The estimation of carbon imbalance and driving factors in China's urban residential building sector

You, Kairui; Chen, Liu; Huang, Ruopeng

DOI
10.1016/j.uclim.2023.101571

Publication date
2023

Document Version
Final published version

Published in
Urban Climate

Citation (APA)
You, K., Chen, L., & Huang, R. (2023). The estimation of carbon imbalance and driving factors in China's urban residential building sector. *Urban Climate*, *49*, Article 101571. https://doi.org/10.1016/j.uclim.2023.101571

Urban Climate 49 (2023) 101571

Contents lists available at ScienceDirect

Urban Climate

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

The estimation of carbon imbalance and driving factors in China's urban residential building sector

Kairui You [a,c], Liu Chen [a], Ruopeng Huang [b,*]

[a] School of Management Science and Real Estate, Chongqing University, Chongqing 400044, PR China
[b] Faculty of Architecture and The Built Environment, Delft University of Technology, Delft 2628BL, the Netherlands
[c] Institute of Technology for Carbon Neutrality, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen, 518055, China

ARTICLE INFO

Keywords:
Urban residential building
Carbon emissions
Imbalance analysis
Kaya identity
Zenga index

ABSTRACT

Understanding the imbalance of carbon emissions in the urban residential building (URB) sector is beneficial for equitable and effective emission reduction policies. However, carbon imbalance in URB and its major driving factors remain unclear. Therefore, according to the Kaya identity and Zenga index, this study aims to analyze the imbalance in carbon emissions and carbon emission unit area of URB from 2005 to 2019. The results represent the following: 1) Although the overall carbon emission unit area reached its peak value (36.17 $kgCO_2/m^2$) in 2011, the overall carbon emission of URB did not reach the peak value, arriving at 0.86 $BtCO_2$ in 2019; 2) the obvious imbalance of carbon emission and carbon emission unit area was led by the population and energy consumption unit area, respectively; 3) Compared to the difference in economy, the difference in climate had a larger impact on inter-group imbalance of carbon emission unit area without heating. In summary, these results and provided policies facilitate future formulation of fair and effective provincial decarbonization responsibility and emission mitigation implementation policies.

1. Introduction

To mitigate global climate change, China has declared its climate targets: carbon peak by 2030 and carbon neutrality by 2060 (You et al., 2023a). Chinese building sector was regarded as a key point in achieving the Chinese dual carbon target (Wang et al., 2022) since it was responsible for nearly one-quarter of Chinese energy-related CO_2 emissions. And urban residential buildings (URB) accounted for the largest share (47.6% in 2018) (CABEE, 2021). However, the per capita residential energy consumption still be in a low level, only was 72% of Japan, 21% of the US, and 23% of the UK (IEA, 2021). Along with the increasing residents' income, the residents' energy demand will face a rigid growth trend (Ma et al., 2020), which severely hinders the achievement of the Chinese dual carbon

Abbreviations: URB, Urban residential buildings; *C*, Carbon emission; *E*, Energy consumption; *A*, Building floor area; *P*, Population; *CI*, Carbon emission unit area; *EI*, Energy consumption unit area; *EF*, Energy-related emission factor; *AS*, Per capita floor area; *D*, Heating period days; INT, Interaction term; NP, North province; TP, Transitional province; SP, South province; HP, High-income provinces; MP, Mid-income province; LP, Low-income province; overall, Carbon emission or energy consumption of Overall part; no-heating, Carbon emission or energy consumption except central heating; heating, Carbon emission or energy consumption of Central heating part; adj-heating, Adjusted carbon emission or energy consumption of Central heating part.

* Corresponding author.
E-mail addresses: youkairui@cqu.edu.cn (K. You), chenliusylvia@cqu.edu.cn (L. Chen), R.Huang-1@tudelft.nl (R. Huang).

https://doi.org/10.1016/j.uclim.2023.101571
Received 18 August 2022; Received in revised form 10 May 2023; Accepted 29 May 2023
Available online 7 June 2023

target.

At the national level, *Action Plan of Carbon Peak in China's Urban and Rural construction* (MOHURD, 2022a) and *Building energy conservation and green building development Plan in the 14th Five-Year* (MOHURD, 2022b) have been formulated to accelerate the decarbonization process of Chinese URB (Ma et al., 2022). However, there is an obvious difference in the energy utilization and energy structure of URB in different provinces (Li et al., 2021). The "One-size-fits-all" emission mitigation approach may cause huge press on the provinces with severe climate and economic conditions, which have grid energy needs and demand growth (Li et al., 2023b; Yan et al., 2022). For example, the heating demand in China's severe cold and cold area made their mean carbon emission unit area (*CI*) (50.01 $kgCO_2/m^2$) approximately four times of other provinces (10.86 $kgCO_2/m^2$)(CABEE, 2021). And the developed economic provinces (i.e. 49.59$kgCO_2/m^2$ in Hebei) have lower end-user energy demand than developed provinces (i.e. 59.27$kgCO_2/m^2$ in Beijing). Therefore, understanding the imbalance and driving factor of provincial URB carbon emission is a prerequisite for formulating effective and equitable decarbonization responsibility and strategies at the provincial level (Wang et al., 2020; Yan et al., 2022). Thus, this study mainly addresses the following questions:

- What represents the total imbalance of carbon emissions of Chinese URB over the last few years?
- What are the main driving factors for the imbalance of carbon emissions of Chinese URB?

To answer these questions, this study assesses the imbalance of carbon emission (C) and emission unit area (CI) in Chinese URB from 2005 to 2019. By combining the Zenga index and Kaya identity (Wang et al., 2020), this study measured the imbalance of C and CI of URB, and it decomposed the imbalance into the contribution of several multiplied driving factors. Additionally, considering the obvious impact of economy and climate on CI of URB, we divided all provinces into three economy groups and three climate groups and explored the inter-group and intra-group imbalance of CI.

The significant contributions of this paper are:1) Analyze the imbalance of C and CI in URB, which concludes the parts of overall emissions ($C_{overall}$), heating emissions ($C_{heating}$), and emissions without heating ($C_{no\_heating}$). Exited studies have evaluated the imbalance of carbon emissions in industrial sectors, and few focus on the imbalance of carbon emission in URB (Cheng et al., 2021; Li et al., 2021; Wang and Feng, 2021). Wang and Feng (2021) adopted the Theil index to analyze the imbalance of carbon emission on URB, they focused on the per-capita carbon emission rather than the carbon emission unit area, and ignored carbon emissions of central heating. 2) Assesses the impact of climate on the imbalance of C and CI of URB. The climatic condition has an obvious impact on the energy consumption of URB and has been integrated into formulating building energy efficiency standards and policies (You et al., 2023b). However, exited studies have not evaluated the impact of climate conditions on emission imbalances, and mainly focused on social-economic parameters causing the imbalance of carbon emission (Cheng et al., 2021; Li et al., 2021; Wang and Feng, 2021). By adopting heating periods to amend $C_{heating}$ and $CI_{heating}$, this study developed an extended Kaya identity of the emission on central heating to explore the imbalance between $C_{heating}$ and $CI_{heating}$. This study also explored the inter-group and intra-group imbalance of $CI_{no\_heating}$ between climate zone groups.

The structure of this paper is as follows: Section 2 reviewed relevant literature. Section 3 introduces the data and research methods, including the computing processes of the Kaya identity and Zenga index. Thereafter, the data sources were introduced. Sections 4 present the results and discussion at the national and group levels, and put some policy implications. The main conclusions and future research directions are presented in Section 5.

2. Literature review

2.1. Research on quantifying the carbon emission of URB

Accurate data foundation is a prerequisite for estimating the imbalance of carbon emission in provincial URB. There are two methods of accounting data: bottom-up and up-bottom methods (You et al., 2023b). The bottom-up method collects the energy intensity of representative buildings and multiplies it by building floor area to obtain national building energy consumption (Swan and Ugursal, 2009). Surveys and engineering simulations are the main methods for collecting building energy intensity (Huo et al., 2018). A residential energy consumption survey requires to collect nationally representative samples. The USA. (EIA, 2020), European Union (Eurostat, 2022) and other developing countries have established residential energy consumption surveys covering energy characteristics in the housing unit, usage patterns, and household demographics. Engineering simulation relies on input data (i.e. climate, dwelling characteristics, appliance and system characteristics, and occupant behavior) (Swan and Ugursal, 2009), and adopted equations describing the physical behavior of systems to calculate the building energy intensity (ASHRAE, 2009). The bottom-up method facilitates to obtain energy consumption in end-user services and analyze the difference in carbon emissions and energy consumption of different regions (Huo et al., 2018; Swan and Ugursal, 2009). But it usually needs some hypothesis and large-scale survey. There is little authoritative open data for reference in China (Wang et al., 2023). By contrast, up-bottom methods mainly adopt splitting energy balance sheets to establish time series of URB energy consumption and carbon emission (Huo et al., 2018), which is official and authoritative, such as the International Energy Agency (IEA, 2021), Energy Information Agency (EIA, 2020), China's Yearbook (NBS, 2020), and Eurostat (Eurostat, 2022). In China, Wang and Feng (2021) established the time series of URB during the period of 2005–2017, but not deduct other household energy consumption such as household transportation. Li et al. (2021) solved this problem by deducting part of the oil consumption from the energy balance sheet but ignored the central heating consumption since central heating consumption belongs to the heating sector, not the residential sector. You et al. (2021) combined data derived from the Chinese Urban Yearbook with the regional energy balance sheet to calculate the carbon emissions of central heating.

In summary, based on existing studies, this study established an energy consumption and carbon emission database of URB including overall URB emissions ($C_{overall}$), heating emissions ($C_{heating}$), and emissions without heating ($C_{no\_heating}$).

2.2. Research on the imbalance of carbon emission

Existing studies have adopted different methods to estimate the imbalance of regional carbon emission and analyze its driving factors (Ahn and Uejio, 2022; You et al., 2023b). The three common method categories include spatial econometric analysis, convergence analysis, and imbalance index (Wang et al., 2020). Spatial econometric analysis adopted Moran' I Index to investigate interrelationships of regional carbon emissions. According to Moran' I Index, Yu et al. (2022) investigated the spatial agglomeration of Chinese urban carbon intensity and pointed out its spatial agglomeration increased in the past years. However, spatial econometric analysis mainly focuses on spatial autocorrelation characteristics of carbon emission (spatial agglomeration level) and doesn't comprehensively discuss the regional difference.

By contrast, convergence analysis is usually adopted to estimate the imbalance of regional carbon emissions. δ convergence analysis and β convergence analysis are the most common convergence analysis methods (Dogah and Awaworyi Churchill, 2022; Ivanovski and Awaworyi Churchill, 2020). The former means the reduction of horizontal differences between regions, while the latter means that countries with a relatively low level tend to rise relatively quickly, thus realizing the catch-up hypothesis (Zheng and Yuan, 2023). Han et al. (2018) analyzed the energy efficiency convergence of countries along the "One Belt And One Road" from 2000 to 2014. They found that the energy efficiency differences among countries showed a convergence trend before 2010, and then showed a trend of divergence. Song et al. (2021) found that carbon emissions in different parts of China are converging in the form of a convergence club (countries of the same type show a tendency to converge), and the high-emission club converges fastest.

The imbalance index is most common for estimating the imbalance of regional carbon emission since it can descript the imbalance of carbon emission at the global level and be decomposed into the contributions of multiple driving factors or regions (Wang et al., 2020). Common imbalance indices include coefficient of variation (You et al., 2021), Gini index (Ahn and Uejio, 2022), Theil index (Li et al., 2021) and Zenga index (Wang et al., 2020). Gini index and Theil index have been widely adopted to evaluate the imbalance of carbon emission and its driving factors in regions (Ahn and Uejio, 2022), transportation (Liu et al., 2021), industry sector (Zhang and Dong, 2022) and other sectors. The imbalance of URB carbon emission has been few focused. It is noticed that, although Li et al. (2021) and Wang and Feng (2021) adopted the imbalance index to analyze the imbalance of carbon emission on URB, they focused on the per capita carbon emission rather than the carbon emission unit area and ignored carbon emissions of central heating. Besides, decomposing Gini index and Theil index usually exist residual (Li et al., 2021). This study adopted Zenga index, which can be completely decomposed without residuals and can measure the imbalance in the each location in distribution and reveal the contribution to the total imbalance (Wang et al., 2020).

3. Data and methods

3.1. Research workflow diagram

The research workflow diagram is shown in Fig. 1, and mainly included three steps: 1) referring to the method of Huo et al. (2018) and You et al. (2021), this study calculated carbon emission without heating ($C_{no\_heating}$) and heating emission ($C_{heating}$) in provincial URB; 2) calculated the Zenga index to estimate the imbalance of carbon emission of provincial URB, and combined the Zenga index with Kaya identity to quantify the contribution of driving factors on the imbalance (Wang et al., 2020).3) considering the obvious impact of economic and climate conditions on the energy consumption of URB, the study divided 30 provinces into three climate zone groups and three economy groups, respectively. and decomposed the imbalance into inter-group and intra-group imbalance. *ZK* index is employed to analyze the polarization which reflects the relationship between groups and groups' cohesion (Zenga and Radaelli, 2012).

3.2. Study area and data source

Due to the lack of energy balance sheet in Tibet, this study selected other 30 provinces in China mainland as the study area. Referring to the method of Huo et al. (2018) and You et al. (2021), this study employed splitting energy balance sheet method to quantify the carbon emission and energy consumption of provincial URB during the period 2005–2019. The carbon emission and energy consumption include heating and no-heating parts. The provincial urban residential building area from the Chinese building energy and emission database (CABEE, 2021), which is calculated by building stock turnover model. Population and per capita disposable income are derived from the National and Provincial Statistical Yearbook (NBS, 2020). The heating period used to adjust heating energy consumption is derived from the Chinese Building Energy Efficiency Standard (MOHURD, 1995).

Besides, in order to quantify the contribution of inter-group and intra-group imbalance on overall imbalance, this study divided 30 provinces into three climate zone groups and three economy groups, respectively (Table.A1). The principle of climate zone groups refers Chinese Building Energy Efficiency Standard (MOHURD, 1995), which divided China into five climate zones based on heating degree days (HDD) and cooling degree days (CDD): Sever cold area (HDD $\geq$ 3800), Cold area (3800 $\geq$ HDD $\geq$ 2000), Hot summer and cold winter area (1200 $\geq$ HDD $\geq$ 700), Hot summer and warm winter area (700 $\geq$ HDD, CDD $\geq$ 10), and Moderate area (HDD $\leq$ 700, CDD $\leq$ 10). According to the heating behavior, we merged Sever cold area and Cold area into the North area (adopt central heating), merged the Hot summer and warm winter area and Moderate area into the South area (no heating), and called the Hot summer and

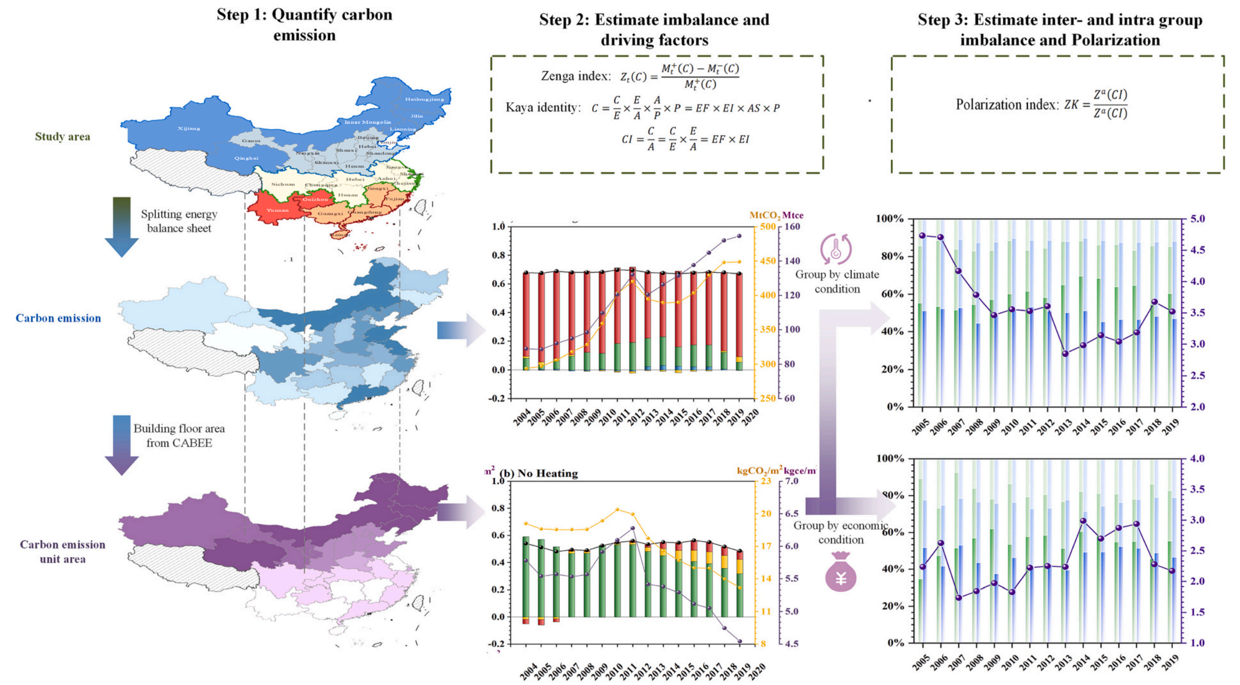

Fig. 1. Research workflow.

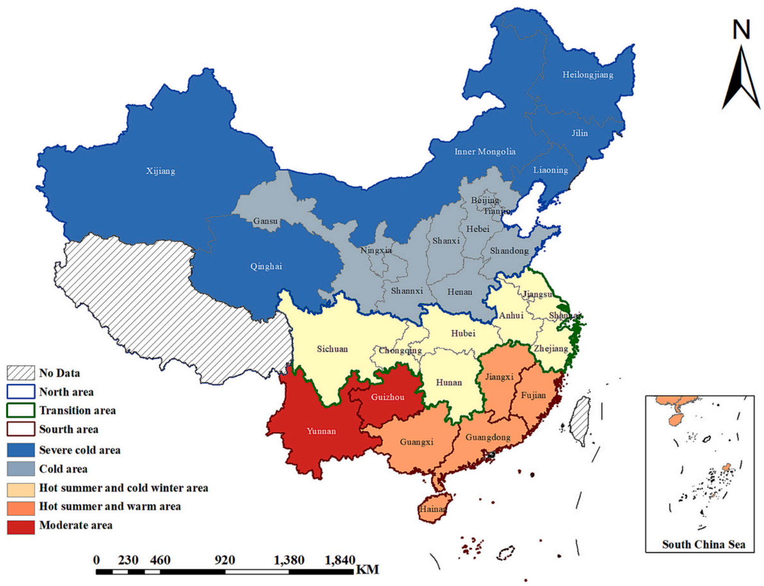

Fig. 2. Study and climate division.

cold winter area as Transition area (adopt individual heating) (Li et al., 2023a) (See Fig. 2). The principle of the economic group is based on per capita disposable urban residents' income and all provinces are divided equally into three groups. Take 2019 as an example, per capita disposable urban residents' income of high, mid, and low-income provinces is 73,848–40,782, 40,782–36,016, and 36,016–32,299 yuan, respectively.

3.3. Extended Kaya identity of URB

Kaya identity has been used to represent the coupling relationship between carbon emissions and related driving factors (Kaya, 1989). The original Kaya identity measured carbon emissions using four parameters, population, per capita GDP, energy intensity, and emission factor (O'Mahony, 2013). Previous studies have developed the Kaya identity of each sector, such as industry (Zhang and

Table 1
Driving factors of Kaya identity in residential building sector.

Resources	Period	Driving factors
Li et al. (2020)	2000–2017	Emission factor, energy consumption per unit of GDP, per capita GDP, population
Wang and Feng (2021)	2005–2017	Emission factor, energy structure, energy intensity, per capita income, population
You et al. (2021)	2000–2017	Emission factor, energy consumption unit area, per capita floor area, population
Huo et al. (2021)	2000–2015	Emission factor, energy intensity, per capita income, population
Liang et al. (2019)	2000–2016	Emission factor, energy consumption unit area, per capita income, per capita floor area, population, housing purchasing power, housing price-to-income ratio

Dong, 2022) and regions (O'Mahony, 2013). Notably, associated with the characteristics of building energy consumption, some scholars have developed the Kaya identity of carbon emission on residential building sector (Liang et al., 2019; Wang and Feng, 2021). Based on above studies (See Table 1), this study selected four driving factors (emission factor, energy consumption unit area, per capita floor area, population) and establish the Kaya identity of *C* and *CI* in URB. In addition, this study doesn't integrate economic parameter into kaya identity since the residents' incomes are considered as a basis for grouping to calculate the inter-group imbalance of different economic groups.

The formulas are as follows:

$$C = \frac{C}{E} \times \frac{E}{A} \times \frac{A}{P} \times P = EF \times EI \times AS \times P \tag{1}$$

$$CI = \frac{C}{A} = \frac{C}{E} \times \frac{E}{A} = EF \times EI \tag{2}$$

where *E, P,* and *A* indicate energy consumption, urban population, and floor area of urban residential building, respectively, and *EF, EI,* and *AS* indicate the emission factor, energy consumption unit area, and per capita floor area of URB, respectively. Additionally, this study divides the overall carbon emission ($CI_{overall}$) of URB into two parts, carbon emissions excluding central heating ($CI_{no\text{-}heating}$) and carbon emissions from central heating ($CI_{heating}$). Because climatic condition can lead an underestimate or overestimate on the real central heating techniques conditions, which doesn't have the interference of climate condition and reflects the real central heating techniques (e.g building envelope, heating-produce-related techniques). Refer the method of You et al. (2021), we selected the heating period days (*D*) to amend $CI_{heating}$ to conduct a fairly assess. *D* considers the combined action of regional temperature and actual heating period days. For example, Shenyang and Taiyuan have the same actual heating period days (150 days); however, *D* of Shenyang (152 days) is longer than that of Taiyuan (135 days) (MOHURD, 1995). *D* of each province is weighted mean of *D* in prefecture-level cities weighted by the population. The Kaya identity of amended carbon emission unit area ($CI_{adj\text{-}heating}$) is as follows:

$$C_{adj_{heating}} = \frac{C_{heating}}{D} = \frac{C_{heating}/D}{E_{heating}} \times \frac{E_{heating}}{A} \times \frac{A}{P} \times P = EF_{heating} \times EI_{adj_{heating}} \times AS \times P \tag{3}$$

$$CI_{adj_{heating}} = \frac{C_{adj_{heating}}}{A} = \frac{C_{adj_{heating}}}{E_{adj_{heating}}} \times \frac{E_{adj_{heating}}}{A} \tag{4}$$

where $EF_{heating}$, $EI_{heating}$ represents the energy-related emission factor and amended energy consumption unit area, respectively.

3.4. Zenga index in the imbalance of C and CI on URB

Zenga index uses the relative gap between average upper carbon emissions and average lower carbon emissions to estimate the imbalance in carbon emissions (Pasquazzi and Zenga, 2018; Shao et al., 2020). The Zenga index of $C_{overall}$, $C_{heating}$, $C_{no\_heating}$, and $C_{adj\_heating}$ were calculated using the same method. To save space, *C* and *CI* were used to explain the method. To measure the imbalance of *C*, we first ranked Chinese provinces in ascending order of *C* and used province *t* ($t = 1, 2, \ldots, 30$) to represent the province with the t^h lowest *C*. Mathematically, the Zenga index is based on the weighted ratio of the upper and lower averages (Zenga and Radaelli, 2012).

$$M_t^-(C) = \frac{\sum_{i=1}^t C_i}{t} = \frac{\sum_{i=1}^t C_i}{\sum_{i=1}^t E_i} \times \frac{\sum_{i=1}^t E_i}{\sum_{i=1}^t A_i} \times \frac{\sum_{i=1}^t A_i}{\sum_{i=1}^t P_i} \times \frac{\sum_{i=1}^t P_i}{t} = M_t^-(EF)M_t^-(EI)M_t^-(AS)M_t^-(P) \tag{5}$$

$$M_t^+(C) = \begin{cases} \dfrac{\sum_{i=t+1}^{30} C_i}{30-t} = \dfrac{\sum_{i=t+1}^{30} C_i}{\sum_{i=t+1}^{30} E_i} \times \dfrac{\sum_{i=t+1}^{30} E_i}{\sum_{i=t+1}^{30} A_i} \times \dfrac{\sum_{i=t+1}^{30} A_i}{\sum_{i=t+1}^{30} P_i} \times \dfrac{\sum_{i=t+1}^{30} P_i}{30-t} \\ \quad = M_t^+(EF)M_t^+(EI)M_t^+(AS)M_t^+(P), & t < 30; \\ C_t = M_t^+(EF)M_t^+(EI)M_t^+(AS)M_t^+(P), & t = 30 \end{cases} \tag{6}$$

where $M_t^+(C), M_t^+(EF), M_t^+(EI), M_t^+(AS)$, and $M_t^+(P)$ are the means of C, EF, EI, AS, and P in provinces with a higher C than C_t, respectively, and $M_t^-(EF), M_t^-(EI), M_t^-(AS)$, and $M_t^-(P)$ are means of EF, EI, AS, and P in provinces with a lower C than C_t, respectively.

According to Eq. (7), the contribution of province t to the imbalance of C can be calculated. Meanwhile, we used the method of Wang et al. (2020) to decompose the contribution of province t into the contributions of five driving factors: $Z_t^{EF}(C)$, $Z_t^{EI}(C)$, $Z_t^{EI}(C)$, $Z_t^{EI}(C)$, and $Z_t^{int}(C)$.

$$Z_t(C) = \frac{M_t^+(C) - M_t^-(C)}{M_t^+(C)} = \frac{M_t^+(EF)M_t^+(EI)M_t^+(AS)M_t^+(P) - M_t^-(EF)M_t^-(EI)M_t^-(AS)M_t^-(P)}{M_t^+(C)} = Z_t^{EF}(C) + Z_t^{EI}(C) + Z_t^{EI}(C) + Z_t^{EI}(C) - Z_t^{int}(C) \tag{7}$$

The calculations of $Z_t^{EF}(C)$, $Z_t^{EI}(C)$, $Z_t^{EI}(C)$, and $Z_t^{EI}(C)$ are similar. $Z_t^{EF}(C)$ was used as an example.

$$Z_t^{EF}(C) = \frac{\left[M_t^+(EF) - M_t^-(EF)\right] \times K_p(EF)}{M_t^+(\mathrm{C})} \tag{8}$$

$$K_p(EF) = \left(\frac{M_t^+(EI)M_t^+(AS)M_t^+(P)}{2} + \frac{M_t^-(EI)M_t^-(AS)M_t^+(P)}{3} + \frac{M_t^-(EI)M_t^+(AS)M_t^-(P)}{3} + \frac{M_t^+(EI)M_t^-(AS)M_t^-(P)}{3} - \frac{M_t^-(EI)M_t^+(AS)M_t^+(P)}{6} - \frac{M_t^+(EI)M_t^-(AS)M_t^+(P)}{6} - \frac{M_t^+(EI)M_t^+(AS)M_t^-(P)}{6}\right) \tag{9}$$

The contribution of the interaction term ($Z_t^{int}(C)$) was calculated using the following formula:

$$Z_t^{int}(C) = \frac{\left[M_t^+(EF) - M_t^-(EF)\right]\left[M_t^+(EI) - M_t^-(EI)\right]\left[M_t^+(AS) - M_t^-(AS)\right]\left[M_t^+(P) - M_t^-(P)\right]}{M_t^+(C)} \tag{10}$$

The overall imbalance of C in URB was calculated using Eq. (11). The calculations of the contribution of EF, EI, AS, and P and the interaction term were similar.

$$Z(C) = \frac{\sum Z_t(C)}{30} \tag{11}$$

Similarly, according to a previous method (Greselin et al., 2013) and Eq. (2), we measured the imbalance of CI and decomposed it into three driving factors, $Z_t^{EF}(CI)$, $Z_t^{EI}(CI)$, and $Z_t^{int}(CI)$. The formulas are as follows:

$$M_t^-(CI) = \frac{\sum_{i=1}^{t} C_i}{\sum_{i=1}^{t} A_i} = \frac{\sum_{i=1}^{t} C_i}{\sum_{i=1}^{t} E_i} \times \frac{\sum_{i=1}^{t} E_i}{\sum_{i=1}^{t} A_i} = M_t^-(EF)M_t^-(EI) \tag{12}$$

$$M_t^+(CI) = \begin{cases} \dfrac{\sum_{i=t+1}^{30} C_i}{\sum_{i=t+1}^{30} A_i} = \dfrac{\sum_{i=t+1}^{30} C_i}{\sum_{i=t+1}^{30} E_i} \times \dfrac{\sum_{i=t+1}^{30} E_i}{\sum_{i=t+1}^{30} A_i} = M_t^+(EF)M_t^+(EI), & \mathrm{t} < 30; \\ C_t = \dfrac{C_t}{E_t} \times \dfrac{E_t}{A_t} = M_t^+(EF)M_t^+(EI), & \mathrm{t} = 30 \end{cases} \tag{13}$$

where $M_t^+(CI), M_t^+(EF)$, and $M_t^+(EI)$ are the means of CI, EF, and EI in provinces with a higher CI than CI_t, respectively, and $M_t^-(CI)$, $M_t^-(EF)$, and $M_t^-(EI)$ are the means of CI, EF, and EI in provinces with lower CI than CI_t, respectively.

The contribution of province t to the imbalance of CI can be calculated, and the contribution of province t can be decomposed into three multiplied driving factors, $Z_t^{EF}(CI)$, $Z_t^{EI}(CI)$, and $Z_t^{int}(CI)$.

$$Z_t(CI) = \frac{M_t^+(CI) - M_t^-(CI)}{M_t^+(CI)} = \frac{M_t^+(EF)M_t^+(EI) - M_t^-(EF)M_t^-(EI)}{M_t^+(CI)} = \frac{\left[M_t^+(EF) - M_t^-(EF)\right] \times M_t^-(EI)}{M_t^+(CI)} + \frac{\left[M_t^+(EI) - M_t^-(EI)\right]M_t^-(EF)}{M_t^+(CI)} + \frac{\left[M_t^+(EF) - M_t^-(EF)\right]\left[M_t^+(EI) - M_t^-(EI)\right]}{M_t^+(CI)} = Z_t^{EF}(CI) + Z_t^{EI}(CI) + Z_t^{int}(CI) \tag{14}$$

3.5. Measuring the inter-group and intra-group imbalance of $CI_{no\_heating}$

There are the significant influence of climatic and economic condition on provincial $CI_{no\_heating}$ of URB (Wang et al., 2021). We think the provinces group with same climatic or economic condition may achieve emission mitigation more easily by a mutual technology spillover or reference. In order to explore this possible, this study further explored the imbalance of different types of regional groups. We first ranked the provinces in ascending order of $CI_{no\_heating}$, and divided the 30 provinces into three climate zone groups and three economy groups, respectively. The Zenga index can be decomposed into intra-group ($Z^a(CI)$) and inter-group imbalance ($Z^b(CI)$), and it does not have a residual term (Shao et al., 2020; Wang et al., 2020). The formulas are as follows:

$$Z(CI) = Z^a(CI) + Z^b(CI) \tag{15}$$

$$Z^a(CI) = \sum_{g=1}^{3} \left\{ \sum_{t=1}^{30} \left[\frac{Z_{gt}^+(CI) - Z_{gt}^-(CI)}{Z_t^+(CI)} \right] b(g|t) u(g|t) \frac{A_t}{A_{total}} \right\} \tag{16}$$

$$Z^b(CI) = \sum_{g=1}^{3} \sum_{h:h \neq g} \left\{ \sum_{t=1}^{30} \left[\frac{Z_{ht}^+(CI) - Z_{gt}^-(CI)}{Z_t^+(CI)} \right] b(g|t) u(h|t) \frac{A_t}{A_{total}} \right\} \tag{17}$$

where A_t represents the building floor area of province t, A_{total} represents the floor area of national urban residential building, and $Z_{gt}^+(CI)$ and $Z_{gt}^-(CI)$ represent the mean of $CI_{no\_heating}$ of provinces of group g with higher and lower $CI_{no\_heating}$ than province t. $Z_{ht}^+(CI)$ represents the mean of $CI_{no\_heating}$ of provinces of group h than province t. $b(g|t)$, $u(g|t)$, and $u(h|t)$ were calculated using the following formulas:

$$b(g|t) = \frac{A_{gt}^-}{A_t^-} \tag{18}$$

$$u(g|t) = \frac{A_{gt}^+}{A_t^+} \tag{19}$$

where A_{gt}^- and A_{gt}^+ represent the sum of A of provinces with lower and higher $CI_{no\_heating}$ than province t, respectively, and A_t^- and A_t^+ represent the sum of A of provinces with lower or equal and higher $CI_{no\_heating}$ than province t, respectively. Additionally, according to Eqs. (12), (13), (14), the intra-group and inter-group imbalances of $CI_{no\_heating}$ can be divided into the contributions of three driving factors.

Polarization reflects the relationship between groups and groups' cohesion (Duclos et al., 2004). In other words, as $CI_{no\_heating}$ within the group diminishes, that is, as the groups become more homogeneous internally, differences across groups are, relatively speaking, magnified, and the polarization is higher. The ZK index usually explains the polarization effect (Wang and Tsui, 2000) since it is calculated based on the intra-group and inter-group imbalances as follows:

$$ZK = \frac{Z^a(CI)}{Z^a(CI)} \tag{20}$$

4. Results and discussion

4.1. The carbon imbalance of URB at the national level

4.1.1. The imbalance in carbon emissions of URB

The total imbalance of $C_{overall}$ in URB is shown in Fig. 3. Overall, there were significant imbalances in the $C_{overall}$ of URB between the 30 provinces, all of which were higher than 0.75 in overall study period. $C_{overall}$ from the urban residential building sector in each province were still unevenly distributed. Although, the imbalance in the $C_{overall}$ of URB was continuously decreased, the decreased trend was inconspicuous. Meanwhile, the $C_{overall}$ of URB represented an increasing trend. It increased from 0.57 $BtCO_2$ in 2005 to 0.86 $BtCO_2$ in 2019, and it still not reached the peak value, which is consistent with the results of Ma et al. (2020). On contrary, CI of Chinese URB achieved a peak value in 2011, reaching 36.17 $kgCO_2/m^2$.

Fig. 3a also shows that population and energy consumption unit area were the major contributors to the imbalance of $C_{overall}$, and they accounted for >90% of the total imbalance, emphasizing that provinces with higher carbon emissions in URB are characterized by more population and energy consumption unit area. On contrary, although, the contribution of emission factor was much lesser, accounting for <2%, it had changed impacts on the imbalance of Chinese URB in different periods. For example, after 2014, the imbalance of emission factor exchange from mitigating to exacerbating, and resulted in 0.71% of the imbalance of $C_{overall}$ in Chinese URB.

Heating carbon emissions usually account for a larger proportion of $C_{overall}$ and $E_{overall}$ in URB (Lin and Lin, 2017). The data indicated that the urban residential building sector produced 0.41 $BtCO_2$ from heating in 2019, accounting for 47.57% of carbon emissions of the URB sector (CABEE, 2021; Du et al., 2018). Therefore, this study suggests that central heating may be an important factor leading to an imbalance in carbon emissions in URB. Fig. 3b shows the imbalances of URB carbon emissions without central heating. Compared to Fig. 1a, the Zenga Index was significantly smaller (<0.7 in the overall study period, consistent with the above assumption).

Fig. 3c and d show the imbalance of $C_{heating}$ and $C_{adj\_heating}$, respectively. The Zenga Index of $C_{heating}$ showed a slightly decreasing trend from 0.72 in 2005 to 0.66 in 2019. Emission factor and energy consumption unit area had the most positive and negative impacts on the imbalance of $C_{heating}$, respectively, indicating that provinces with higher $C_{heating}$ usually have a lower energy consumption unit area and higher emission factor. Therefore, provinces with higher $C_{heating}$ and those with lower $C_{heating}$ can achieve emission reductions in reducing emission factor and energy consumption unit area, respectively, through mutual technology spillover and reference

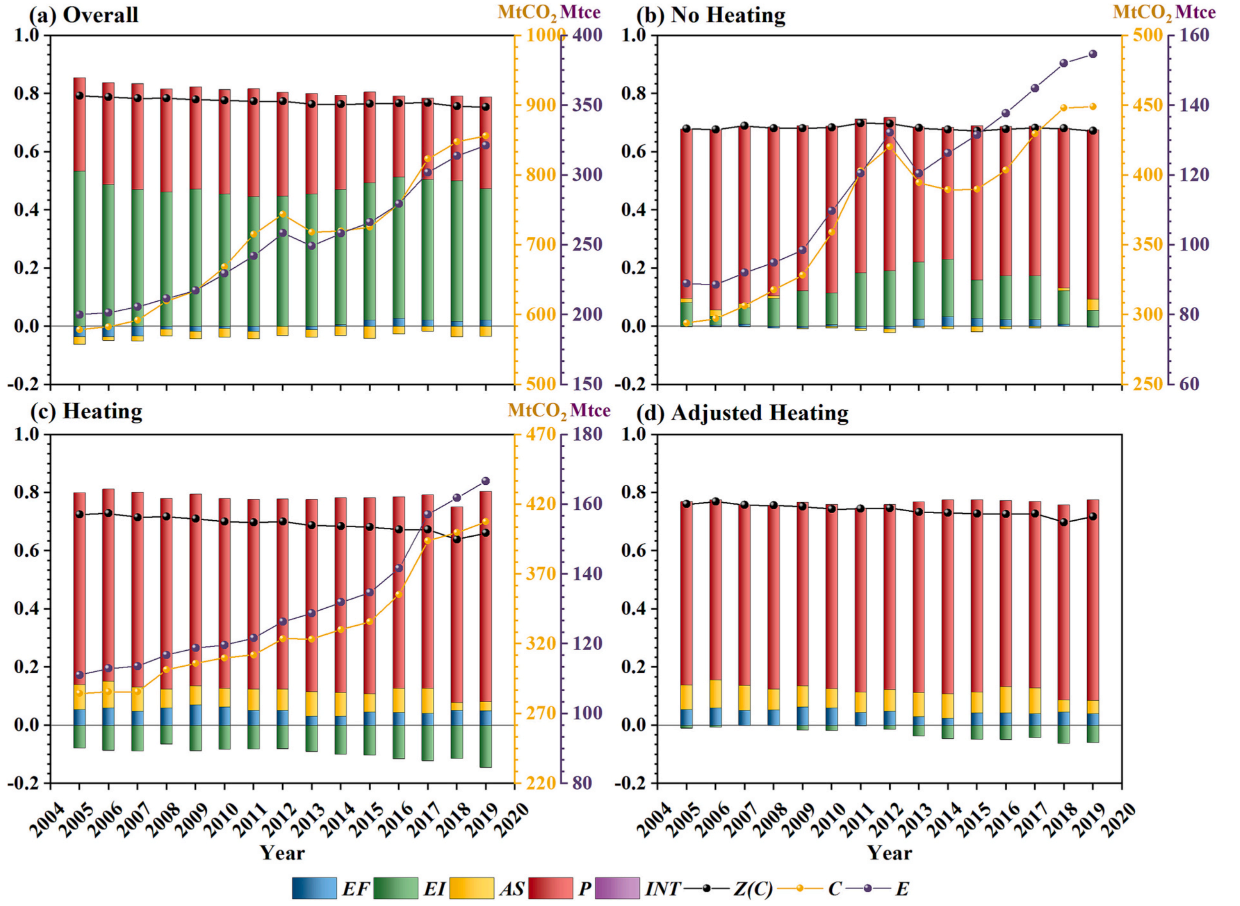

Fig. 3. The imbalance of carbon emissions in URB.
(Note: Fig. 3a, b, c, and d represent imbalances in $C_{overall}$, $C_{no\_heating}$, $C_{heating}$, and $C_{adj\_heating}$, respectively. *EF, EI, AS, P* and *INT* represent emission factor, energy consumption unit area, per capita floor area, population and interaction term, respectively.)

between them. Additionally, we found that the Zenga index of $C_{adj\text{-}heating}$ was obviously larger than that of $C_{heating}$ during the study period, indicating that climatic differences magnified the imbalance of $C_{heating}$. This was because the climate parameter reduced the imbalance of energy consumption unit area, the absolute contribution of energy consumption unit area reduced by >6% of the overall imbalance after adjusting in overall study periods.

4.1.2. The imbalance in CI of URB

As shown in Fig. 4a, before 2011, the decreased speed of $CI_{heating}$ (1.04 kg/m^2/year) exceeded the increased speed $CI_{no\text{-}heating}$ (0.42 kg/m^2/year), the CI_{overall} exhibited continuous decreased trend is study period.

The $CI_{overall}$ represented an obvious imbalance, and the Zenga index was >0.7 in the overall study period. The contribution of emission factor exchanged from negative to positive after 2013. That results may be related to the more clean energy structure in southern provinces. Specifically, coal's share of the total final energy consumption in southern and north provinces arrived at 6.48% and 21.56% in 2019. At the same time, at the major energy type, electricity generation owned a lower emission factor in south provinces (3.01 kgCO_2/kgce) compared with north provinces (5.63kgCO_2/kgce)(CABEE, 2021). Additionally, the imbalance of energy consumption unit area was the major contributor to the imbalance of $CI_{overall}$, accounting for >80% of the total study period.

Similar to Section 4.1, this study also showed an imbalance of $CI_{no\_heating}$, $CI_{heating}$, and $CI_{adj\_heating}$ in Fig. 4b, c, and d, respectively. Compared with Fig. 4a, we found that the imbalance of $CI_{no\_heating}$ was significantly less than the imbalance of $CI_{overall}$, which indicates that central heating was one of the major reasons leading to the high imbalance of $CI_{overall}$.

As for $CI_{heating}$ and $CI_{adj\_heating}$, the Fig. 4c and d represent that $CI_{heating}$ (32.61 kgCO_2/m^2 in 2019) was obviously higher than $CI_{overall}$ (25.16 kgCO_2/m^2 in 2019), although $CI_{heating}$ and $EI_{heating}$ continuously decreased in the overall study period. By comparing the Zenga index of $CI_{heating}$ and $CI_{no\_heating}$, we found that climatic differences significantly magnified the imbalance of $CI_{heating}$. Therefore, to accurately assess the real provincial heating technology and make rational emission mitigation share targets and policies, policy-making departments should fully consider the magnifying effect on $CI_{heating}$ nergy consumption unit area.

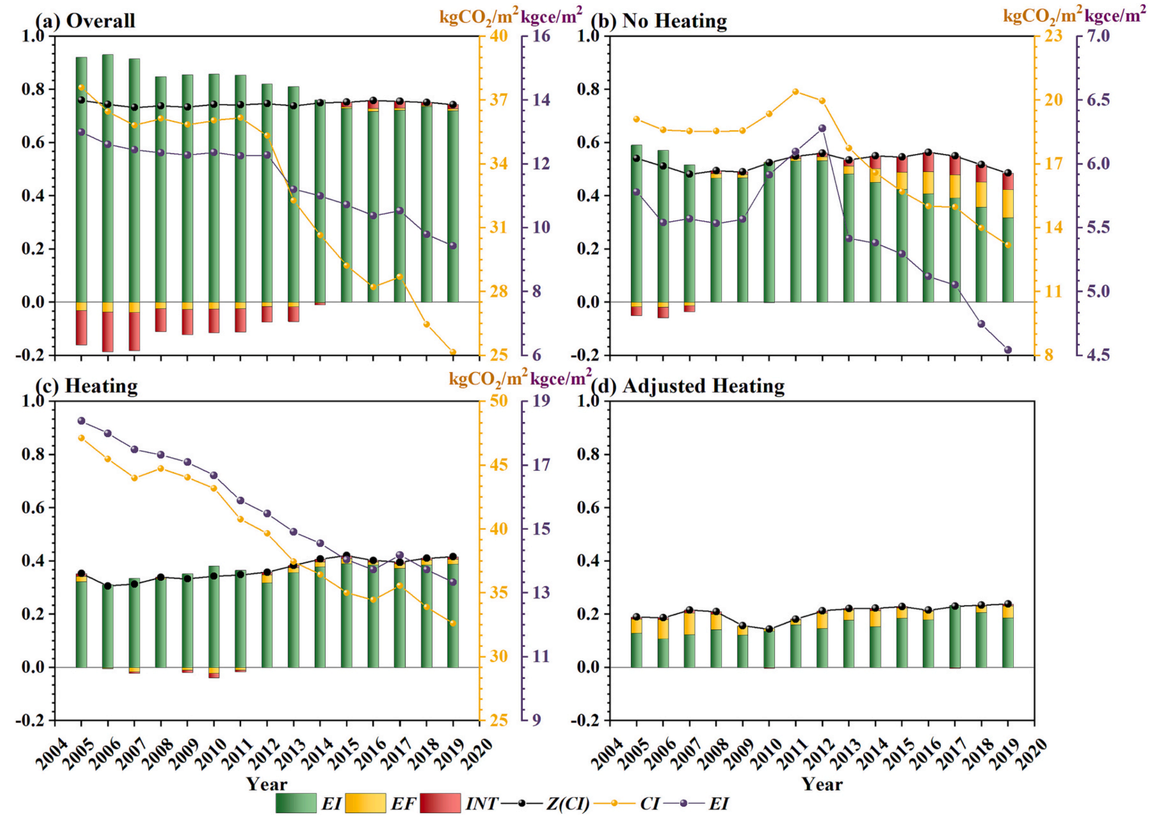

Fig. 4. The Imbalance in *CI* of URB.
(Note: Fig. 4a, b, c, and d represent imbalances in $CI_{overall}$, $CI_{no\_heating}$, $CI_{heating}$, and $CI_{adj\_heating}$, respectively. *EF, EI,* and *INT* represent emission factor, energy consumption unit area, and interaction term, respectively.)

4.2. The carbon imbalance of URB at the group level

4.2.1. The spatial distribution of $CI_{no\_heating}$

Fig. 5a represents the spatial distribution of carbon emission unit area excluding heating part ($CI_{no\_heating}$) in 2019, and it indicates that there is a significant difference in $CI_{no\_heating}$ at the provincial level. In specifically, the largest $CI_{no\_heating}$ (Inner Mongolia, 48.80kgCO_2/m^2) was nearly 8 times of the smallest (Yunnan, 6.49kgCO_2/m^2).

Furthermore, $CI_{no\_heating}$ represents obvious difference in climate and economy group. First, because of the difference in climate condition, Chinese provinces are usually divided into three geographical climate groups, north provinces (NPs), transitional provinces (TPs) and south provinces (SPs) (You et al., 2023a). As shown in Fig. 5a, $CI_{no\_heating}$ (17.49 kgCO_2/m^2) of north provinces was higher than that of south provinces (10.16 kgCO_2/m^2) and transitional provinces (11.04 kgCO_2/m^2) since the higher energy consumption unit area and emission factor of NPs. In specifically, because of the heating utilization, that energy consumption unit area of SPs (3.89 kgce/m^2) and TPs (4.13 kgce/m^2) were obviously lower than that of NPs (5.42 kgce/m^2). Meanwhile, Fig. 5b indicates emission factor of SPs (2.61 kgce/m^2) and TPs (2.68 kgce/m^2) were lower than that of NPs (3.22 kgce/m^2), that may be caused by a high proportion of coal in the energy structure. In 2019, coal accounted for 21.84% of the total energy consumption of URB of NPs. However, in SPs and TPs, coal has been replaced by natural gas, which has a lower carbon emission unit area, and only accounted for 3.29% and 4.99% of the total energy consumption of the URB of SPs and TPs, respectively (CABEE, 2021). As a major energy in the energy consumption of URB, electricity usually owns a higher emission factor in NPs due to a high proportion of thermal plants in the energy structure of generation. The electricity emission factor of NPs (5.63 kgCO_2/kgce) was >1.5 times that of TPs (3.60 kgCO_2/kgce) and SPs (3.01 kgCO_2/kgce). Considering the high cost of natural gas and high emission factor of electricity, emission reduction by optimizing the building energy structure is not easy to achieve and it is more of a long-term objective (Zenga and Radaelli, 2012).

Secondly, Fig. 5d shows that the differences of $CI_{no\_heating}$ on URB may be a result of differences in economic condition to a large extent. For example, although Beijing and Henan are located in the same climate zone. As an economic developed province, Beijing owned $CI_{no\_heating}$ of 26.23 kgce/m^2, far exceeding the Henan (9.64 kgce/m^2). That is caused by the high end user service demand of high-income families (Li et al., 2021). Similar condition can be seen in global wide, the China's per capital building energy intensity only was 21% of the US, 72% of Japan and 23% of the UK (IEA, 2021). In summary, considering the differences in economy and climate, adopting convergence emission reduction policies on all provinces to reduce $CI_{no\_heating}$ rather than formulating pointed

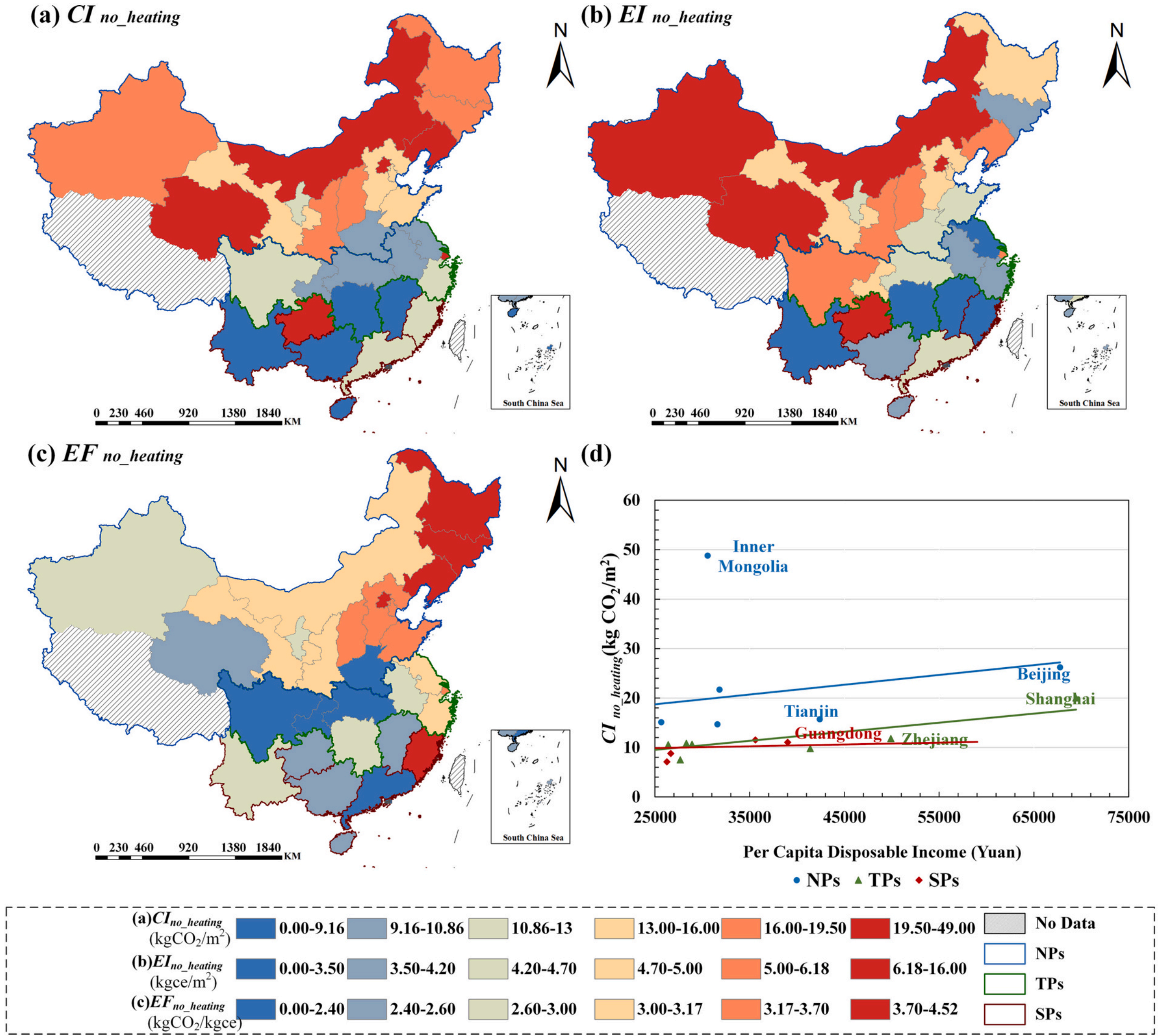

Fig. 5. The provincial URB condition of $CI_{no\_heating}$ in 2019.
(Note: Fig. 5a, b, and c represent the spatial distribution in $CI_{no\_heating}$, $EI_{no\_heating}$, and $EF_{no\_heating}$, respectively. *CI, EF,* and *EI* represent carbon emission unit area, emission factor and energy consumption unit area, respectively. NPs, TPs and SPs represents north, transitional and south provinces, respectively.)

emission reduction targets based on the regional imbalance within different provinces groups is bound to have a negative impact on emission reduction and harm social equity and residents' welfare. According to IPCC, formulating emission reduction policies should follow the principle of "common but differentiated" (Harris, 1999). Particularly, provinces with the same economic and climate conditions can easily achieve decreases in $CI_{no\_heating}$ through intra-group technology spillover and local technology improvements. Therefore, further analysis of the causes of emission inequality at the group level using Eqs. (15)–(20) is helpful to put forward pertinent suggestions and set reasonable carbon emission reduction targets. In this study, based on the climate zone and per capita income, we divided 30 provinces into three climate zone groups (north, transitional, south provinces) and three economic groups (provinces with high residents' income (HPs), provinces with middle residents' income (MPs) and provinces with low residents' income (LPs)). The group divisions are listed in Table A1 (Appendix A).

4.2.2. The imbalance of $CI_{no\_heating}$ at climate zone group level

The Fig. 6 represents imbalance of $CI_{no\_heating}$ in the inter- and intra-climate zone groups. The results showed that inter-group imbalance was the major contributor to the overall imbalance of $CI_{no\_heating}$, accounting for >70%. Meanwhile, there was a severe polarization in $CI_{no\_heating}$ of URB, and the ZK index was more than three, indicating that the inter-group imbalance was more than three times the intra-group imbalance. Polarization was largely caused due to imbalances between NPs and other groups, accounting for >65% of the overall imbalance of $CI_{no\_heating}$. On the contrary, the imbalance between SPs and NPs was smaller, reaching only 9.30% in 2019.

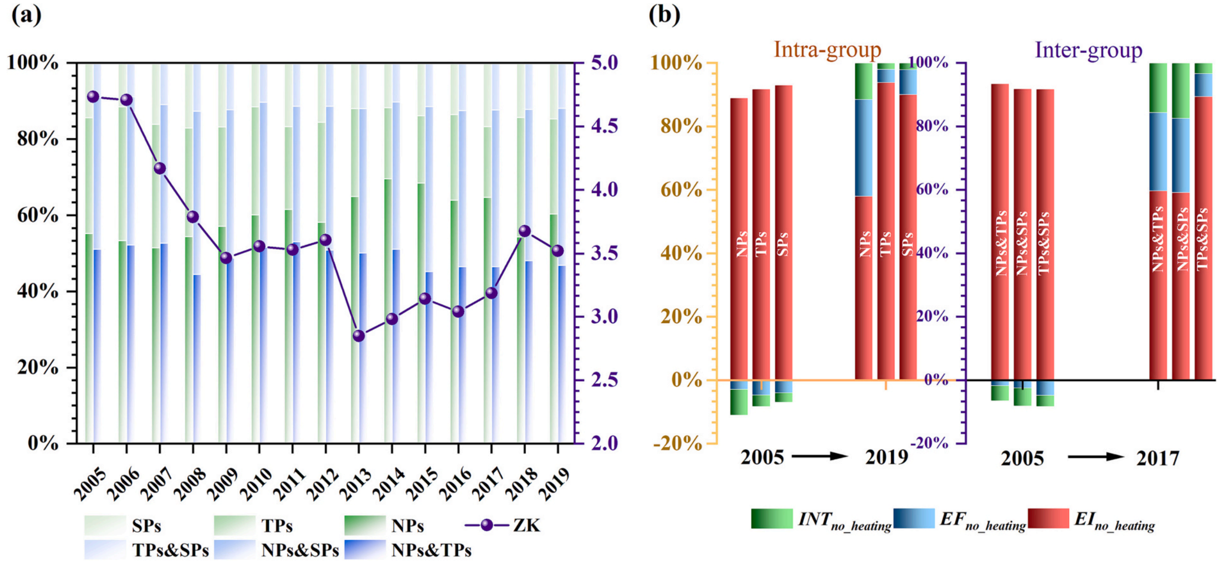

Fig. 6. Imbalance of $CI_{no\_heating}$ at the climate zone group level.
(Note: Fig. 6a represents the imbalance of inter and intra climate zone groups; Fig. 6b represent the contribution of each driving factors. The percentage of each sub-figure is the ratio of the contribution of different driving factors to the sum of the absolute values of all the driving factor contributions. NPs, TPs and SPs represents north, transitional, and south provinces, respectively. *INT*, *EF*, and *EI* represents interaction term, emission factor and energy consumption, respectively.)

The intra-group imbalance was smaller; however, it still amounted to approximately 22% of the overall imbalance of $CI_{no\_heating}$, and it represented an increasing trend from 17.44% in 2005 to 22.12% in 2019, which suggests that reducing the intra-climate zone group imbalance of $CI_{no\_heating}$ can significantly mitigate carbon emissions. The largest intra-group imbalance of $CI_{no\_heating}$ was NPs, with >10% of the overall imbalance of $CI_{no\_heating}$, indicating that NPs can easily achieve carbon emission reduction through intra-group technology spillover. The imbalance of energy consumption unit area was the major cause of intra-group imbalance in $CI_{no\_heating}$.

4.2.3. Imbalance of $CI_{no\_heating}$ at the economy group level

Fig. 7 represents the imbalance of $CI_{no\_heating}$ in the inter-and intra-economy groups. Compared to the impact of climate zone, the economy had a lesser impact on the imbalance of $CI_{no\_heating}$ because the ZK index of economy groups was <3.0 in the overall study period. The contribution of the imbalance of energy consumption unit area on the inter-group imbalance of $CI_{no\_heating}$ decreased in the past five years, suggesting that the provincial gap of energy consumption unit area converged. This may be attributed to two reasons, 1) the near saturation demand for household energy in developed provinces and 2) the rapidly increasing demand for household energy in less developed provinces. Taking Guizhou as an example, in 2019, the number of air conditioners per 100 households (37.23) doubled as compared to that in 2013(18.70) (NBS, 2020). This suggests that less-developed provinces should pursue a mix of policies to improve building energy efficiency to offset the negative impact of rising energy demand on China's emission targets (Wang and Feng, 2021).

For the intra-group imbalance, high-income provinces represented the largest contribution, accounting for >14%, and the imbalance in energy consumption unit area contributed the most to the overall imbalance (>80%) of High-income provinces $CI_{no\_heating}$. Therefore, high-income provinces should exploit the possibility of emission reduction by improving their building energy efficiency. Considering the higher income of residents of high-income provinces, the option is easier to achieve by adopting more efficient household appliances and promoting energy renovation of buildings (Lekavičius et al., 2020). In contrast, low-income provinces had the smallest impact on the imbalance of $CI_{no\_heating}$, and the contribution of the imbalance of low-income provinces' energy consumption unit area on the imbalance of low-income provinces' $CI_{no\_heating}$ decreased, indicating that the gap between energy consumption unit area of low-income provinces' gradually narrowed.

4.3. Policy implications

4.3.1. Impact of EI on the emission mitigation of URB

For both $CI_{no\_heating}$ and $CI_{heating}$, energy consumption unit area (*EI)* has always been the major contributor leading to imbalance, which indicates the importance of improving the energy efficiency of URB. The future change in *EI* is affected by two factors, the residents' demand for end-user services(e.g., heating, cooling, lighting, cooking, hot water, and other household appliances) and techniques for building energy efficiency (Zhou et al., 2018). The former is largely based on residents' income (Yang et al., 2017), and the residents of high-income provinces usually tend to have frequent household energy utilization behaviors (Li et al., 2021). Income can influence residents' behaviors (Jin et al., 2022) and caused household energy consumption imbalance. The results of this study

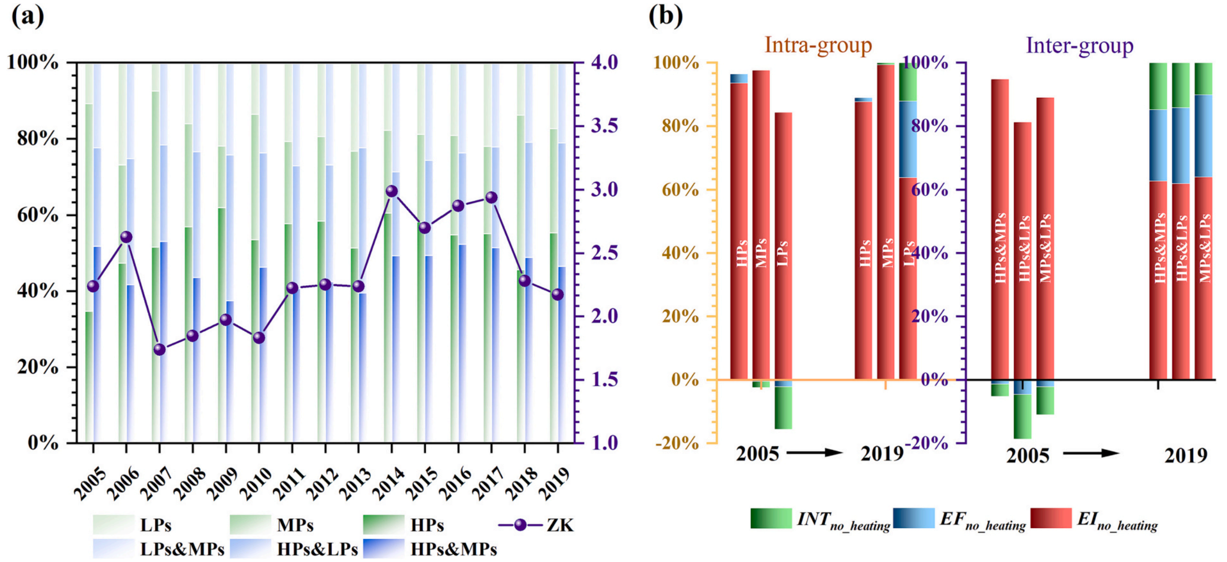

Fig. 7. Imbalance of $CI_{no\_heating}$ at the economy group level.
(Note: Fig. 7a represents the imbalance of inter and intra economic groups; Fig. 7b represent the contribution of each driving factors. The percentage of each sub-figures is the ratio of the contribution of different driving factors to the sum of the absolute value of the contribution of all driving factors. HPs, MPs and LPs represents high, mid, and low income provinces, respectively. *INT*, *EF*, and *EI* represents interaction term, emission factor and energy consumption unit area, respectively.)

showed that the gap in *EI* between the three economic groups gradually narrowed, indicating that mid-income provinces and low-income provinces will face a faster rigid growth in end-user service demand for a long time in the future. This is undoubtedly a significant challenge to the emission reduction of URB (Ma et al., 2020). To offset this energy demand growth and to further promote the reduction of *EI* and *CI,* the national and provincial governments should promote higher mandatory building energy efficiency design standards for new URB and energy renovation for existing URB to improve the performance of lighting systems, building thermal insulation, and heating and air conditioning systems (You et al., 2023a). Meanwhile, the government also promotes the utilization of highly efficient household appliances (LBNL, 2016). Additionally, occupant behavior is thought to be one of the major reasons for the difference in *EI* (Jiang, 2015; Li et al., 2021). Especially for high-income provinces whose energy demand is higher, the local government actively guides residents' awareness of green life by formulating relevant policies and completing market mechanisms, such as implementing charges by heating metering, reasonable electricity ladder prices (Sun, 2015), and green lifestyle propaganda (You et al., 2023a) to form a low-carbon and environmentally friendly sustainable development system for URB.

4.3.2. Impact of EF on the emission mitigation of URB

Although emission factor (*EF)* has a smaller impact on the imbalance between $CI_{no\_heating}$ and $CI_{heating}$, the impact represents a sharply increasing trend, indicating that optimizing the energy structure plays an increasingly important role in the achievement of carbon peak and carbon neutrality of URB (Li et al., 2021; Ma et al., 2020), especially for north provinces. First, the URB sector should actively promote the clean utilization of primary energy by implementing the coal-to-gas project (Tanaka et al., 2019) and adopting the techniques of renewable energy in buildings, such as building integrated photovoltaics and ground-source heat pumps (IEA, 2020a). For secondary energy, the secondary energy of Chinese URB mainly has two forms, central heating and electricity. For central heating, the national and provincial governments should eliminate the outdated and inefficient small- and medium-sized fired boilers as soon as possible and promote efficient large coal-fired boilers and cogeneration boilers to improve fuel conversion efficiency (Du et al., 2018). Meanwhile, associated with provincial resource endowment, fully tap the emission mitigation potential of renewable energy on central heating (IEA, 2020b). For example, Heilongjiang, Liaoning, Jilin, and other heavy industry provinces can increase industrial waste heat recovery, and Inner Mongolia can increase the application of wind energy in central heating. As the major energy forms of URB (CABEE, 2021), there was an obvious difference in the regional emission factor of electricity generation (Fig. 8). Particularly, the electricity emission factor of NPs was significantly higher than that of SPs and TPs, which was approximately 2.5 times of coal and four times of natural gas, respectively. Therefore, the electricity process of north provinces needs to be carefully arranged based on the appliance efficiency and cost. For example, the energy efficiency ratio (EER) of a heating pump was higher than three, and the EER of heating by directly firing coal was less than one, indicating that this "coal-to-electricity" process was environmental friendly. However, due to a similar EER of the electric water heater and coal-fired water heater, the "coal-to-electricity" process should be delayed. Additionally, for provinces with similar natural resource endowments, technology spillovers between provinces will easily achieve the optimization of energy structure (Wang et al., 2020).

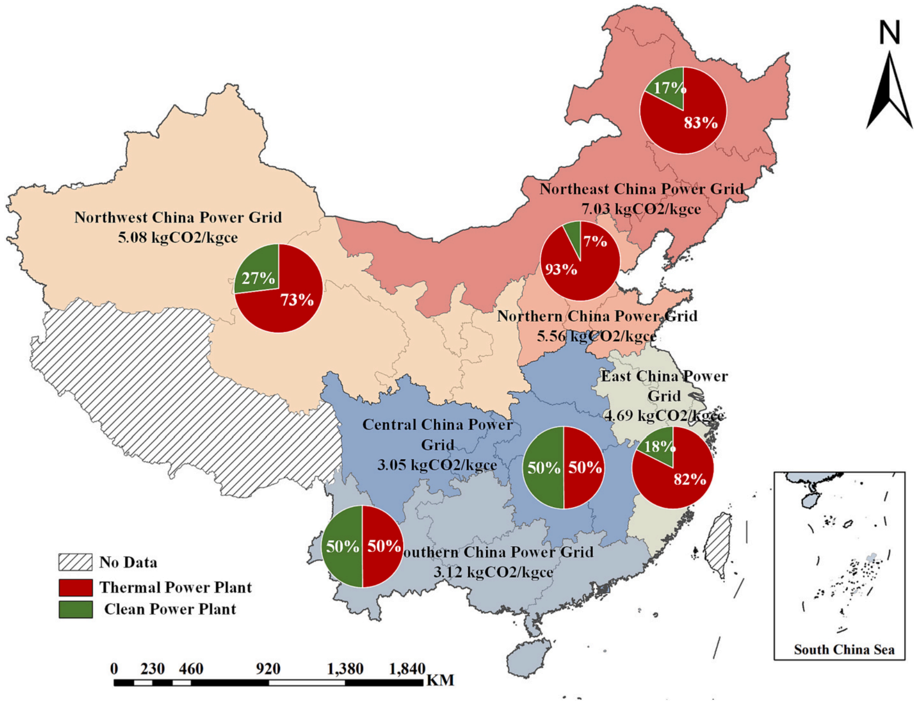

Fig. 8. The electricity generation condition.

5. Conclusion and future research orientation

5.1. Main conclusion

This study adopted an approach based on the Zenga index and an extended Kaya identity to analyze the imbalance of C and CI (overall emissions, emissions excluding central heating, emissions on central heating, and adjusted emission of central heating) on URB for 2005–2019, and it decomposed the Zenga index into several contributors' multiplication. Furthermore, based on the residents' income and climate zone, we decomposed the imbalance of $CI_{no\_heating}$ into intra- and inter-groups.

The main conclusions are as follows:

1) The overall C of URB increased from 0.57 $BtCO_2$ in 2005 to 0.86 $BtCO_2$ in 2019, and it has kept rising ever since. In contrast, $CI_{overall}$, $CI_{no\_heating}$, and $CI_{heating}$ achieved a peak in 2011 (36.17$kgCO_2/m^2$), 2011 (20.39 $kgCO_2/m^2$), and before 2005 (47.12 $kgCO_2/m^2$).
2) There was an obvious imbalance in C and CI of URB. The imbalance of population was the major contributor to the imbalance of $C_{overall}$, which accounted for >60% and showed an increasing trend. The imbalance of energy consumption unit area dominated the imbalance of $CI_{overall}$. Meanwhile, the central heating exacerbated the imbalance of $C_{overall}$ and $CI_{overall}$, and the climate parameter (heating period day, D) had a significant impact on the imbalance between $C_{heating}$ and $CI_{heating}$.
3) Climate and per capita residents' income were major reasons for the provincial gap in $CI_{no\_heating}$. North provinces had a higher $CI_{no\_heating}$ due to the high-carbon energy structure of URB. Meanwhile, the high demand for $EI_{no\_heating}$ caused by high per capita residents' income renders high-income provinces to have a higher $CI_{no\_heating}$.
4) There was an obvious polarization on $CI_{no\_heating}$. Specifically, the inter-group imbalance of $CI_{no\_heating}$ was approximately thrice that of the intra-group imbalance of $CI_{no\_heating}$ in 2019. Compared to the impact of the difference in climate, the difference in economy had a lesser impact on the imbalance of $CI_{no\_heating}$.

5.2. Future research orientation

Although some meaningful findings were obtained in this study, several gaps can be filled with future endeavors. Firstly, in the perspective of sector, the study focused only on the URB sector. Given the different energy consumption characteristics, the major contributors to the imbalance of CI in different building types, such as URB, rural residential buildings, and commercial buildings, may vary significantly. For example, economic development of the tertiary industry may have a larger impact on the CI of commercial buildings. In the perspective of space, there is only the national and provincial energy balance energy sheet in China. The data of URB at city level is lack. Future study will establish time serials of carbon emission in URB at Urban level and analyze their imbalance, which will benefit to formulate more specific URB decarbonization strategies and exploit the potential of technology spillovers between cities.

In the perspective of time series, because of the data limitation, this study only focused on the carbon emission imbalance before 2019. Future study can be extended to after 2019, and considers the impact of COVID-19 on the imbalance.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Kairui You: Conceptualization, Validation, Visualization, Formal analysis, Writing – original draft. **Liu Chen:** Validation, Writing – review & editing. **Ruopeng Huang:** Data curation, Validation, Writing – review & editing.

Declaration of Competing Interest

The author(s) declare no potential conflicts of interest for the research, authorship, and/or publication of this article.

Data availability

Data will be made available on request.

Appendix A. Appendix

Table A1
The groups division.

Climate Zone Group	Province	Economy Group			
		2005	2010	2015	2019
North Provinces (NPs, Central Heating Area)	Beijing	HP	HP	HP	HP
	Gansu	LP	LP	LP	LP
	Hebei	MP	MP	LP	LP
	Heilongjiang	LP	LP	LP	MP
	Henan	MP	MP	LP	LP
	Inner Mongolia	MP	HP	HP	HP
	Jilin	MP	LP	LP	MP
	Liaoning	MP	HP	HP	HP
	Ningxia	LP	LP	LP	LP
	Qinghai	LP	LP	LP	LP
	Shandong	HP	HP	HP	MP
	Shaanxi	LP	MP	MP	HP
	Shanxi	MP	MP	LP	LP
	Tianjin	HP	HP	HP	HP
	Xinjiang	LP	LP	MP	LP
Transition Province (TPs)	Anhui	LP	MP	MP	MP
	Chongqing	HP	MP	MP	MP
	Hubei	MP	MP	MP	MP
	Hunan	HP	MP	MP	MP
	Jiangsu	HP	HP	HP	HP
	Shanghai	HP	HP	HP	HP
	Sichuan	LP	LP	LP	MP
	Zhejiang	HP	HP	HP	HP
South Province (SPs)	Fujian	HP	HP	HP	HP
	Guangdong	HP	HP	HP	HP
	Guangxi	MP	MP	MP	LP
	Guizhou	LP	LP	LP	LP
	Hainan	LP	LP	MP	MP
	Jiangxi	MP	LP	MP	MP
	Yunnan	MP	MP	MP	LP

Note: HP, MP, and LP represent the provinces with high, middle, and low income, respectively. The climate zone group of each province did not change during the entire study period.

References

Ahn, Y., Uejio, C.K., 2022. Modeling air conditioning ownership and availability. Urban Clim. 46, 101322 https://doi.org/10.1016/j.uclim.2022.101322.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), 2009. 2009 ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigeration and Air-Conditioning Engineers.

CABEE (China Academy of Building Research), 2021. China Building Energy and Emission Database.

Cheng, S., et al., 2021. Multi-sectoral determinants of carbon emission inequality in Chinese clustering cities. Energy 214, 118944. https://doi.org/10.1016/j.energy.2020.118944.

Dogah, K.E., Awaworyi Churchill, S., 2022. Carbon emissions convergence and determinant analysis: evidence from ASEAN countries. J. Environ. Manag. 323, 116299 https://doi.org/10.1016/j.jenvman.2022.116299.

Du, M., et al., 2018. Quantification and scenario analysis of CO2 emissions from the central heating supply system in China from 2006 to 2025. Appl. Energy 225, 869–875. https://doi.org/10.1016/j.apenergy.2018.05.064.

Duclos, J.Y., et al., 2004. Polarization: concepts, measurement, estimation. Econometrica 72 (6), 1737–1772. https://doi.org/10.1111/j.1468-0262.2004.00552.x.

EIA (Energy Information Agency in the USA), 2020. Residential Energy Consumption Survey. https://www.eia.gov/consumption/residential/about.php.

Eurostat, 2022. Complete Energy Balances. https://ec.europa.eu/eurostat/web/main/data.

Greselin, F., et al., 2013. Contrasting the Gini and Zenga indices of economic inequality. J. Appl. Stat. 40 (2), 282–297. https://doi.org/10.1080/02664763.2012.740627.

Han, L., et al., 2018. Energy efficiency convergence across countries in the context of China's belt and road initiative. Appl. Energy 213, 112–122. https://doi.org/10.1016/j.apenergy.2018.01.030.

Harris, P.G., 1999. Common but differentiated responsibility: the Kyoto protocol and United States policy. NYU Envtl. LJ 7, 27. https://heinonline.org/HOL/LandingPage?handle=hein.journals/nyuev7&div=8&id=&page=.

Huo, T., et al., 2018. China's energy consumption in the building sector: a statistical yearbook-energy balance sheet based splitting method. J. Clean. Prod. 185, 665–679. https://doi.org/10.1016/j.jclepro.2018.02.283.

Huo, T., et al., 2021. Decoupling and decomposition analysis of residential building carbon emissions from residential income: evidence from the provincial level in China. Environ. Impact Assess. Rev. 86, 106487 https://doi.org/10.1016/j.eiar.2020.106487.

IEA (International Energy Agency), 2020a. GlobalABC Roadmap for Buildings and Construction 2020–2050. https://www.iea.org/reports/globalabc-roadmap-for-buildings-and-construction-2020-2050.

IEA (International Energy Agency), 2020b. Renewable Energy Policies in a Time of Transition: Heating and Cooling. https://www.iea.org/reports/renewable-energy-policies-in-a-time-of-transition-heating-and-cooling.

IEA (International Energy Agency), 2021. World Energy Statistics in 2021. https://www.iea.org/data-and-statistics/data-product/world-energy-balances.

Ivanovski, K., Awaworyi Churchill, S., 2020. Convergence and determinants of greenhouse gas emissions in Australia: a regional analysis. Energy Econ. 92, 104971 https://doi.org/10.1016/j.eneco.2020.104971.

Jiang, Y., 2015. Roadmap of Building Energy Efficiency in China. China Architecture and Building Press.

Jin, C., et al., 2022. What attracts young talents? Understanding the migration intention of university students to first-tier cities in China. Cities 128, 103802. https://doi.org/10.1016/j.cities.2022.103802.

Kaya, Y., 1989. Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. In: Intergovernmental Panel on Climate Change/Response Strategies Working Group. https://archive.ipcc.ch/publications_and_data/publications_ipcc_first_assessment_1990_wg3.shtml.

LBNL (Lawrence Berkeley National Laboratory), 2016. Reinventing Fire: China—the Role of Energy Efficiency in China's Roadmap to 2050. https://china.lbl.gov/publications/reinventing-fire-china-role-energy.

Lekavičius, V., et al., 2020. Distributional impacts of investment subsidies for residential energy technologies. Renew. Sust. Energ. Rev. 130, 109961 https://doi.org/10.1016/j.rser.2020.109961.

Li, H., et al., 2020. Spatial-temporal characteristics and drivers of the regional residential CO2 emissions in China during 2000–2017. J. Clean. Prod. 276, 124116 https://doi.org/10.1016/j.jclepro.2020.124116.

Li, H., et al., 2021. The regional disparity of per-capita CO2 emissions in China's building sector: an analysis of macroeconomic drivers and policy implications. Energy Build. 244, 111011 https://doi.org/10.1016/j.enbuild.2021.111011.

Li, R., et al., 2023a. Echelon peaking path of China's provincial building carbon emissions: considering peak and time constraints. Energy 127003. https://doi.org/10.1016/j.energy.2023.127003.

Li, R., et al., 2023b. Interprovincial differences in the historical peak situation of building carbon emissions in China: causes and enlightenments. J. Environ. Manag. 332, 117347 https://doi.org/10.1016/j.jenvman.2023.117347.

Liang, Y., et al., 2019. Carbon dioxide intensity and income level in the Chinese megacities' residential building sector: decomposition and decoupling analyses. Sci. Total Environ. 677, 315–327. https://doi.org/10.1016/j.scitotenv.2019.04.289.

Lin, B., Lin, J., 2017. Evaluating energy conservation in China's heating industry. J. Clean. Prod. 142, 501–512. https://doi.org/10.1016/j.jclepro.2016.06.195.

Liu, J., et al., 2021. Regional differences and driving factors analysis of carbon emission intensity from transport sector in China. Energy 224, 120178. https://doi.org/10.1016/j.energy.2021.120178.

Ma, M., et al., 2020. Low carbon roadmap of residential building sector in China: historical mitigation and prospective peak. Appl. Energy 273, 115247. https://doi.org/10.1016/j.apenergy.2020.115247.

Ma, M.-D., et al., 2022. What decarbonized the residential building operation worldwide since the 2000s. Pet. Sci. 19 (6), 3194–3208. https://doi.org/10.1016/j.petsci.2022.10.016.

MOHURD (Ministry of Housing and Urban-Rural Development in China), 1995. Design Standard for Energy Conservation of Civil Buildings (JGJ26–1995).

MOHURD (Ministry of Housing and Urban-Rural Development in China), 2022a. Action Plan of Carbon Peak in China's Urban and Rural Construction.

MOHURD (Ministry of Housing and Urban-Rural Development in China), 2022b. Building Energy Conservation and Green Building Development Plan in the 14th Five-Year.

NBS (National Bureau of Statistics), 2020. Chinese Statistical Yearbook (2020). Chinese Statistical Press.

O'Mahony, T., 2013. Decomposition of Ireland's carbon emissions from 1990 to 2010: an extended Kaya identity. Energy Policy 59, 573–581. https://doi.org/10.1016/j.enpol.2013.04.013.

Pasquazzi, L., Zenga, M., 2018. Components of Gini, Bonferroni, and Zenga inequality indexes for EU income data. J. Off. Stat. 34 (1), 149–180. https://nbn-resolving.org/urn:nbn:de:0168-ssoar-73312-3.

Shao, S., et al., 2020. Enlarging regional disparities in energy intensity within China. Earth's Future 8 (8). https://doi.org/10.1029/2020EF001572 e2020EF001572.

Song, Y., et al., 2021. Identifying characteristic changes in club convergence of China's urban pollution emission: a spatial-temporal feature analysis. Energy Econ. 98, 105243 https://doi.org/10.1016/j.eneco.2021.105243.

Sun, C., 2015. An empirical case study about the reform of tiered pricing for household electricity in China. Appl. Energy 160, 383–389. https://doi.org/10.1016/j.apenergy.2015.09.030.

Swan, L.G., Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. Renew. Sust. Energ. Rev. 13 (8), 1819–1835. https://doi.org/10.1016/j.rser.2008.09.033.

Tanaka, K., et al., 2019. Asserting the climate benefits of the coal-to-gas shift across temporal and spatial scales. Nat. Clim. Chang. 9 (5), 389–396. https://doi.org/10.1038/s41558-019-0457-1.

Wang, M., Feng, C., 2021. The inequality of China's regional residential CO2 emissions. Sustain. Prod. Consum. 27, 2047–2057. https://doi.org/10.1016/j.spc.2021.05.003.

Wang, Y.Q., Tsui, K.Y., 2000. Polarization orderings and new classes of polarization indices. J. Public Econ. Theor. 2 (3), 349–363. https://doi.org/10.1111/1097-3923.00042.

Wang, C., et al., 2020. Regional carbon imbalance within China: an application of the Kaya-Zenga index. J. Environ. Manag. 262, 110378 https://doi.org/10.1016/j.jenvman.2020.110378.

Wang, X., et al., 2021. Identifying household cooling savings potential in the hot summer and cold winter climate zone in China: a stochastic demand frontier approach. Energy 237, 121588. https://doi.org/10.1016/j.energy.2021.121588.

Wang, J., et al., 2022. Gravity center change of carbon emissions in Chinese residential building sector: differences between urban and rural area. Energy Rep. 8, 10644–10656. https://doi.org/10.1016/j.egyr.2022.08.208.

Wang, X., et al., 2023. Using real building energy use data to explain the energy performance gap of energy-efficient residential buildings: a case study from the hot summer and cold winter zone in China. Sustainability 15 (2). https://doi.org/10.3390/su15021575.

Yan, R., et al., 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, T., et al., 2017. CO2 emissions in China's building sector through 2050: a scenario analysis based on a bottom-up model. Energy 128, 208–223. https://doi.org/10.1016/j.energy.2017.03.098.

You, K., et al., 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., et al., 2023a. 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.

You, K., et al., 2023b. The change in temporal trend and spatial distribution of CO2 emissions of China's public and commercial buildings. Build. Environ. 229, 109956 https://doi.org/10.1016/j.buildenv.2022.109956.

Yu, Q., et al., 2022. Economic agglomeration and emissions reduction: does high agglomeration in China's urban clusters lead to higher carbon intensity? Urban Clim. 43, 101174 https://doi.org/10.1016/j.uclim.2022.101174.

Zenga, M., Radaelli, P., 2012. Decomposition of Zenga's inequality index by sources. Stat. Appl. 10 (1), 3–31. https://doi.org/10.15611/aoe.2020.1.05.

Zhang, X., Dong, F., 2022. Determinants and regional contributions of industrial CO2 emissions inequality: a consumption-based perspective. Sustain. Energy Technol. Assess. 52, 102270 https://doi.org/10.1016/j.seta.2022.102270.

Zheng, S., Yuan, R., 2023. Sectoral convergence analysis of China's emissions intensity and its implications. Energy 262, 125516. https://doi.org/10.1016/j.energy.2022.125516.

Zhou, N., et al., 2018. Scenarios of energy efficiency and CO 2 emissions reduction potential in the buildings sector in China to year 2050. Nat. Energy 3 (11), 978–984. https://doi.org/10.1038/s41560-018-0253-6.