO_2/m^2$), while the US was 18 $kgCO_2/m^2$.

The abovementioned literature review shows that although there have been many studies related to CKC, two gaps are yet to be fulfilled:

Based on the CKC hypothesis, few literature on the topic of historical carbon emission trajectories of residential building operations have been reported at a global scale. The presence, peak states, and curve characteristics of CKCs have been exhaustively analyzed in current works [28]. Nevertheless, majority of studies aimed at the nation-regional emissions and ignored the role of operational carbon in buildings [29]. Residential buildings, as an important part of the building sector, might become the biggest uncertainty in the future carbon–neutral transition worldwide due to the rapid growth of household energy demand and residential building stocks in emerging economies [30]. Therefore, it is urgent to review and track the operational carbon changes of residential buildings worldwide.

The heterogeneity of CKCs among different economies has scarcely been evaluated in the context of global residential buildings. The heterogeneity of CKCs reveals that different countries have different environmental pressure and economic development patterns, leading to the classic inverted U-shaped nexus between economy and emissions may not occur [31]. Thus, different results about the presence, peak states, and features of the CKC need to be drawn through scientific cluster analysis to provide reliable references for all economies to determine the carbon emission trajectories of residential building operations.

To this end, this study aims to cover the above gaps by investigating the presence, peak states, and features of CKCs of residential building operations at different emission scales in 30 countries from 2000 to 2019. Correspondingly, this study makes the following two contributions:

- **The CKCs' features and corresponding decoupling effects of global residential building operations at various emission scales are investigated for the first time.** This study establishes the CKC model at four emission scales, including the total emissions, emission per household, per capita, and per floor space. Based on that, the presence, peak states, and features of the CKCs across different economies are analyzed. Moreover, the robustness of CKCs is verified via the decoupling elasticity analysis and the threshold regression model.
- **The first attempt to fully explore the heterogeneity of CKCs in global residential building operations is achieved in this study.** Through investigating the CKC and the corresponding decoupling status of global residential building operations worldwide, the heterogeneity of CKCs can be observed. The heterogeneity reflects different environmental pressure and economic development patterns exist in different economies, thereby the classic inverted U-shaped nexus between economy and emissions may not occur. To face the heterogeneity, the threshold regression model is used to analyze the heterogeneity of CKCs among different country groups.

3. Methods and materials

The CKC model is developed in Section 3.1 to evaluate the nexus between economic development and carbon emissions, and the Tapio decoupling model is proposed in Section 3.2 to observe the decoupling effect. Furthermore, the main data are noted in Section 3.3.

3.1. Empirical fitting model of CKCs

As an empirical fitting model, CKC is widely used to represent the nexus between economic growth and carbon emissions due to its easy calculation, simple and understandable principles. It is widely acknowledged that CKCs in residential buildings are divided into four types. This study used the traditional Kuznets model combined with the extended form of residential buildings [32] to propose the following four CKC models with various emission scales, taking gross national income (GNI) per capita to represent the economic growth indicator:

$$lnC_{n,jt} = f[(lni_{jt})^3, (lni_{jt})^2, lni_{jt}, 1] = \sum_{k=0}^{3} m_k (lni_{jt})^k \tag{1}$$

Where j represents different country samples ($j = 1, 2, 3\cdots30$) and t represents the investigation period $t = (2000, 2001, 2002\cdots2019)$. In Eq. (1), n can be expressed as f, h, p, c. $C_{f,jt}$ indicates the carbon emission per floor space of country j in year t, $C_{h,jt}$ is the carbon emission per household of country j in year t, $C_{p,jt}$ and $C_{c,jt}$ represent emission per capita and the total emissions, respectively; i_{jt} represents GNI per capita of country j in year t, which is measured in 2010 US dollars; m_k denotes the polynomial coefficient. When $k = 3$, if $m_k \neq 0$, the function is a monadic cubic polynomial, and the curve is expressed as an N-shape or inverted N-shape; conversely, if $m_k = 0$, the function degenerates to a quadratic polynomial, and the curve is expressed as an inverted U-shape.

Taking Eq. (1) as an example, the N-shape and inverted N-shape can be obtained as $m_3 \neq 0$; by derivation, the GNI per capita corresponding to its turning year i_{TY} can be obtained:

$$\frac{d}{d(i_{jt})} lnC_{n,jt} = \frac{3m_3(lni_{jt})^2 + 2m_2 lni_{jt} + m_1}{i_{jt}} = 0 \tag{2}$$

$$i_{TY} = \exp\left(\frac{-2m_2 \pm \sqrt{(2m_2)^2 - 12m_1m_3}}{6m_3}\right) \tag{3}$$

Similarly, the inverted U-shape can be obtained as $m_3 = 0$, $m_2 < 0$ and $m_1 > 0$; by derivation, the peak value of emission per floor space corresponding to its turning point can be obtained:

$$\frac{d}{d(i_{jt})} lnC_{n,jt} = \frac{m_1 + 2m_2 lni_{jt}}{i_{jt}} = 0 \rightarrow C_{n,TY} = exp(\frac{4m_0m_2 - m_1^2}{4m_2}) \tag{4}$$

The GNI per capita at the time of the turning point is:

$$i_{TY} = \exp(\frac{-m_1}{2m_2}) \tag{5}$$

3.2. Tapio decoupling model

As mentioned in Section 2, Tapio model can better explore the decoupling relationship between carbon emissions and economic development. Therefore, this study chose the Tapio decoupling model to explore the decoupling relationships between economic indicators (i.e., GNI per capita) and different carbon emission scales. According to the definition, the decoupling index can be obtained:

$$\varphi_j = \frac{\Delta c_{j|0\to T}/c_{j|0}}{\Delta i_{|0\to T}/i_{|0}} \tag{6}$$

As shown in Eq. (6), j denotes the country samples ($j = 1,2,3\cdots30$), $\Delta c_{j|0\to T}$ and $\Delta i_{|0\to T}$ represent the change in carbon emissions in residential building operation and GNI per capita during the research period [0, T], respectively. $c_{j|0}$ and $i_{|0}$ represent the carbon emissions and GNI per capita in base year 0, respectively.

According to the criterion from Tapio [21], decoupling status can be divided into eight categories with the size of the coefficient. As shown in Fig. 1, when the economy grows (i.e., $\Delta i > 0$), a smaller φ denotes that carbon emissions weaken, which represents a better decoupling effect, indicating that the nexus between economic growth and carbon emissions is receding. Conversely, when the economy weakens (i.e., $\Delta i < 0$), a smaller φ denotes that carbon emissions grow, which represents a worse decoupling effect, indicating that the nexus between economic growth and carbon emissions is enhancing. Note that this study pursues a strong decoupling status to ensure low-carbon development, so the second (i.e., strong negative decoupling) and fourth quadrants (i.e., strong decoupling) represent the worst and best results, respectively.

3.3. Dataset

The historical data of 30 countries were accessed from the International Energy Agency (https://www.iea.org/), covering the carbon emissions and gross floor space of the residential building sector from 2000 to 2019. The data on population size and GNI were collected from the World Bank Database (https://data.worldbank.org). The explanations of the five main parameters in the CKC model are presented in Table 1.

4. Results

This study counted and described the CKCs in the residential building of 30 countries, illustrating the presence, peak states, and features of

Table 1
Variable definitions.

Symbol	Meaning	Unit	Definition
C_f	Carbon emission per floor space	Kilograms of carbon dioxide ($kgCO_2$) per square meter	Eq. (1)
C_h	Carbon emission per household (carbon intensity)	$kgCO_2$/person	Eq. (1)
C_p	Carbon emission per capita	$kgCO_2$/household	Eq. (1)
C_c	The total carbon emissions	Million tons of CO_2 ($MtCO_2$)	Eq. (1)
i	Gross national income per capita	The United States dollars (USD)	Eq. (1)
$\Delta c_{0\to T}$	Carbon emission changes during ΔT	$MtCO_2$	Eq. (6)
$\Delta i_{0\to T}$	Income per capita changes during ΔT	USD	Eq. (6)
φ	Decoupling elasticity index	–	Eq. (6)

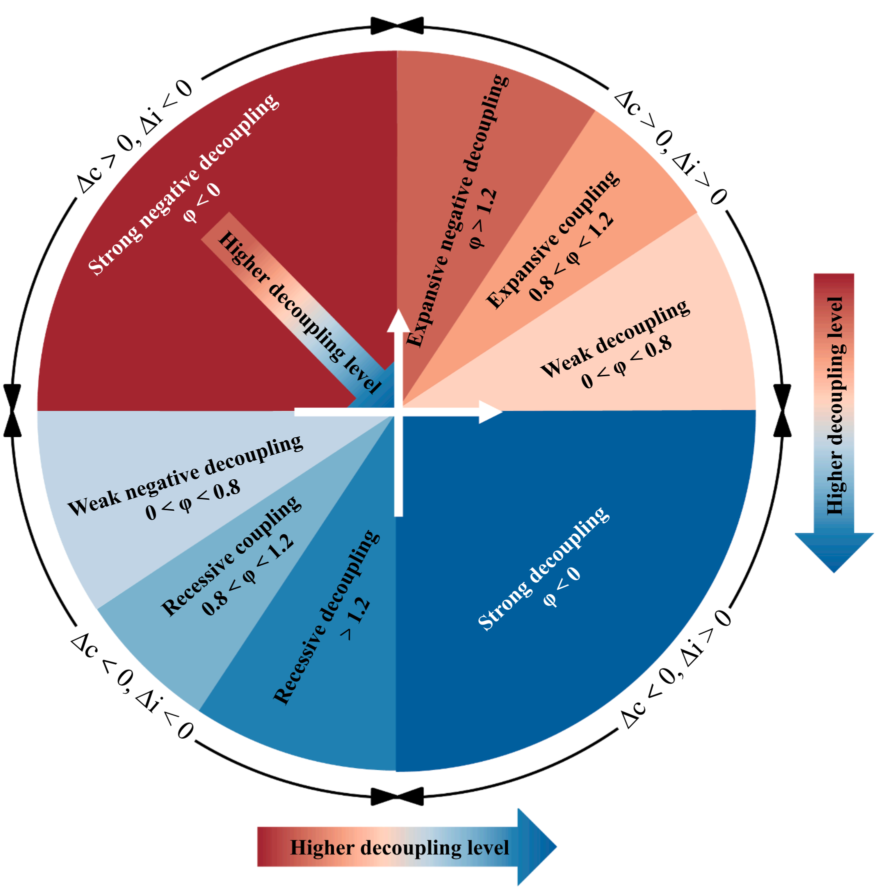


Fig. 1. The decoupling status of the Tapio model [21].

CKCs over different emission scales, income levels and geographical locations. Section 4.1 focuses on the overall situation of 30 samples, exploring the presence, features, and turning points of the CKCs. Section 4.2 analyzes the differences in CKCs between various countries under different economic levels. In Section 4.3,30 countries were divided into groups considering the different geographical locations and political organization to describe the CKCs' characteristics.

First, the distribution of the raw data across 30 countries involved in the CKC analysis was described, as shown in Fig. 2. The descriptive statistics of the original variables using different approaches (e.g., box charts, normal distribution overlays, and scatter plots [33]) indicate the validity of data.

4.1. Overview of CKCs in 30 countries

Based on the empirical fitting model of CKCs described in Section 3.1, this section illustrates the CKC fitting status of residential buildings in 30 emitters during 2000–2019. According to various emission scales, the CKCs' peaking status can be divided into four types, as shown in Fig. 3. The CKCs for aggregated 30 countries under four emission scales all present an inverted U-shape. The turning point under four emission scales all occurred during the study period, and the peaking sequence satisfies the following order: emission per floor space < emission per household (carbon intensity) < emission per capita < the total emissions. It should be noted that people usually subjectively believe that emission per capita peaks earlier than emission per household. However, due to the low birth rate in developed countries and the declining average household size, emission per household is more likely to reach its peak in actual conditions. According to the existing historical data analysis, the turning point for emission per floor space occurred in 2001, when the equivalent income and emission per floor space were 16715.5 United States dollars (USD) (measured with 2010 US dollars) and 38.6 $kgCO_2$ per square meter, respectively. Correspondingly, the turning years for the remaining three emission scales occurred in 2003, 2007, and 2013.

This section also focuses on statistics and analysis of CKCs' features for the 30 countries. As illustrated in Fig. 4a, over 57% of the four scales corroborate the CKC hypothesis. Specifically, countries with CKCs had the largest proportion of emission per capita (73%), followed by emission per household (70% of countries with CKCs), emission per floor space (67%) and the total emissions (57%). In the presence of CKC, the peak state changes with various emission scales. As indicated by Fig. 4b, all countries at emission per floor space peaked, followed by emission per household and emission per capita (95% of countries peaked), and the total emissions had the lowest proportion (88%). Timing sequence investigated in Fig. 4b is the same as a result indicated by Fig. 3. In Fig. 4c, in the presence of CKC, more than 76% of countries exhibit an inverted U-shape regardless of the indicator. Around 5% of countries show an inverted N-shape in addition to emission per floor space. More than 12% at various emission scales show an N-shape, and the proportion increases with a higher percentage of peaks. The result illustrates the potential for the environment to deteriorate again after carbon emissions peaked.

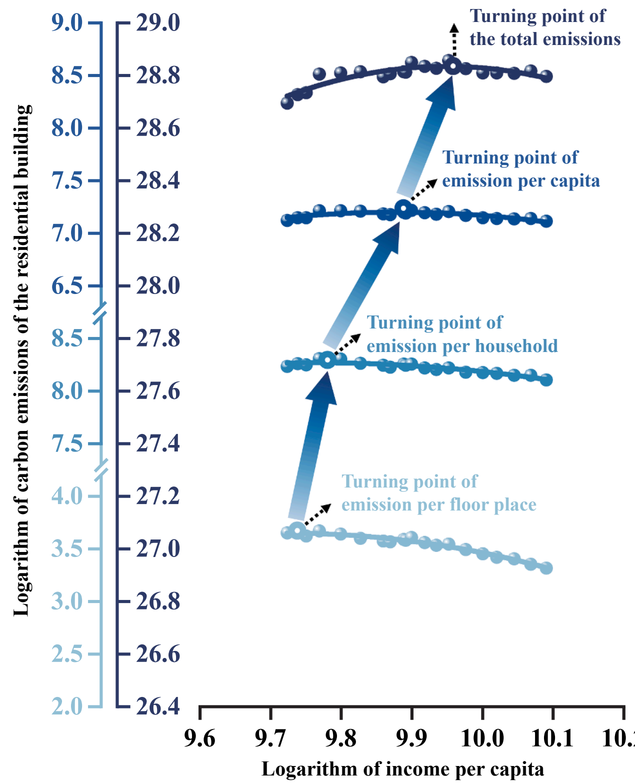


Fig. 3. Peaking status of CKCs for aggregated 30 countries.

Three categories based on the presence and peaking status of CKCs

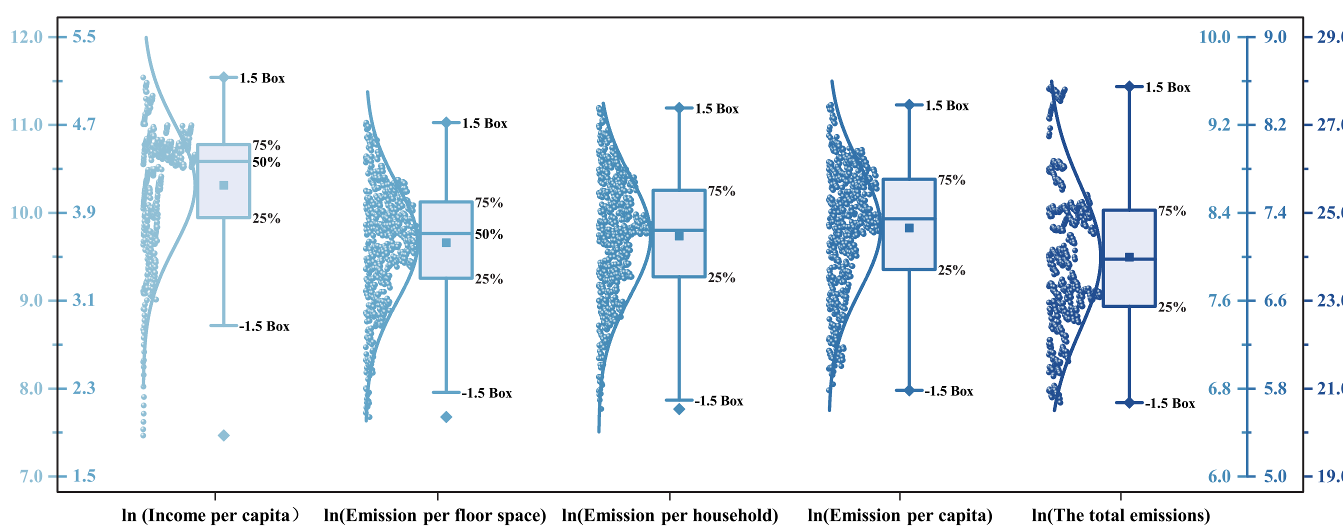


Fig. 2. The descriptive statistics of the original variables across 30 countries from 2000 to 2019. Note: The scatter denotes the samples, the diamond represents the maximum and minimum values, the square denotes the mean, the horizontal line in the center of the cabinet indicates the median value, and the box's sides reflect the 75% and 25% distribution levels, respectively.

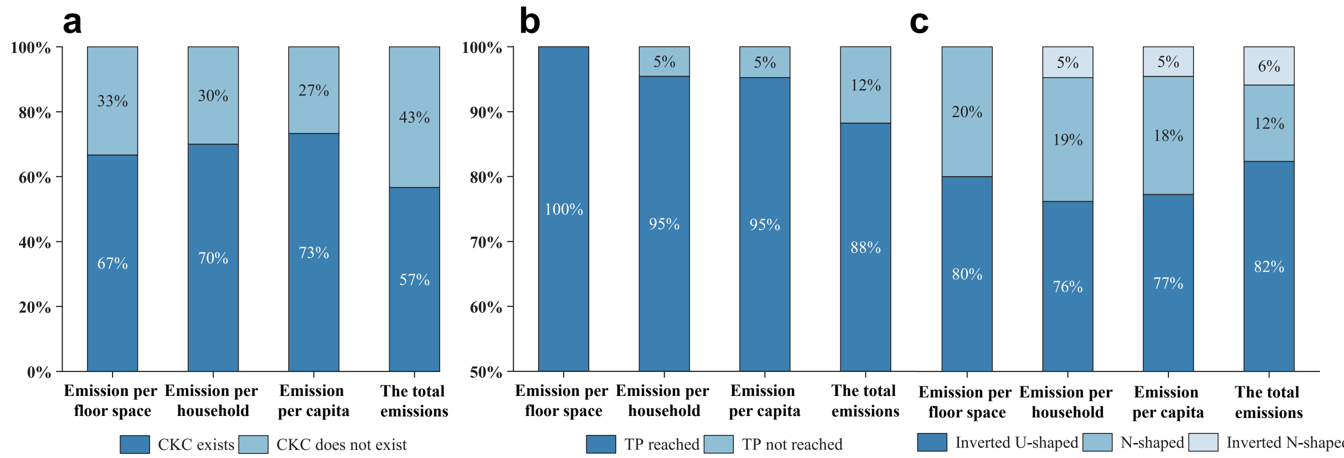


Fig. 4. Presence, curve features and peak states of CKCs in 30 countries. Note: TP is the abbreviation of turning point.

were used to intuitively observe the spatial distribution of peaking status in 30 countries. Fig. 5a illustrates that for emission per floor space all the countries peaked in the presence of CKC. For the total emissions, in the presence of CKC, only China and Korea have not peaked. Due to economic development and the implementation of emission reduction policies, whether carbon emissions reach the peak exists a spatial clustering effect between countries. Countries in which the total emissions (as illustrated in Fig. 5d) peaked are mostly in Europe, including the United Kingdom, Greece, Poland. For the turning year, the United Kingdom reached its peak in 2003, Greece in 2003 and Poland in 2008. The other two countries (New Zealand and the US) reached their peaks in 2003 and earlier than 2000, respectively.

In general, the examination of CKCs' presence, peaking states and characteristics for 30 countries at the aggregate and individual levels indicates the peaking sequence, which addresses Issue 1 in Section 1.

4.2. CKCs' characteristics at various economic levels

This section further investigates the nexus between economy and emissions at different income levels and discusses the features of CKCs. That is, this section intends to further compare the CKC characteristics of 30 countries at different economic levels by exploring the variation at various emission scales.

As shown in Fig. 6, this study divided 30 countries into four categories using 2019 GNI per capita. The analysis revealed that the income levels of 30 countries conform to the normal distribution. This study used the mean and standard deviation in a normal distribution to calculate the values and round to classify the income levels. According to historical data, six countries had GNI per capita<20,000 USD (measured with 2010 US dollars). After classification according to the normal distribution, there are 8, 12, and 4 countries with GNI per capita

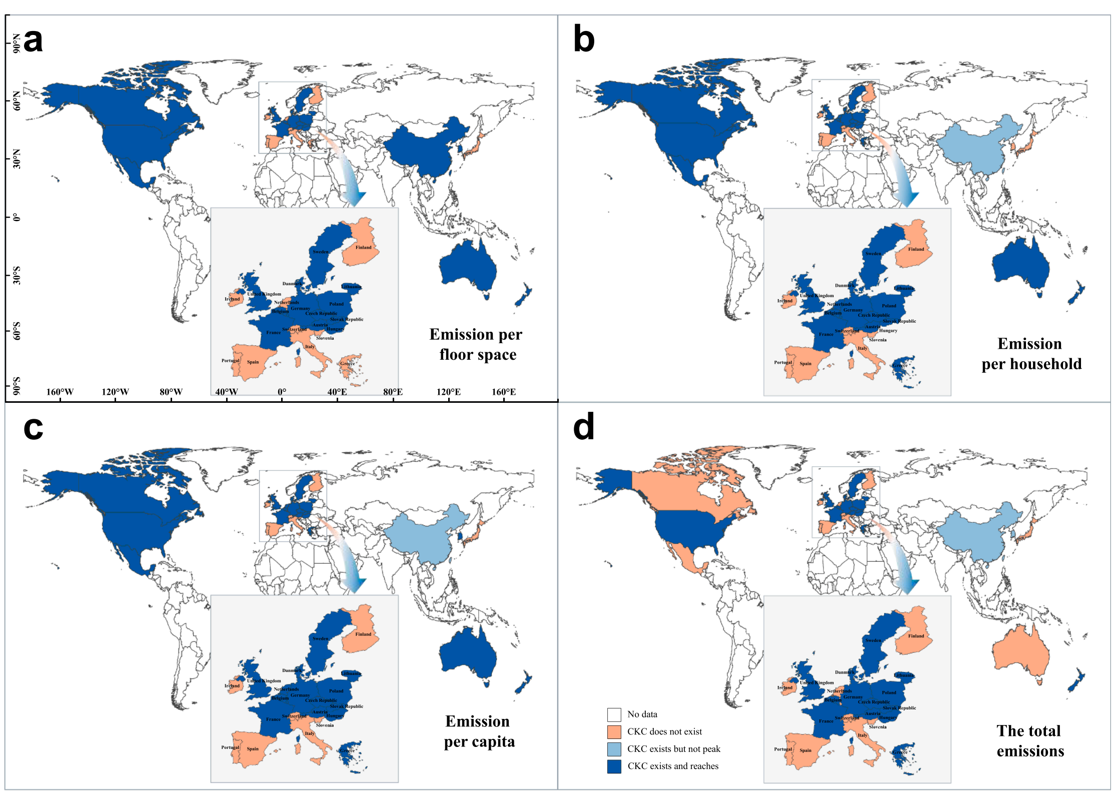


Fig. 5. Spatial distribution of peaking status of CKCs.

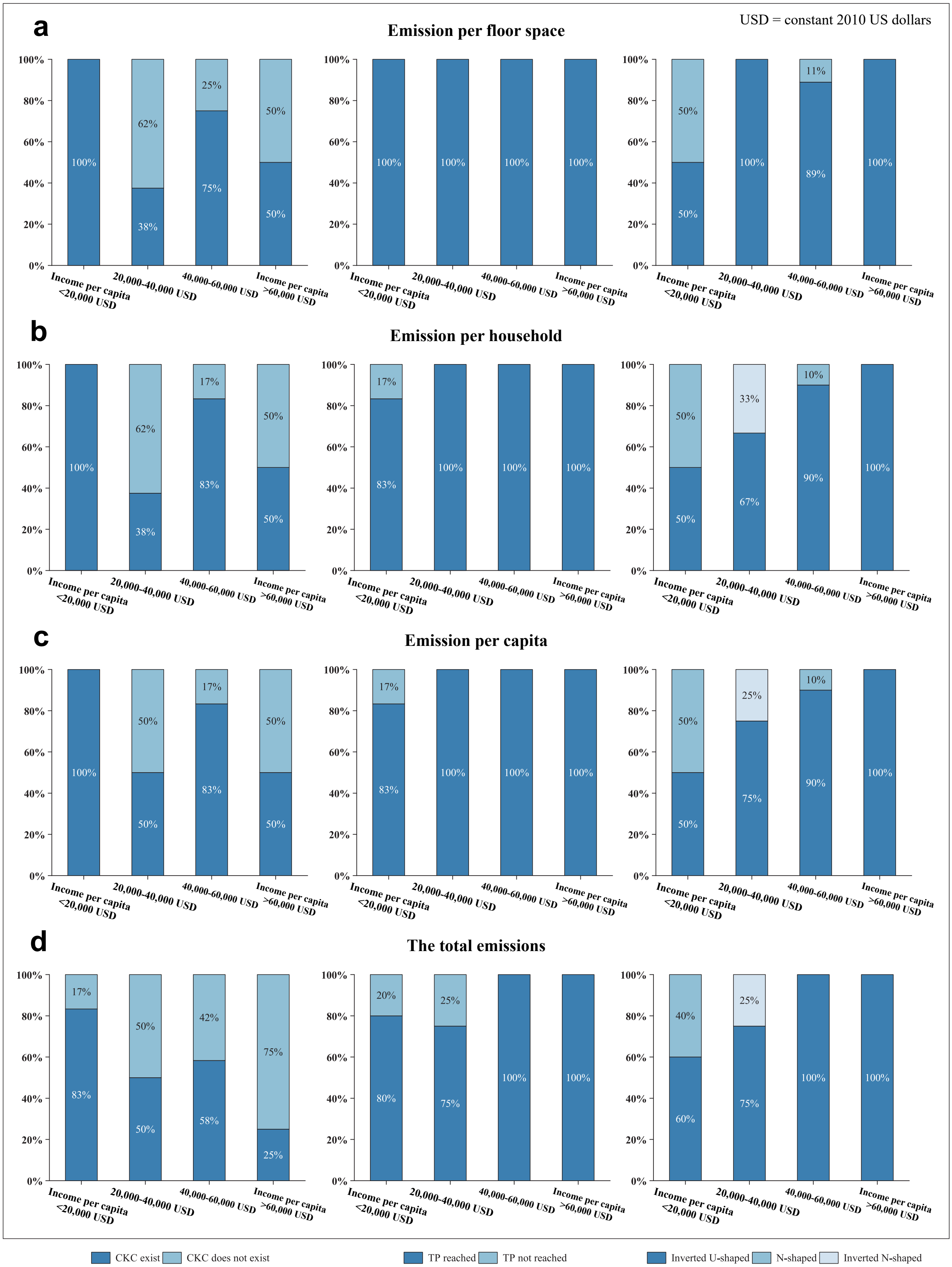


Fig. 6. CKCs' presence, curve features and peak status at four economic levels of 30 countries. Note: TP is the abbreviation of turning point.

ranging from 20,000 to 40,000 USD, 40,000 to 60,000 USD, and greater than 60,000 USD, respectively. It is difficult to discover the nexus between CKC presence and economic level in regard to CKC presence. For the peaking status, using income per capita < 20,000 USD as an example, the sequence of peaking is exactly the same as the one indicated above, which confirms the assumption made in Section 4.1. Fig. 6a to Fig. 6d, show peaking status demonstrating the trend of decreasing peak probability at this same economic level. For the same emission scales, taking emission per household as an example, as the economic level increases, the more developed countries have a higher probability of peaking. Carbon emissions are typically higher in developed countries, and high-carbon-emission living habits accompany higher income levels [34]. Despite having larger carbon emissions, developed countries are more likely to choose environmentally friendly items due to an earlier awareness of the need to reduce emissions; additionally they have a higher level of household electrification [35]. Compared with countries at lower economic levels, developed countries can efficiently reduce carbon emissions and reach peaks sooner.

In regard to the three types of CKCs, the inverted U-shape is the most common, followed by the N-shape, while the inverted N-shape is the least common. As shown in Fig. 6, using total emissions as an example, the N-shape mainly exists in countries with income per capita < 20,000 USD. This is mainly because these countries reached the peak relatively early (earlier than 2000), and then rebounded.

In summary, the investigation of the CKCs at different income levels reveals that a developed country has a higher probability of peaking, which gives a further explanation to Issue 1 in Section 1.

4.3. CKCs' characteristics in different geographical locations

For economic development and the implementation of emission reduction policies, there are similarities between countries based on their geographical location. To better analyze the CKC fit status of relevant countries, this study divided the 30 countries into seven categories, including Northeast Asia, Mexico, the European Union, the United Kingdom, Oceania, North Americas, and Switzerland. As shown in Fig. 7a, all seven samples exist CKC and reached their peaks, with Northeast Asia peaking in 2013 and the United Kingdom in 2002. Mexico and Switzerland present inverted N-shapes, with N-shapes for emission per household (as shown in Fig. 7b), and the remaining five samples exhibit inverted U-shapes. In Fig. 7b, all samples except Northeast Asia have reached their peaks, indicating that countries with higher economic levels more easily reach their peaks, which is similar to the result in Section 4.2. The relative positions of different CKCs in Fig. 7 a-c are all approximately the same, while the result in Fig. 7d is quite different. For example, in comparing Switzerland to Northeast Asia, Switzerland has relatively high emission per capita and per household, but relatively low total emissions. The relatively high income per capita

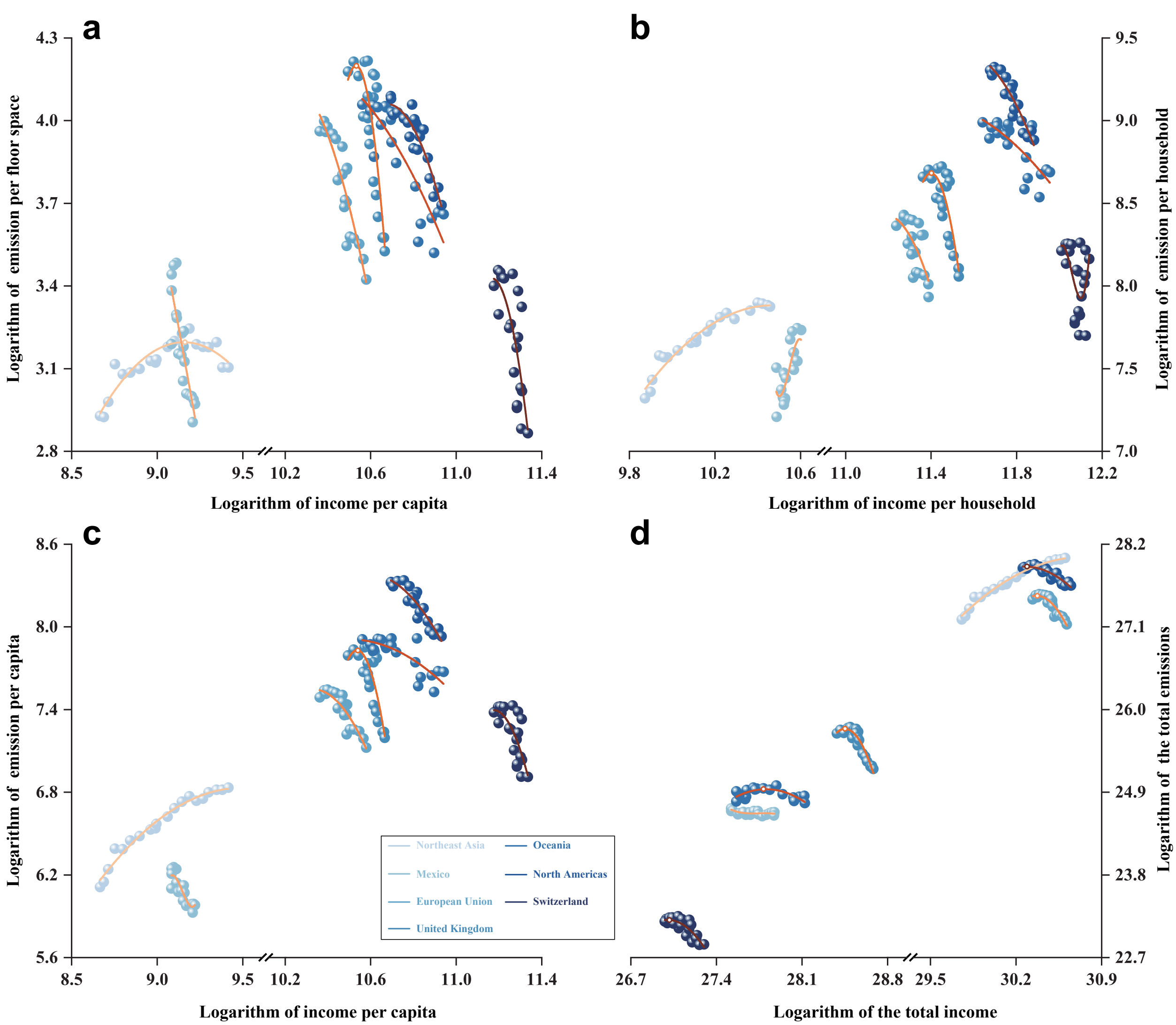


Fig. 7. CKCs for 30 countries divided into seven combinations.

and consumption level lead to high carbon emissions per capita and per household in Switzerland, but the sparse population and small residential building area are the main reasons for its low total income and total emissions [36]. In contrast, despite its relatively high total emissions, construction floor space and population in Northeast Asia mean that its emission per floor space and per capita are relatively low. For China, the annual area of newly built civic buildings is approximately 2.5 billion square meters and 1 billion demolished, for a net growth of 1.5 billion, three times Switzerland's residential building stock in 2019.

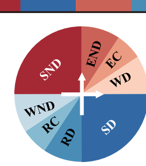
Overall, the results illustrate the characteristics of the CKCs for

Emission per floor space

Country \ Period	00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	00-19
China	WD	EC	END	SD	WD	WD	WD	WD	WD	WD	WD	WD	WD	SD	SD	SD	WD	SD	WD	WD
Mexico	WND	RD	SD	SD	SD	SD	WD	RD	SND	SD	SD	SD	RD	SD	SD	SD	SD	SD	RD	SD
Poland	END	SD	WD	WD	WD	WD	SD	SD	SD	END	SD	SD	SD	SD	SD	WD	SD	SD	SD	SD
Hungary	WD	SD	END	SD	SD	SD	RD	SD	RD	END	SD	RD	SD	SD	END	WD	END	SD	SD	SD
Lithuania	WD	SD	SD	SD	WD	SD	SD	SD	RC	END	SD	SD	SD	SD	SD	EC	SD	WD	SD	SD
Slovak Republic	END	SD	SD	SD	SD	SD	SD	SD	WND	END	SD	SD	WD	SD	WD	SD	END	SD	SD	SD
Czech Republic	WD	SD	WD	SD	SD	WD	SD	SD	WND	END	SD	END	RD	SD	WD	END	SD	SD	SD	SD
Greece	WD	WD	EC	SD	SD	RD	SD	RD	RD	RC	SND	RD	RD	SD	SND	RD	END	SD	SD	SD
Portugal	SD	END	RD	SD	END	RD	SD	RD	SND	SD	SD	WND	SD	SD	END	EC	END	SD	SD	SD
Slovenia	WD	SD	WD	SD	SD	SD	SD	END	SND	END	SD	RD	RD	SD	SND	END	SD	SD	SD	SD
Korea	END	SD	WD	END	SD	SD	SD	SD	SD	WD	WD	SD	SD	SD	SD	WD	EC	EC	SD	SD
Spain	SD	END	SD	END	END	SD	SD	RD	RD	SD	SND	SND	RD	SD	END	SD	END	SD	SD	SD
Italy	EC	RD	SND	END	SD	SD	SD	WND	WND	END	SD	RC	RD	RD	END	SD	SD	SD	SD	SD
New Zealand	END	SD	END	SD	END	SD	SD	SND	SD	RD	SD	END	SD	SD	SD	SD	END	SD	END	SD
United Kingdom	END	SD	END	WD	SD	SD	SD	RD	RD	END	SD	SND	SD	SD	SD	SD	SD	SD	SD	SD
France	SD	RD	END	SD	WD	SD	SD	RD	RC	EC	SD	SND	WD	SD	END	END	SD	SD	SD	SD
Belgium	END	SD	END	WD	WD	SD	SD	END	RD	END	RD	EC	END	SD	END	SD	SD	SD	SD	SD
Germany	END	RD	SND	SD	SD	WD	SD	END	RC	WD	SD	END	END	SD	WD	SD	SD	SD	SD	SD
Finland	END	END	END	SD	SD	END	SD	SD	SND	END	SD	RD	RD	RD	SD	END	SD	WD	SD	SD
Austria	END	SD	END	SD	SD	SD	SD	SD	WND	END	SD	RD	SND	RD	SND	EC	END	SD	EC	SD
Japan	SD	SND	SD	SD	WD	SD	END	RD	WND	END	END	END	SD	SD	SD	END	WD	SD	SD	SD
Canada	SD	SD	WD	SD	SD	SD	END	RD	RD	SD	WD	SD	WD	WD	SD	SD	SD	END	SD	SD
Netherlands	SND	RD	END	SD	RD	SD	SD	SND	WND	END	SD	SND	SND	RD	END	EC	SD	SD	SD	SD
United States	SD	SD	WD	SD	SD	SD	END	SND	SND	END	SD	SD	END	END	SD	SD	SD	END	SD	SD
Australia	SD	SND	WND	SND	SD	SD	RD	WND	WD	WND	WND	SD	SD	SD	WD	WD	WND	RD	SD	SD
Sweden	SD	EC	WD	EC	SD	SD	SD	RD	WND	END	SD	RD	SD	SD	SD	END	WD	SD	SD	SD
Ireland	SD	SD	SD	WD	SD	SD	SD	SND	RC	WD	RD	RD	SD	SD	WD	WD	SD	WD	SD	SD
Denmark	END	SD	END	SD	SD	END	RD	RD	SND	END	SD	SD	END	SD	SD	END	SD	SD	SD	SD
Luxembourg	SD	SND	SND	WD	SD	WND	SD	SND	SND	SD	RD	SND	RD	SD	END	RC	END	RD	SD	RD
Switzerland	SND	RD	END	SD	WD	SD	RD	SND	SD	END	RD	END	END	RD	END	SND	RD	SD	SD	SD

Higher income level ↓

Weak decoupling ($\Delta c>0$, $\Delta i>0$, $0<\varphi<0.8$)
Expansive coupling ($\Delta c>0$, $\Delta i>0$, $0.8<\varphi<1.2$)
Expansive negative decoupling ($\Delta c>0$, $\Delta i>0$, $\varphi>1.2$)
Strong negative decoupling ($\Delta c>0$, $\Delta i<0$, $\varphi<0$)



Weak negative decoupling ($\Delta c<0$, $\Delta i<0$, $0<\varphi<0.8$)
Recessive coupling ($\Delta c<0$, $\Delta i<0$, $0.8<\varphi<1.2$)
Recessive decoupling ($\Delta c<0$, $\Delta i<0$, $\varphi>1.2$)
Strong decoupling ($\Delta c<0$, $\Delta i>0$, $\varphi<0$)

Fig. 8. The decoupling statuses of economic growth from emission per floor space of 30 countries.

countries clarified by different geographical locations and explore the external factors of the carbon emissions peak, which comprehensively answers Issue 1 in Section 1.

5. Discussion

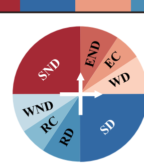
To test the robustness of the CKC results, Section 5.1 calculates the Tapio decoupling elasticity index and provides a comprehensive verification of the results of CKCs through decoupling states at different

The total emissions

Country \ Period	00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	00-19
China	EC	END	END	SD	EC	WD	WD	WD	WD	WD	EC	WD	EC	SD	WD	EC	WD	WD	WD	WD
Mexico	SND	END	SD	SD	EC	SD	END	SD	SND	SD	WD	SD	SD	SD	WD	WD	WD	WD	RD	SD
Poland	END	SD	END	EC	WD	EC	SD	WD	EC	END	SD	WD	SD	SD	WD	WD	SD	SD	SD	SD
Hungary	WD	SD	END	SD	WD	SD	RD	SD	RD	END	SD	RD	SD	SD	END	EC	END	SD	SD	SD
Lithuania	WD	SD	SD	SD	WD	SD	SD	SD	SND	SND	SD	SD	SD	SD	RD	END	SD	WD	SD	SD
Slovak Republic	END	SD	SD	SD	SD	SD	SD	SD	WND	END	SD	SD	WD	SD	WD	SD	END	SD	SD	SD
Czech Republic	WD	SD	WD	SD	SD	WD	SD	SD	WND	END	SD	EC	RD	SD	WD	END	SD	SD	SD	SD
Greece	WD	WD	END	SD	WD	RD	SD	RD	RD	RC	SND	RD	RD	SD	SND	RD	END	SD	SD	SD
Portugal	SD	END	RD	END	END	SD	SD	RD	SND	SD	SND	WND	SD	SD	END	WD	END	SD	SD	SD
Slovenia	WD	WD	WD	SD	SD	SD	SD	END	SND	EC	SD	RD	RD	SD	SND	END	SD	SD	SD	SD
Korea	END	SD	WD	END	END	SD	SD	EC	END	EC	EC	WD	SD	SD	WD	END	END	END	SD	WD
Spain	WD	END	WD	END	END	SD	EC	SD	RD	SD	SND	SND	RD	WD	END	SD	END	SD	SD	SD
Italy	END	SD	END	END	WD	SD	SD	WND	WND	END	SD	WND	RD	SD	END	SD	SD	SD	SD	SD
New Zealand	END	SD	END	SD	END	SD	SD	SND	SD	SD	SD	END	SD	SD	SD	SD	END	SD	END	SD
United Kingdom	END	SD	END	WD	SD	WD	SD	RD	RD	END	SD	END	SD	SD	SD	SD	SD	WD	SD	SD
France	WD	SD	END	WD	EC	SD	SD	SD	RC	END	SD	SND	END	SD	END	END	WD	SD	SD	SD
Belgium	END	SD	END	WD	WD	SD	SD	END	RD	END	SD	WD	END	SD	END	SD	SD	SD	SD	SD
Germany	END	RD	SND	SD	SD	WD	SD	END	RC	END	SD	END	END	SD	WD	WD	SD	SD	SD	SD
Finland	END	EC	END	SD	SD	END	SD	SD	SND	END	SD	RD	WND	SD	SD	END	SD	WD	SD	SD
Austria	END	SD	END	SD	SD	SD	SD	SD	WND	END	SD	SD	END	SD	SND	WD	END	SD	EC	SD
Japan	SD	END	WD	WD	WD	SD	END	RD	WND	END	END	END	SD	SD	SD	END	WD	SD	SD	WD
Canada	SD	WD	EC	SD	SD	SD	END	SD	RD	SD	EC	SD	EC	EC	SD	SD	WD	END	SD	SD
Netherlands	END	SD	END	SD	SD	SD	SD	SND	SND	END	SD	SND	SND	RD	END	END	SD	SD	SD	SD
United States	END	SD	END	WD	SD	SD	END	SD	RC	END	SD	SD	END	END	SD	SD	SD	END	SD	SD
Australia	WD	END	SND	SND	WD	WD	SND	SND	WD	WND	WND	SD	SD	SD	EC	WD	WND	SD	SD	SD
Sweden	SD	END	WD	SD	SD	SD	SD	RD	WND	END	SD	RD	SD	SD	SD	END	WD	SD	SD	SD
Ireland	END	SD	SD	WD	WD	SD	SD	SND	WND	END	RD	RD	SD	SD	WD	WD	SD	WD	SD	SD
Denmark	END	SD	END	SD	SD	END	SD	SD	SND	END	SD	SD	END	SD	SD	END	SD	SD	SD	SD
Luxembourg	END	SND	SND	WD	SD	WND	SD	SND	SND	SD	RD	END	RD	SD	END	SD	WD	SD	SD	SD
Switzerland	SND	RD	END	WD	WD	SD	RD	SND	SD	EC	RD	END	END	SD	END	END	RD	SD	WD	SD

Higher income level

Weak decoupling (Δc>0, Δi>0,0<φ<0.8)
Expansive coupling (Δc>0, Δi>0, 0.8<φ<1.2)
Expansive negative decoupling (Δc>0, Δi>0, φ>1.2)
Strong negative decoupling (Δc>0, Δi<0, φ<0)



Weak negative decoupling (Δc<0, Δi<0,0<φ<0.8)
Recessive coupling (Δc<0, Δi<0, 0.8<φ<1.2)
Recessive decoupling (Δc<0, Δi<0, φ>1.2)
Strong decoupling (Δc<0, Δi>0, φ<0)

Fig. 9. The decoupling statuses of economic growth from the total emissions of 30 countries.

emission scales. Section 5.2 introduces the threshold regression model to further check the robustness and to verify the heterogeneity of CKCs among different country groups. In addition, Section 5.3 presents the effective strategies to strengthen the decarbonization effect in global residential building operations.

5.1. Decoupling effect at different emission scales

By using the Tapio model mentioned in Section 3.2, this study illustrated the decoupling status of income and carbon emissions at different emission levels for 30 countries. To ensure the integrity of the results, the decoupling period was divided into both the entire study period and the individual year to present the decoupling status in different periods.

Decoupling status can validate the CKC fitting result to a certain extent [37]. When a country's emissions reach a peak, meaning income increases while carbon emissions decrease, decoupling status presents the strong decoupling. To intuitively observe the change in the decoupling status in different periods, this study used red-colored padding and blue-colored padding to express the increase and decrease in carbon emissions respectively. For the decoupling status of the entire study period in emission per floor space, all samples except those for China and Luxembourg demonstrated strong decoupling, which corresponds to the result analyzed in Section 4.1. For China, the decoupling status presents weak decoupling, while the original CKC fitting result indicated it had reached the peak. The main reason for this discrepancy is that CKC is a fitted curve based on the existing data, while decoupling elasticity is only assessed through data collected at the start and the end of the study period. China reached its peak in 2014, but for emission per floor space in 2000, the reductions were smaller than the increase during the study period, which led to the different results. As shown in Fig. 8, the decoupling status of 30 countries varies greatly with income levels. Taking China as an example, the decoupling status of the red-colored padding part (i.e., carbon emissions increased) occupied 63.2%. In contrast, Ireland, which has relatively high income per capita, accounts for only 31.6%, which indicates that developed countries reach their peaks and undertake carbon emission reduction work earlier. Additionally, it is worth noting that some major international events may lead to different decoupling statuses. From 2007 to 2009, there were fewer countries with strong decoupling than for any other period, which may be due to the global financial crisis that occurred in 2008. In the US, for example, household consumption expenditure increased continuously before and after the crisis and reached its lowest point in 2009. Consumption levels influence human behavior and thus affect energy structure and carbon emissions [38,39]. The carbon emissions generated by the use of natural gas in the US in 2008 were 1.1 times that of 2006, and the reduction in combined emission factors from 2007 to 2008 was 1.5 times higher than the reduction from 2006 to 2007. It is worth noting that China's GNI per capita and carbon emissions both increased during the financial crisis, which is believed to be the result of a 4 trillion RMB economic stimulus plan proposed for people's livelihood, ecological construction and infrastructure construction [40]. Similarly, Greece experienced a national debt crisis in 2009, its economy receded, and carbon emissions declined over the next few years.

For the decoupling status of the entire study period in the total emissions (as shown in Fig. 9), all the samples except China, Korea and Japan present strong decoupling, which verified the CKC fitting result shown in Fig. 5d. Although the decoupling status is similar between the above scales throughout the entire period, the result of individual years varies greatly. Obviously, the red-colored padding part of the total emissions has a larger proportion than emission per floor space, which indicates that emission per floor space will reach its peak earlier than the total emissions. Similarly, the result of developed countries peaking earlier and implementing emission mitigation strategies are also verified in Fig. 9. For example, China's decoupling status in the blue-colored filled part (i.e., carbon emissions decreased) occupied 10.5%, and Sweden, as a developed country, accounted for 73.7%.

To further explain the difference in decoupling statuses under various economic levels and various emission scales, the proportion of decoupling statuses is analyzed. As shown in Fig. 10, for emission per household, the blue part, which includes four decoupling statuses representing decreased carbon emissions, accounted for 56.1% in countries with income per capita < 20,000 USD, 61.2% for 20,000–40,000 USD, 62.3% for 40,000–60,000 USD and 63.2% for greater than 60,000 USD, respectively. Thus, for the same emission scale, in relation to economic growth, the proportion of the red part (carbon emissions growth) always decreases as economic levels increase, while the proportion of the blue part (carbon emissions reduction) increases as economic levels increase. This verifies the hypothesis that countries with higher economic levels reach their peaks earlier. Under the same economic level, such as GNI per capita < 20,000 USD, emission per floor space accounted for 65.8%, which is the largest proportion of the blue part, followed by emission per household (56.1%), emission per capita and the total emissions (50.9%). Note that at the same economic level, the proportion of decoupling status representing carbon emission reduction from highest to lowest is the same as the rules mentioned before. This indicates that the sequence of carbon emissions peaked at different scales, which is the same as the hypothesis proposed in Section 4.1.

Overall, the discussion above evaluates the decoupling effect at different emission levels and income levels, verifying the robustness of CKCs and answering Issue 2 in Section 1.

5.2. Reinvestigation of CKCs' heterogeneity via the threshold regression

The heterogeneity of CKCs reveals that different countries have different environmental pressure and economic development patterns, leading to the classic inverted U-shaped nexus between economy and emissions may not occur [31]. In Section 4, this paper observed the heterogeneity of CKCs at different economic levels and in geographical locations. It shows the CKCs with N-shape or inverted N-shape also exist. To further verify the heterogeneity above and overcome the weakness from the subjective grouping in Fig. 6, a threshold regression model was employed to further analyze the heterogeneity of CKCs among different country groups in this section. The method of the threshold regression model can be found in Appendix B.

First, the 2019 GNI per capita was still used as the samples of the threshold regression estimation. The three threshold values were estimated by utilizing a global optimization algorithm [41], and the 30 countries were divided into 4 groups, as shown in Table 2.

Considering the space limitation, this study only performed the fixed effects regression at the scale of the total emissions. According to the panel data of 30 economies in 2000–2019, the four groups classified by the normal distribution in Section 4.2 and the above four groups classified by the threshold regression were subjected to test the CKCs of residential building operations (see the detailed test in Appendix C). The features of CKCs were determined by the goodness-of-fit, as shown in Fig. 11.

By comparing the CKCs' features of each country group determined by the two classifications, it can be found that the CKCs exist and the curves were fitted by the inverted U-shape in regard to Groups A and A' as well as Groups C and C', which indicates that the economic levels corresponding to the peaks of carbon emissions grew in pace with the countries' economic growth [42]. On the other hand, the inconsistency of CKCs in Groups B and B' can be interpreted as the reversal phenomenon of CKC. Especially for countries with low economic levels, once the economic level exceeds the first turning point, structural and technological changes within the economic development may lead to the second reversal, and the carbon emissions convert to a continuous increase along with economic growth [43]. For Groups D and D', the inversion of the inverted U-shaped CKCs indicates that the developed countries with higher economic growth may have multiple turning points due to their complete development in the aspects of economy, technology, and,

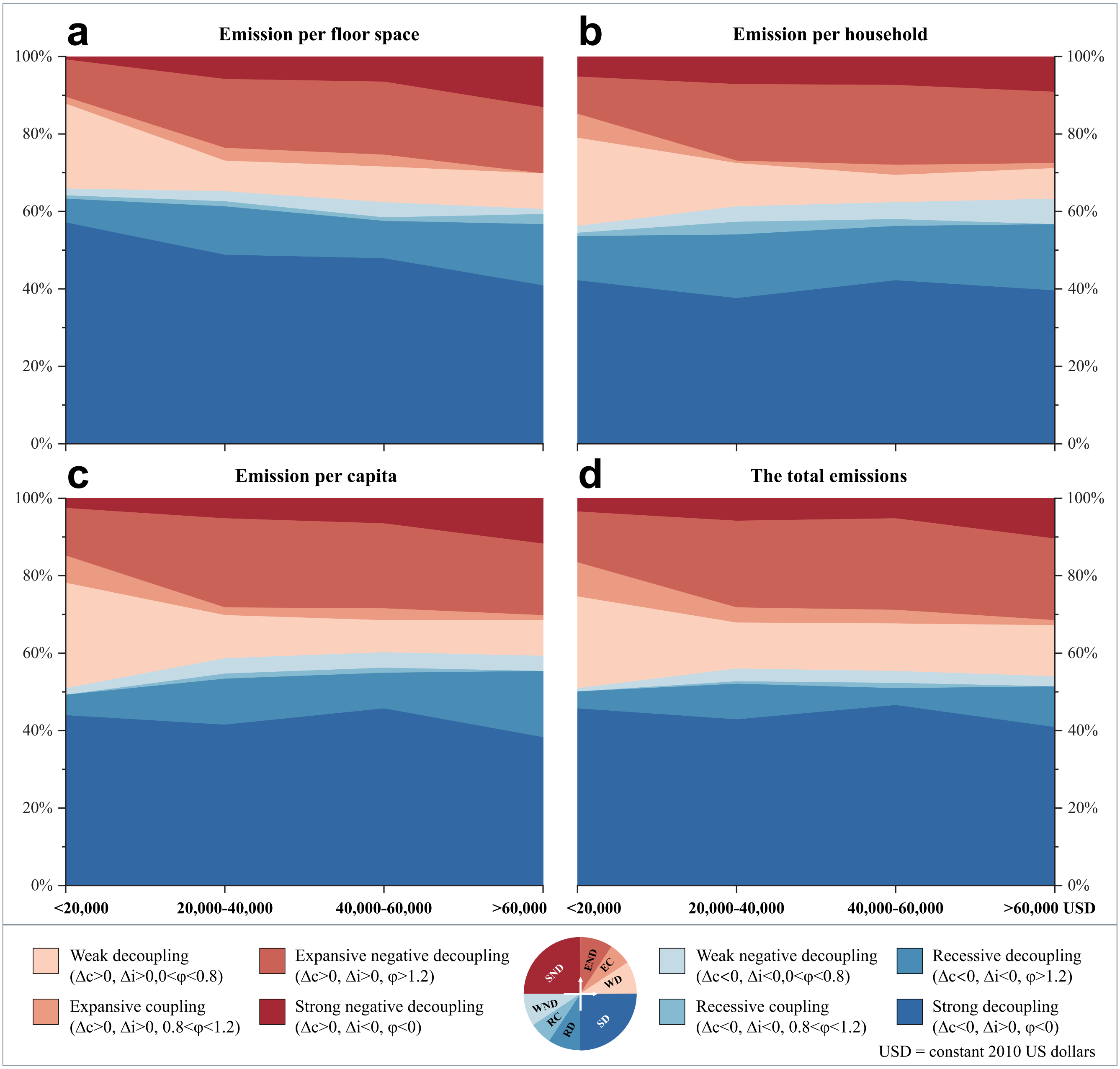


Fig. 10. The proportion of decoupling status for four income levels at various emission scales.

Table 2
Grouping results of the threshold regression model.

Variable	Threshold value	Corresponding range of income per capita (USD)	Countries
lni_{jt}	9.690, 10.031, 11.159	(0, 16162]	China, Mexico
		(16162, 22729]	Poland, Hungary, Lithuania, Slovak Republic
		(22729, 70214]	Czech Republic, Greece, Portugal, Slovenia, Korea, Spain, Italy, New Zealand, United Kingdom, France, Belgium, Germany, Finland, Austria, Japan, Canada, Netherlands, US, Australia, Sweden, Ireland, Denmark
		(70214, +∞)	Luxembourg, Switzerland

society. Hence, their CKCs (the inverted U-shaped curves) don't exist [44].

Overall, the above finding is consistent with that in Section 4.2, which explains the heterogeneity of CKCs of global residential buildings and answering Issue 2 in Section 1 completely.

5.3. Strategies to strengthen the decarbonization effect of global residential buildings

This section discusses the improvement strategies of electrification and energy efficiency in building operations, as the effective approach to strengthening the decarbonization effect and seeking the carbon neutral pathway of future residential buildings worldwide.

The significant increase in electrification with renewable electricity will result in a reduction in the consumption of end-use fossil fuels and the pollutant emissions from end-use consumption, while using energy efficiently [45,46]. To better observe the changes in electrification rates

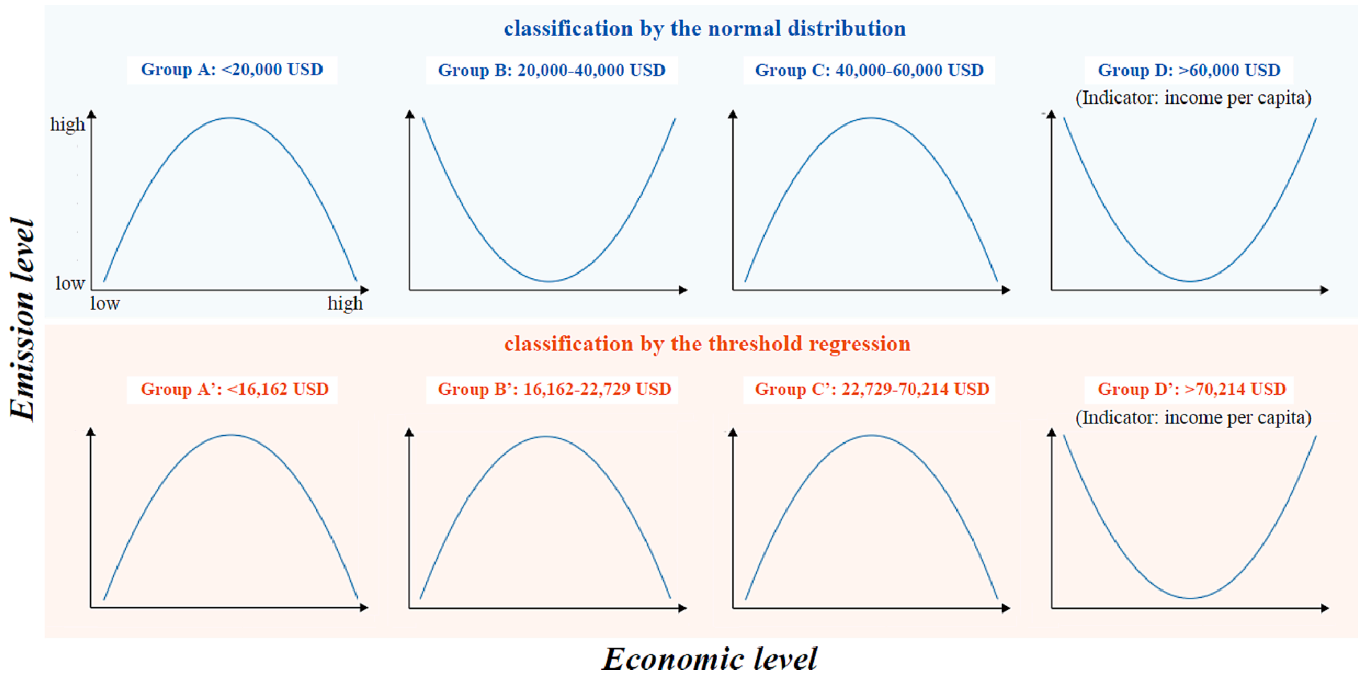


Fig. 11. The features of CKCs in different groups measured by GNI per capita. Note: The economic level was measured by the per capita income on the horizontal axis and the emission level was measured by the total emissions on the vertical axis, and they were both logarithmic in the fixed effect regression. To express the features of CKCs clearly, the antilogarithm of variables abovementioned was not involved and the values on the axes were removed.

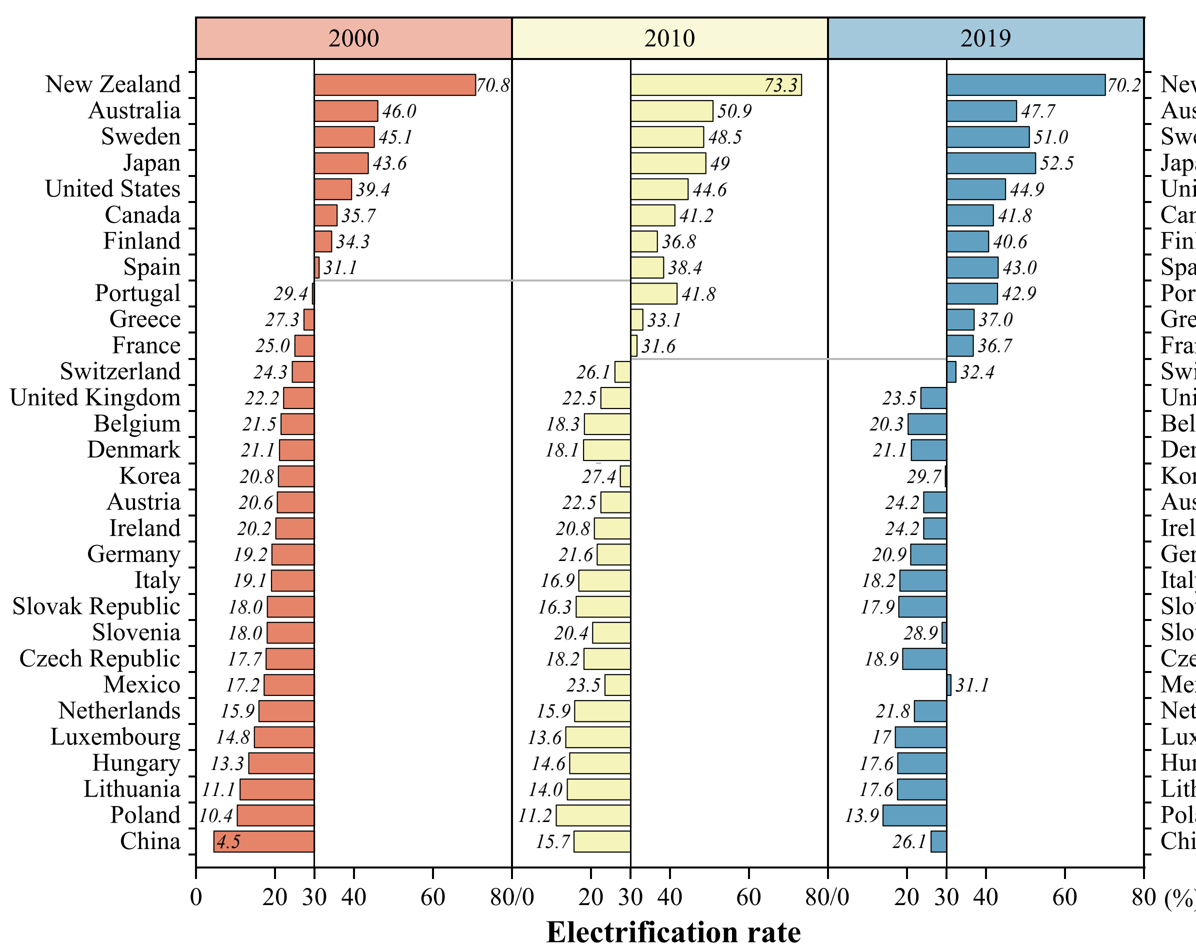


Fig. 12. The electrification rate of 30 countries' residential buildings in 2000, 2010 and 2019.

in different countries, this study investigated the residential building electrification rate of 30 countries in 2000, 2010, and 2019. As shown in Fig. 12, for better visual observation, this study used 30% as the dividing line to observe the changes in electrification rate. Specifically, the proportion of samples with an electrification rate of more than 30% was 26.7% in 2000, then rose to 36.7% and 43.3% in 2010 and 2019, respectively. Urbanization, growth in gross domestic product per capita and a growing middle class have stimulated the consumption structure of economic entities in various countries, indirectly stimulating the consumption of household appliances [47,48].

As the two largest emitters worldwide, China and the US show large differences in the development of electrification. The electrification rate of the US was 39.4% in 2000 and rose by an average of 0.6% per year from 2000 to 2019. China's electrification rate was 4.5% in 2000, and the average annual electrification rate increased by 2.4% during the observation period. In other words, the electrification rate of the US at the beginning of the observation period was nearly 9 times that of China, but the growth rate of the electrification rate in China was 6 times that of the US. Although the electrification level in China has grown the fastest, China still had a relatively low electrification rate in 2019. This is mainly due to China's large rural population base; an urbanization rate of 63.9% in 2020 indicates that nearly 40% of the population live in rural areas, resulting in a low overall electrification rate [49].

The development gap of national society and economy also leads to the differences in strategy deployment of energy efficiency improvement. This study mainly analyzed the energy efficiency improvement strategies of China and the US, providing references for developing and developed countries to achieve the high decarbonization in residential building operations. In 1986, China established a residential building energy efficiency system by promulgating JGJ26-1986. In 2006, the three energy-saving targets of 30%, 50%, and 65% were promoted widely. In 2019, China issued a design standard for the energy efficiency of residential buildings in mild areas, marking that 65% of the energy-saving target has been implemented nationwide. Some regions in China, such as Beijing, Tianjin, and Xinjiang, have even begun implementing the 75% energy efficiency standards in residential buildings. The design standards of ultralow energy buildings, near-zero energy buildings and zero energy buildings were gradually launched to regulate the construction of green buildings. As for the US, the government establishes mandatory minimum energy efficiency standards through legislation. More economically advanced states, such as California, have implemented the most stringent energy efficiency standards and labeling systems for buildings and appliances, and these standards are typically updated every three to five years. To increase public awareness of building energy efficiency, the US has issued many incentives, such as subsidies and tax credits for developers of new energy-efficient homes, to help low-income households retrofit energy efficiency. Fig. 13 shows the roadmap for improving the energy efficiency of residential buildings in China and the US.

The following suggestions can be made based on the status quo: for new buildings, vigorously develop ultralow-energy buildings, and develop near-zero energy buildings and zero-energy buildings where conditions permit [50,51]. For existing buildings, use market-based mechanisms to reduce energy consumption and carry out in-depth energy efficiency renovations in older neighborhoods [52]. For energy infrastructure, increase the proportion of renewable energy heating [53] and the level of electrification to achieve decarbonization of electricity [54,55]. For technical measures, develop negative carbon emission technologies [56,57], strengthen carbon sequestration technologies in forests and grasslands [58], and develop clean and efficient biofuels [59]. Furthermore, governments can improve the construction of the carbon emission trading market and realize that the market value of carbon rights has a facilitating effect on carbon neutrality [60,61].

In summary, by analyzing the residential building electrification rates of different countries and reviewing energy efficiency development strategies using the residential buildings of China and the US as examples, this section makes recommendations for future building decarbonization and answers Issue 3 in Section 1.

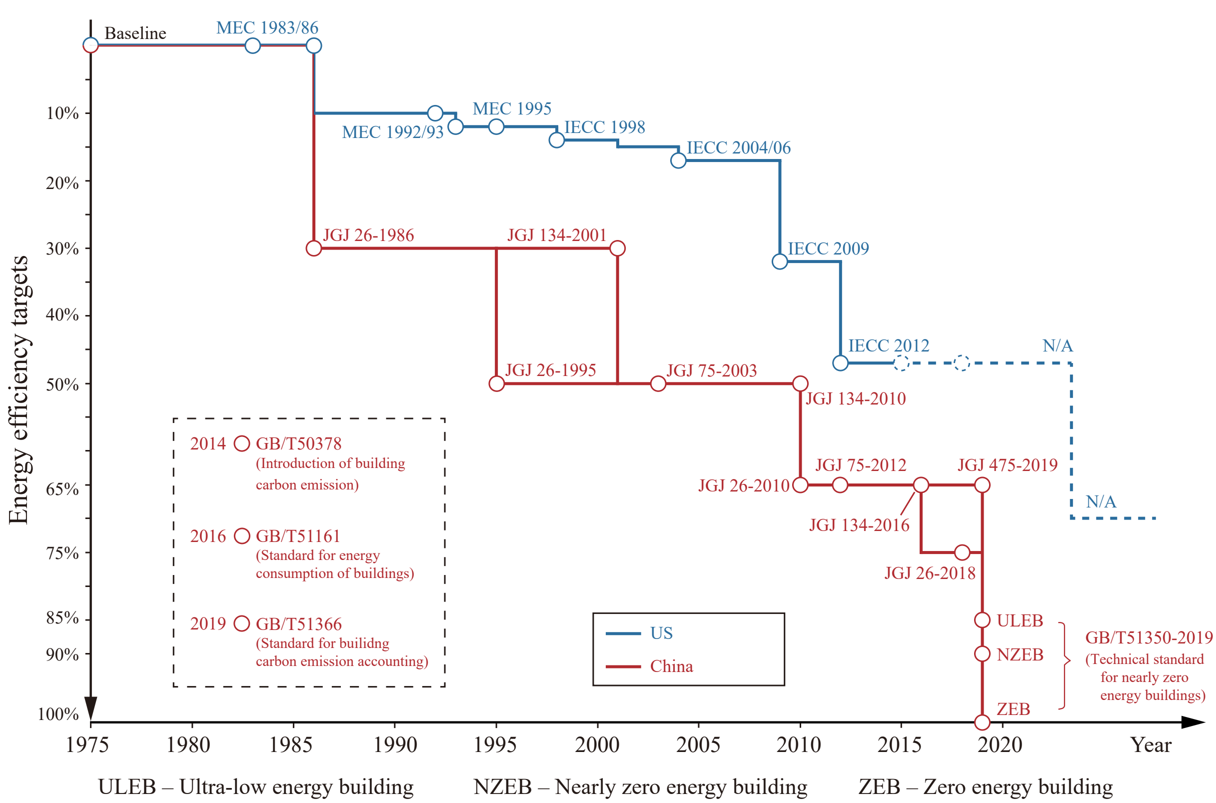


Fig. 13. Energy efficiency development strategies for residential buildings in China and the US.

6. Conclusion

This study constructed the CKC model to identify the presence, peak states, and features of carbon emissions of residential building operations in 30 countries from 2000 to 2019. Besides, the robustness of the CKCs' results was tested through the decoupling elasticity index, and the decoupling effect was evaluated. Furthermore, the threshold regression model was employed to further check the robustness and to verify the heterogeneity of CKC estimations among different country groups. Finally, this study discusses the strategies to strengthen the decarbonization effect of global residential building operations. Key findings are summarized as follows.

6.1. Key findings

- **The CKC model can fit more than half of the samples (for the total emissions: 57%; for emission per household: 70%). The majority of CKCs have an inverted U-shape (for the total emissions: 82%; for emission per household: 76%).** More than 12% of countries at various emission scales show an N-shape, and around 5% of countries show an inverted N-shape in addition to the emission per floor space. The N-shape mainly exists in countries with low economic levels, once the economic level exceeds the first turning point, structural and technological changes within the economic development may lead to the second reversal, thereby the carbon emissions convert to a continuous increase along with economic growth. In addition, developed countries with higher economic level may have multiple turning points due to their complete development in the aspects of economy, technology, and society. Hence, most of their CKCs don't exist.
- **Under the premise of CKC presence, over four-fifths of the global residential buildings reached their peaks. At the same emission scales, relatively developed countries reached their peaks earlier.** In the presence of CKC, all samples peaked at the level of emission per floor space, followed by the scales of emission per household and per capita (~95% of countries peaked), and samples at the scale of total emissions had the lowest proportion (88%). Due to economic development and the implementation of decarbonization policies, a spatial clustering effect can be observed among countries whether carbon emissions reach the peak. The total emissions in European countries have mostly peaked, while only the emissions at the scale of per household in Northeast Asia have not peaked.
- **The Tapio decoupling analysis and the threshold regression test the robustness and the heterogeneity of CKC estimations successfully.** For the decoupling status of the entire study period at the scales of emission per floor space and the total emissions, the strong decoupling was observed in most countries, corresponding to the peak states analyzed by the CKCs. At the same emission scale, the decoupling potential increased along with the increase of economic levels. At the same economic level, the sequence of the proportions of decoupling status from highest to lowest is consist with the peaking sequence at various emission scales. Furthermore, the heterogeneity of CKCs was demonstrated that different countries have different environmental pressure and economic development patterns, leading to the classic inverted U-shaped nexus between economy and emissions may not occur in all emitters.

6.2. Future studies

To further analyze the impact of building operational carbon on global carbon neutrality, some gaps can be filled in future studies. First, models with a wider research range can be selected to predict future carbon emission trajectories of the building sector and the economic cost of carbon neutrality. Such as those simulating future socioeconomic development scenarios in combination with the Shared Socioeconomic Pathways. Second, it is essential to identify the influencing factors of peak state of carbon emissions in the building sector, to help determine the targets responsible for deep decarbonization of different countries and quantify the marginal cost. For example, the generalized Divisia index method or the decomposing structural decomposition method can be used to explore the contribution of related factors to the driving and suppression of carbon emissions.

Author contributions

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

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgment

This manuscript has been authored by an author at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy. The U.S. Government retains, and the publisher, by accepting the article for publication, acknowledges, that the U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.121441.

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