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What drives the carbon mitigation in Chinese commercial building sector? Evidence from decomposing an extended Kaya identity

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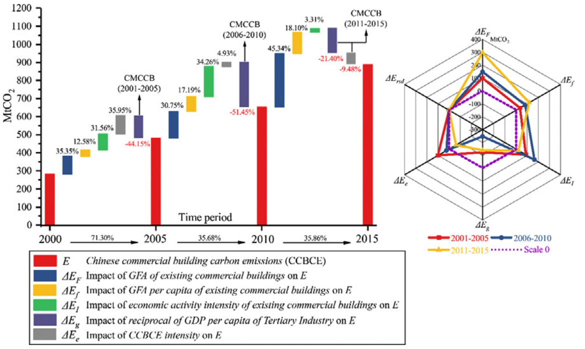
HIGHLIGHTS

- Carbon mitigation in Chinese commercial buildings (CMCCB) in 2001–2015: 625.9 $MtCO_2$
- We utilised the Kaya identity and the LMDI method to assess the CMCCB values.
- Data source is *China Database of Building Energy Consumption and Carbon Emissions*.
- Root cause of the growing CMCCB is the effective building energy efficiency project.

GRAPHICAL ABSTRACT

LMDI-I decomposition results of Chinese commercial building carbon emissions during 2000–2015.



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ABSTRACT

Energy efficiency in the building sector is expected to contribute >50% to the nationwide carbon mitigation efforts for achieving China's carbon emission peak in 2030, and carbon mitigation in Chinese commercial buildings (CMCCB) is an indicator of this effort. However, the CMCCB assessment has faced the challenge of ineffective and inadequate approaches; therefore, we have followed a different approach. Using the *China Database of Building Energy Consumption and Carbon Emissions* as our data source, our study is the first to employ the Logarithmic Mean Divisia Index (LMDI) to decompose five driving forces from the Kaya identity of Chinese commercial building carbon emissions (CCBCE) to assess the CMCCB values in 2001–2015. The results of our study indicated that: (1) Only two driving forces (i.e., the reciprocal of GDP per capita of Tertiary Industry in China and the CCBCE intensity) contributed negatively re$_{m_i}$ to CCBCE during 2001–2015, and the quantified negative contributions denoted the CMCCB values. Specifically, the CMCCB values in 2001–2005, 2006–2010, and 2011–2015 were 123.96, 252.83, and 249.07 $MtCO_2$, respectively. (2) The data quality control involving the CMCCB values proved the reliability of our CMCCB assessment model, and the universal applicability of this model was also confirmed. (3) The substantial achievements of the energy efficiency project in the Chinese commercial building sector were the root cause of the rapidly growing CMCCB. Overall, we believe that our model successfully bridges the research gap of the nationwide CMCCB assessment and that the proposed model is also suitable either at the provincial level or in different building climate zones in China. Meanwhile, a global-level assessment of the carbon mitigation in the commercial building sector is feasible through applying our model. Furthermore, we consider our contribution as constituting significant guidance for developing the building energy efficiency strategy in China in the upcoming phase.

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Nomenclature

Acronyms

CABEE	China Association of Building Energy Efficiency
CBEM	*China Building Energy Model*
CCBCE	(i.e., *E*) Chinese commercial building carbon emissions
CDBECCE	*China Database of Building Energy Consumption and Carbon Emissions*
CMCCB	Carbon mitigation in Chinese commercial buildings
CNY	Chinese Yuan (i.e., *Renminbi*, the currency of PR China)
EEP	energy efficiency project
GFA	gross floor area
LBNL	Lawrence Berkeley National Laboratory, USA
MOHURD of PRC	Ministry of Housing and Urban-Rural Development of PR China
NBOS of PRC	National Bureau of Statistics of PR China
RMI	Rocky Mountain Institute, USA
THUBEEI	Tsinghua University Building Energy Efficiency Institute, PR China

Symbols

e	CCBCE intensity
F	GFA of existing commercial buildings in China
f	GFA per capita of existing commercial buildings in China
G	GDP of Tertiary Industry in China
g	reciprocal of GDP per capita of Tertiary Industry in China
I	economic activity intensity of existing commercial buildings in China
P	employed population of Tertiary Industry in China
ΔE_e	impact of e on E
ΔE_F	impact of F on E
ΔE_f	impact of f on E
ΔE_g	impact of g on E
ΔE_I	impact of I on E
ΔE_{rsd}	random error during the LMDI-I decomposition analysis
ΔE_{tot}	value of E changes during a period

1. Introduction

For the past four decades, China has undergone unparalleled economic development to become the second largest economy worldwide (Mi et al., 2017; Shan et al., 2018; Shen et al., 2016; Shuai et al., 2017b). The country has also become the world's largest carbon emitter, with building carbon emissions representing the second highest amount of nationwide carbon emissions (Berardi, 2017; Delmastro et al., 2015; Dong et al., 2018). The Chinese government has promised that China will achieve a carbon emission peak in 2030, and, in 2017, it issued its official plan for a total carbon emission control strategy (State_Council_of_PRC, 2017). Given that the potentials of achieving energy efficiency and carbon mitigation in the building sector are greater than in the industry and transportation sectors, respectively, achieving energy efficiency in the building sector is expected to provide >50% of the national carbon mitigation required to achieve China's carbon emission peak in 2030 (Lynn et al., 2017; RMI and LBNL, 2016). A strong building energy efficiency strategy can promote carbon mitigation in the building sector effectively (Liang et al., 2014; Lin and Liu, 2015; Zuo et al., 2014). Thus, an effective energy efficiency project (EEP) in the Chinese building sector can be regarded as a key roadmap for achieving the Chinese 2030 carbon emission peak (Kong et al., 2012; McNeil et al., 2016).

As a member of building carbon emissions, Chinese commercial building carbon emissions (CCBCE) constitute >35% of the building carbon emissions in China at present (CABEE, 2017; THUBEEI, 2017). Given that the potential for carbon mitigation in commercial buildings is greater than in residential buildings (Liu et al., 2018, 2017b; Zuo et al., 2012a), launching the EEP in the Chinese commercial building sector should be of high priority (MOHURD_of_PRC, 2017). Moreover, assessing carbon mitigation in Chinese commercial buildings (CMCCB) is urgent for direct examination of the achievements of the EEP in the Chinese commercial building sector.

In view of this, using the *China Database of Building Energy Consumption and Carbon Emissions* (CDBECCE) as our data source, we put forward an assessment model combining the Logarithmic Mean Divisia Index I (LMDI-I) with an extended Kaya identity to decompose five driving forces of CCBCE [i.e., the gross floor area (GFA) of existing commercial buildings in China, the CCBCE intensity, the reciprocal of GDP per capita of Tertiary Industry in China, the GFA per capita of existing commercial buildings in China, and the economic activity intensity of existing commercial buildings in China] for assessing the CMCCB values during 2001–2015. After determining the CMCCB values, a comparative analysis between the official expected and actual values of CMCCB, a data quality control exercise involving the CMCCB values, and a comprehensive evaluation of the CMCCB assessment model were undertaken separately to identify the reliability of our CMCCB assessment model. Moreover, the EEP in the Chinese commercial building sector was discussed in retrospect to reveal the root cause of the rapidly growing CMCCB.

The framework of this study is organised as follows. Section 2 presents the literature review. In Section 3, we introduce the CMCCB assessment model established by the Kaya identity and the LMDI-I decomposition analysis. The leading data source (i.e., our CDBECCE) is shown in Section 4 and Appendix D. The outputs of the LMDI-I and, in particular, the CMCCB values (2001–2015) are shown and analysed in depth in Section 5. In Section 6, we discuss the advantages, shortcomings, and universal applicability of our CMCCB assessment model and launch a retrospective assessment of the EEP in the Chinese commercial building sector from the mid-1990s to 2017. Section 7 illustrates the main findings, policy implications, and further research.

2. Literature review

Reliable time-series data of building carbon emissions are the foundations for exploring carbon mitigation in the building sector (Tanikawa, 2018). Currently, the official process of collecting statistical

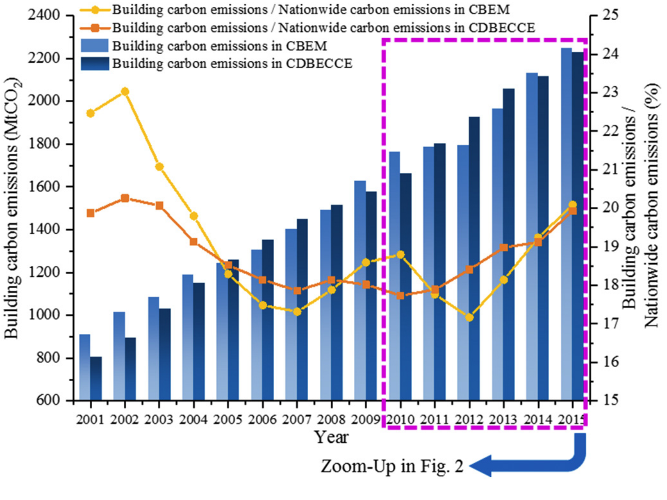
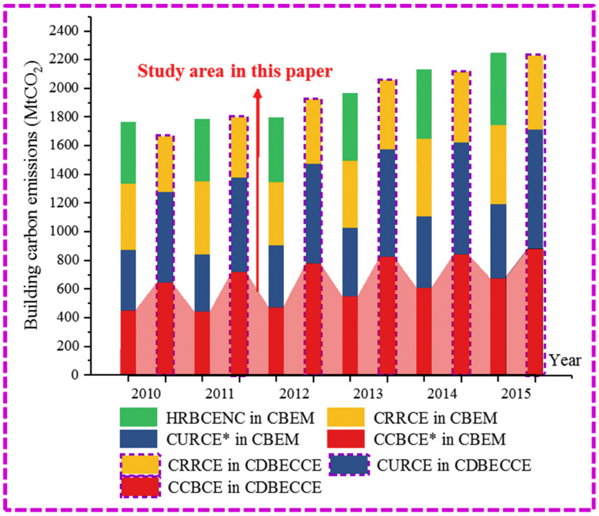


Fig. 1. Data comparison of Chinese building carbon emissions between CBEM and CDBECCE during 2001–2015. *Sources of CBEM: THUBEEI (2017) *Sources of CDBECCE: CABEE (2017).



Notice: CCBCE* - CCBCE (excluding the heating-related building carbon emissions in northern China); CRRCE - Chinese rural residential carbon emissions; CURCE - Chinese urban residential carbon emissions; CURCE* - CURCE (excluding the heating-related building carbon emissions in northern China); HRBCENC - Heating-related building carbon emissions in northern China.

Fig. 2. Data comparison of Chinese building carbon emissions between CBEM and CDBECCE during 2010–2015. *Sources of CBEM: THUBEEI (2017) *Sources of CDBECCE: CABEE (2017).

data on building energy consumption and carbon emissions in China has fallen behind significantly, as building energy consumption data have been not considered independently in the overall statistical data of energy consumption in China. Therefore, official data on building carbon emissions in China are still lacking (Chen et al., 2008a, 2008b; Ma et al., 2017d). Meanwhile, the values of different estimation approaches involving carbon emissions in the Chinese building sector are very different [ranging from constituting 15–50% of the nationwide carbon emissions, e.g., Berardi, 2017; CABEE, 2017; Delmastro et al., 2015; McNeil et al., 2016; THUBEEI, 2017]. However, there are two relatively credible study branches involving data assessment of the building carbon emissions of China; these are approved widely by numerous other works. As a representative bottom-up model to estimate the carbon emissions in the building sector of China, the *China Building Energy Model* (CBEM) indicated a nationwide building carbon emission value of 2246.40 million tons of carbon dioxide (MtCO$_2$), constituting 20.00% of the nationwide carbon emissions in 2015, and the CCBCE value (excluding the heating-related carbon emissions of commercial buildings in northern China) was 690 MtCO$_2$, constituting 30.71% of the building carbon emissions in the same period (THUBEEI, 2017). Meanwhile, as one of the leading achievements of the *China Association of Building Energy Efficiency* (CABEE), the up-bottom building energy consumption statistical model named the *China Database of Building Energy Consumption and Carbon Emissions* (CDBECCE), which was established on the basis of data mining tools and processing methods involving building energy consumption, indicated the detailed Chinese building carbon emission data at both the national and provincial levels during 2000–2015. Specifically, CDBECCE indicated a nationwide building carbon emission value of 2228.20 MtCO$_2$, constituting 19.93% of the nationwide carbon emissions in 2015. Moreover, the CCBCE amounted to 886.6 MtCO$_2$, constituting 39.79% of the nationwide building carbon emissions in the same period (CABEE, 2017). To facilitate understanding of the above two kinds of data estimation methods, a data comparison of CBEM and CDBECCE is demonstrated in Figs. 1 and 2.

As indicated in Figs. 1 and 2, although the CBEM and CDBECCE utilised different approaches to assessing the carbon emissions in the building sector of China, the results of the two methods were very similar for different types of civil buildings during 2001–2015, and

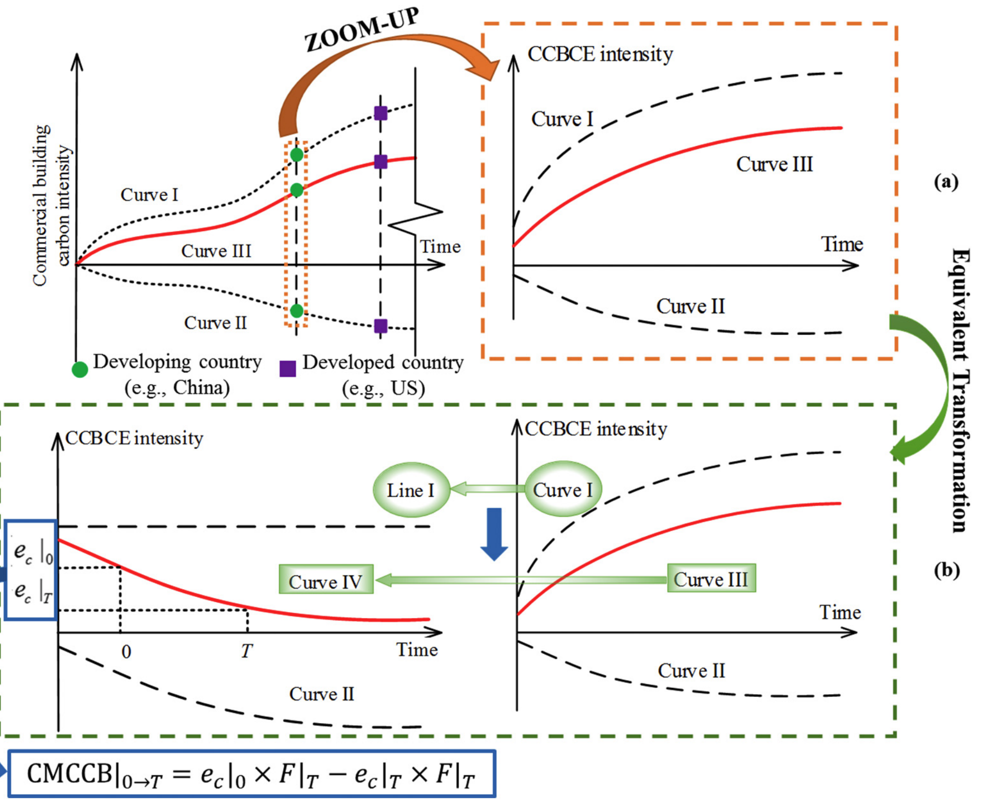


Fig. 3. Schematic of the relationships among the CCBCE intensity (Curve III), the commercial building service index (Curve I), and the commercial building energy efficiency index (Curve II); the approach to assessing the CMCCB values based on the comparable CCBCE intensity (Curve IV), the constant commercial building service index (Line I), and the commercial building energy efficiency index (Curve II).

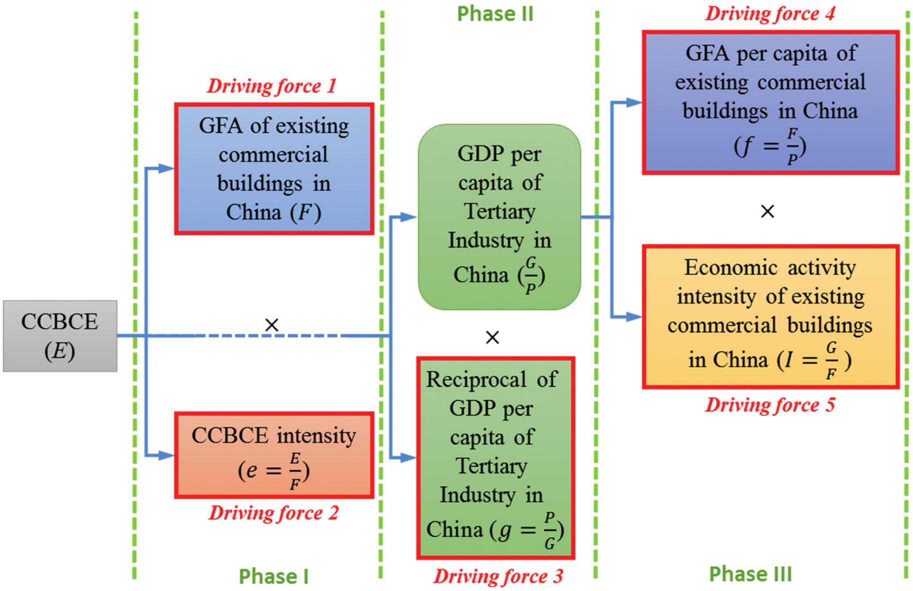


Fig. 4. Framework of the extended Kaya identity of CCBCE.

especially from 2010 to 2015. Currently, an approach that combines the Human Impact, Population, Affluence, and Technology (IPAT) identity (including its extended versions, such as the Kaya identity) and LMDI decomposition analysis is widely applied to explore the energy savings/carbon mitigation in different sectors [e.g., Nie et al. (2018); O'Mahony (2013); Shao et al. (2016a); Štreimikienė and Balezentis (2016); Zhang et al. (2017)]. In the building sector of China, a few existing works have assessed the energy savings/carbon mitigation in different kinds of civil buildings, excluding the commercial building sector. As a typical case, Ma et al. (2017d) utilised LMDI to decompose an IPAT identity of building energy consumption established by a key variable [i.e., the comparable building carbon intensity, which was first proposed by Cai et al., 2014]; the negative parts of the decomposition results indicated the energy saving values in the Chinese civil building sector during 2001–2014. Using similar approaches, Yan et al. (2017) estimated the energy saving values in the residential building sector of China in 2001–2015. Moreover, with the data source of the CDBECCE prototype [i.e., CABEE, 2016], Ma et al. (2017c) established an improved method based on the contribution of Ma et al. (2017d) to evaluate the energy savings and carbon mitigation in existing Chinese civil buildings (the evaluation consisted of three parts: energy savings in residential buildings of urban and rural China, and carbon mitigation in Chinese public buildings) during 2001–2015. However, shortcomings still exist in the efforts of Ma et al. (2017c, 2017d) and Yan et al. (2017); these include relatively low-mature data sources and limited methods, as will be further discussed in Eq. (7).

Two relatively reliable CCBCE data estimation methods and a series of existing works assessing the energy savings/carbon mitigation in the Chinese building sector have been discussed above. In the above-mentioned studies, we observed that:

- At the data source level, as indicated in Figs. 1 and 2, given that the CCBCE values shown in CBEM were incomplete (i.e., the heating-related carbon emissions of commercial buildings in northern China were not involved in the CCBCE values of CBEM), only the CDBECCE provided complete and detailed time-series data of CCBCE. Besides, numerous scholars have employed the CDBECCE (including its prototype) to explore carbon emissions in the building sector of China successfully [e.g., Liang et al., 2017; Ma et al., 2017b, 2017c, 2017d; Shuai et al., 2018; L. Wang et al., 2017; Y. Wang et al., 2017; Wei and He, 2017; Yan et al., 2017]. Thus, CDBECCE can be regarded as a credible data source for assessing the carbon mitigation of commercial buildings in this paper.
- At the assessment model level, the approach, combining the IPAT and LMDI methods, is widely applied to explore energy savings/carbon mitigation in the Chinese building sector. To our knowledge, application of this methodology in the Chinese commercial building sector has been very limited. Due to the commercial building sector is a typical member of the civil buildings, the IPAT and LMDI methods (including their extended versions, such as the Kaya identity and the LMDI-I decomposition analysis) can be utilised equally to assess carbon mitigation in the commercial building sector (Lin and Liu, 2015).

The literature review demonstrated that effective assessment of CMCCB is still lacking, which means that launching an independent study exploring the CMCCB values is an urgent task for direct examination of the achievements of the EEP in the Chinese commercial building sector.

Therefore, the goal of this paper is to establish an effective model to bridge the research gap relevant to CMCCB assessment. Meanwhile, our contribution is as follows.

- We first proposed the CMCCB assessment model based on a Kaya identity of CCBCE that involved five relevant driving forces. Taking into consideration the characteristics of the commercial building sector and the framework of the Kaya identity, we chose five driving forces to build the CCBCE equation (i.e., the GFA of existing commercial buildings in China, the CCBCE intensity, the reciprocal of GDP per capita of Tertiary Industry in China, the GFA per capita of existing commercial buildings in China, and the economic activity intensity of

Table 1
Leading equations of the CMCCB assessment model.

	ΔE_{tot}	$\Delta E_{tot} = E\|_T - E\|_0 = \Delta E_F + \Delta E_f + \Delta E_I + \Delta E_g + \Delta E_e + \Delta E_{rsd}$ (10)
Decomposition method [LMDI-I, sources: Ang, 2015; Ang, 2005]	ΔE_F ΔE_f ΔE_I ΔE_g ΔE_e ΔE_{rsd}	Indicated in Eqs. (B–4) to (B–9), Appendix B
Result	CMCCB	$\sum \|\Delta E_i\|_{0\to T}\|$ $(\Delta E_i\|_{0\to T} \in \{\Delta E_F, \Delta E_f, \Delta E_I, \Delta E_g, \Delta E_e\}, \Delta E_i\|_{0\to T} < 0)$ (11)

Table 2
Key variable definitions.

Symbol	Variable	Unit	References
E	CCBCE	$MtCO_2$	CABEE (2017); Ge et al. (2017); Ma et al. (2017a, 2017d)
F	GFA of existing commercial buildings in China	10^8 m^2	
f	GFA per capita of existing commercial buildings in China	m^2/person	
e	CCBCE intensity	$kgCO_2/m^2$	
P	Employed population of Tertiary Industry in China	10^6 persons	Li et al. (2017); Lin and Liu (2015); Wang and Lin (2017)
G	GDP of Tertiary Industry in China	Billion CNY	Shuai et al. (2017a); Wang and Lin (2017); Zhao et al. (2017)
g	Reciprocal of GDP per capita of Tertiary Industry in China	Person/thousand CNY	
I	Economic activity intensity of existing commercial buildings in China	CNY/m^2	Ge et al. (2017); Lynn et al. (2017); Ma et al. (2017a)
ΔE_{tot}	Value of E changes during a period	$MtCO_2$	Ang (2015); Cai et al. (2014); Ma et al. (2017d, 2018); Shao et al. (2016b); Wang et al. (2015); Zhao et al. (2017)
ΔE_F	Impact of F on E	$MtCO_2$	
ΔE_f	Impact of f on E	$MtCO_2$	
ΔE_I	Impact of I on E	$MtCO_2$	
ΔE_g	Impact of g on E	$MtCO_2$	
ΔE_e	Impact of e on E	$MtCO_2$	
ΔE_{rsd}	Random error during the LMDI-I decomposition analysis	$MtCO_2$	

existing commercial buildings in China). Thereafter, the LMDI-I was used to decompose the five driving forces for assessing the CMCCB value during 2001–2015. Notably, all five driving forces are quantifiable through the whole process of LMDI-I decomposition, which ensures the validity of the CMCCB assessment model and the authenticity of the CMCCB values. It should be noted that, although the approach combining Kaya identity and LMDI-I decomposition analysis has been used in a series of existing studies, to our knowledge, this methodology has been applied rarely in the commercial building sector of China.

- This is the first study to explore the carbon emissions in the commercial building sector of China based on the data source of the official CDBECCE. As the official process of collecting statistical data on building energy consumption and carbon emissions in China has fallen behind significantly, the paucity of reliable data sources makes it difficult to develop a series of quantitative studies involving carbon emissions in the China's building sector, especially in the commercial building sector. With the release of the official CDBECCE, a relatively credible assessment for the CMCCB values based on the complete time-series data of CCBCE is feasible. To a certain extent, our works will enrich the research achievements in the field of building energy efficiency in China.

3. Methodology

3.1. Kaya identity and LMDI-I decomposition analysis

Kaya identity indicates the relationship between man-made carbon emissions (CE) and four relevant kinds of driving forces (i.e., the carbon intensity of energy consumption [CE/EC], energy intensity [EC/GDP], GDP per capita [GDP/P], and population [P]) at a regional level (Kaya, 1989), as shown in Eq. (1). The Kaya identity is a renovated version of the IPAT identity established by Ehrlich and Holdren (1971). A series

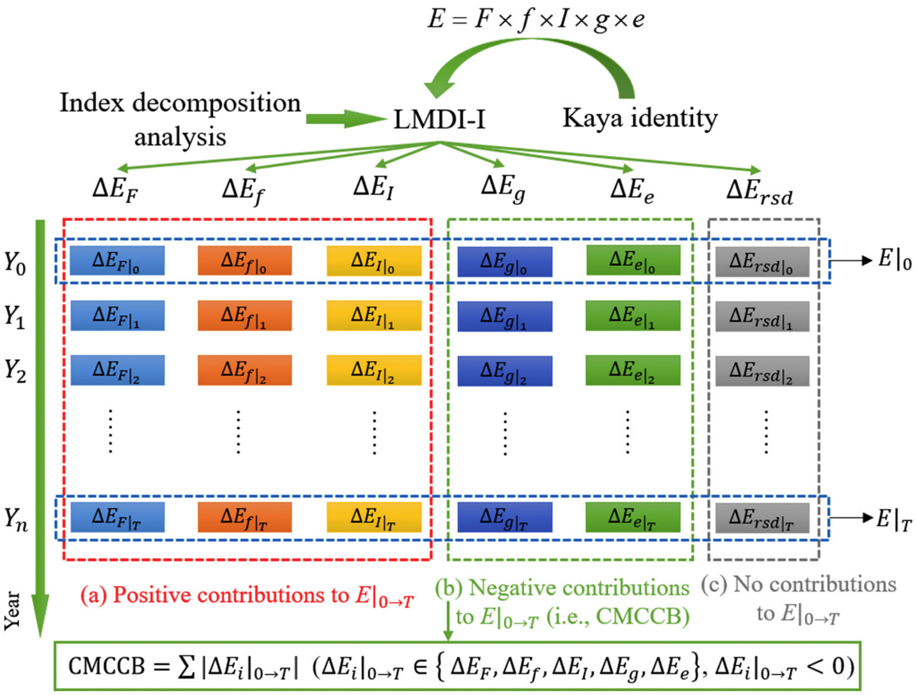


Fig. 5. Schematic of the CMCCB assessment model.

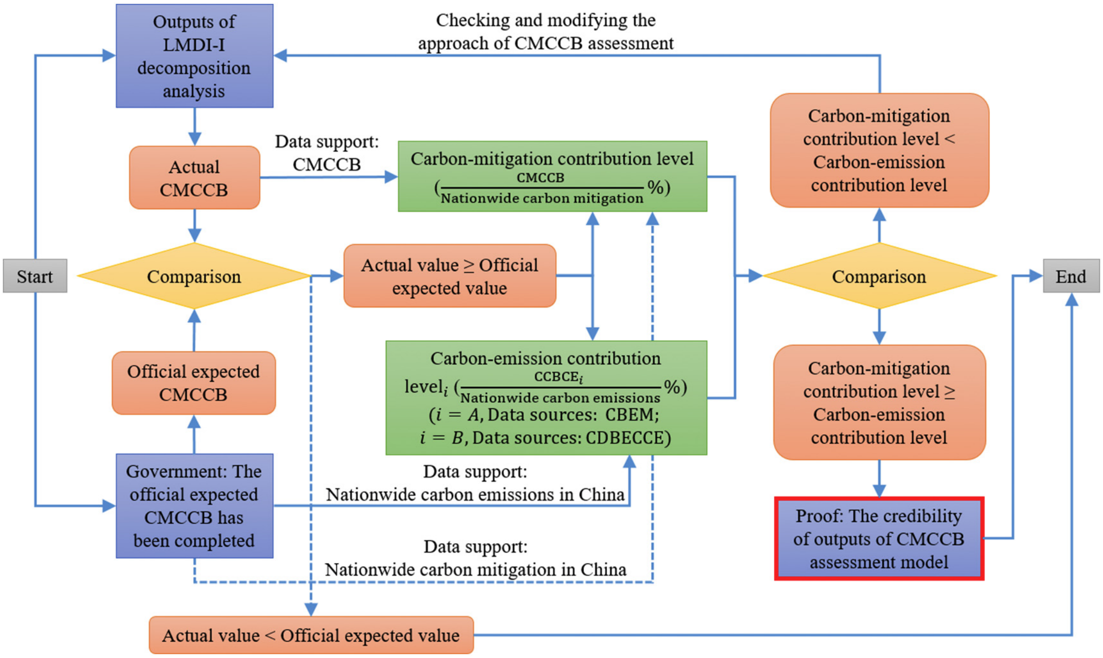


Fig. 6. Framework of data quality control involving CMCCB values.

of studies have witnessed the rapid development and wide application of the Kaya identity in the fields of Energy Economics, Environmental Science, Climate Change, and the like [e.g., Liu and Wang, 2017; O'Mahony, 2013; Rafaj et al., 2014; Štreimikienė and Balezentis, 2016].

$$CE = \frac{CE}{EC} \times \frac{EC}{GDP} \times \frac{GDP}{P} \times P \tag{1}$$

LMDI-I decomposition analysis (i.e., a classic form of the LMDI method), first proposed by Ang and Choi (1997), is a widely approved method for evaluating the impact factors of carbon emissions in numerous sectors (Zhang et al., 2016; Zhang et al., 2017; Zhao et al., 2012). Through this approach, a carbon-emission-related object can be decomposed into several impact factors. Thereafter, quantitative analysis is applied to confirm the contributions of different factors, and the key factors can be labeled for further analysis (Ang, 2015; Chen et al., 2017; Tan et al., 2017). Based on the Kaya identity, Eqs. (2) to (5) demonstrate the universal form of the LMDI-I decomposition analysis during a period (T).

$$\Delta CE_{\frac{CE}{EC}} = L \times \ \ln\left(\frac{\frac{CE}{EC}\big|_T}{\frac{CE}{EC}\big|_0}\right) \tag{2}$$

$$\Delta CE_{\frac{EC}{GDP}} = L \times \ \ln\left(\frac{\frac{EC}{GDP}\big|_T}{\frac{EC}{GDP}\big|_0}\right) \tag{3}$$

$$\Delta CE_{\frac{GDP}{P}} = L \times \ \ln\left(\frac{\frac{GDP}{P}\big|_T}{\frac{GDP}{P}\big|_0}\right) \tag{4}$$

$$\Delta CE_P = L \times \ \ln\left(\frac{P|_T}{P|_0}\right) \tag{5}$$

where L denotes the $L(CE|_T, CE|_0)$, expressing the log-mean of two variables (Ang, 2015), as illustrated in Eq. (6).

$$L(\alpha,\beta) = \begin{cases} \frac{\alpha-\beta}{ln\alpha - ln\beta}, & \alpha \neq \beta \ (\alpha>0, \ \beta>0) \\ 0 \quad , & \alpha = \beta \ (\alpha>0, \ \beta>0) \end{cases} \tag{6}$$

Besides, several existing works have demonstrated the extensive applicability of combining the LMDI-I decomposition analysis with the Kaya identity to identify and evaluate the impact factors of carbon emissions in numerous sectors [e.g., Jiang et al., 2017; Mavromatidis et al., 2016; O'Mahony, 2013; Štreimikienė and Balezentis, 2016], and the two tools are the theoretic basis for the proposed CMCCB assessment model in the next section.

3.2. CMCCB assessment model

In a bottom-up approach to estimating the carbon mitigation of the building sector, a series of previous works have treated the building carbon emission per floor area (i.e., the building carbon intensity) and its comparable value (i.e., the comparable building carbon intensity) as the key to evaluating carbon mitigation [e.g., Cai et al., 2014; Ma et al., 2017b, 2017c, 2017d; Yan et al., 2017]. As a typical case, in the approach of Ma et al. (2017d), the building service index, proposed by Cai et al. (2014), was assumed constant at the national level during a period,

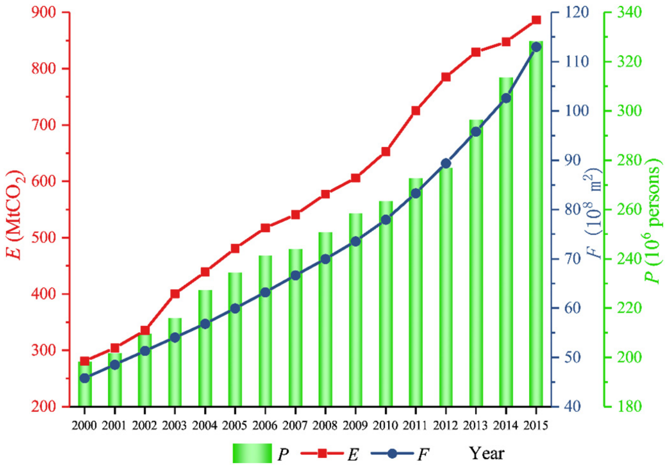


Fig. 7. Time-series data of CCBCE (E), GFA of existing commercial buildings in China (F), and employed population of Tertiary Industry in China (P) in 2000–2015. *Sources of E and F: CABEE (2017) *Sources of P: NBOS_of_PRC (2016).

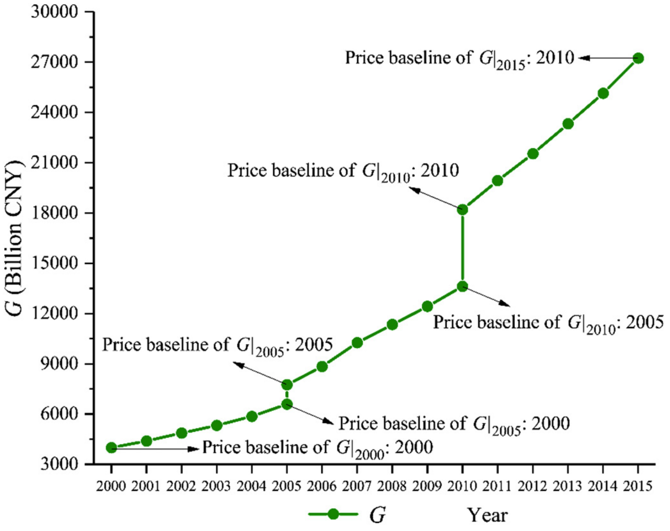


Fig. 8. Time-series data of GDP of Tertiary Industry in China (G) in 2000–2015. *Sources: NBOS_of_PRC (2016).

and the comparable building carbon intensity, assessed by the constant building service index and the building energy efficiency index, was marked as the prerequisite to quantifying further the carbon mitigation in the civil building sector. Given that the commercial building sector is a typical member of the civil buildings, the approach of Ma et al. (2017d) can also be utilised to assess the CMCCB technically. Fig. 3 demonstrates the schematic of assessing the CMCCB values based on the comparable building carbon intensity in Chinese commercial buildings (i.e., the comparable CCBCE intensity).

Fig. 3(a) illustrates that the CCBCE intensity increases under the changes of the commercial building service index (Curve I, symbol of the growing living condition in commercial buildings) and the commercial building energy efficiency index (Curve II, symbol of the improved energy efficiency technology in commercial buildings) during a period. However, the comparable value of CCBCE intensity has decreased in recent years (Ma et al., 2017a). To reveal the comparable CCBCE intensity value, we have assumed that the living condition in commercial buildings remains unchanged over a short period of time (e.g., less than one year); thus, Curve I has changed into Line I in Fig. 3(b). Under the impacts of Line I and Curve II, the comparable CCBCE intensity value (Curve IV) has decreased over a short period of time. Furthermore, the formula to assess the CMCCB values can be proposed based on Fig. 3 (b), as shown in Eq. (7).

$$\mathrm{CMCCB}|_{0\to T} = e_c|_0 \times F|_T - e_c|_T \times F|_T \tag{7}$$

In this case, $F|_T$ denotes the reporting period value of the GFA of existing commercial buildings in China, and $e_c|_T$ and $e_c|_0$ are the comparable CCBCE intensities for the reporting and baseline periods, respectively. However, compared with the CCBCE intensity, the comparable CCBCE intensitye$_m$ is an unquantifiable variable; without any further reliable assumptions, it is impossible to assess the CMCCB values by utilising Eq. (7) (Cai et al., 2014). Thus, the approach of assessing the CMCCB by applying Eq. (7) should be improved considerably.

In this study, we have followed a different approach to assessing the CMCCB without the impact of the comparable CCBCE intensity. In other words, the CCBCE intensity has replaced the comparable CCBCE intensity, and will be regarded as an independent driving force to explore the CMCCB values with other meaningful driving forces established by the Kaya identity, as shown below.

- Taking into consideration that the CCBCE intensity is the key to assessing the CMCCB, along with the original framework of the Kaya identity (Liu et al., 2015; Ma et al., 2017d; Štreimikienė and Balezentis, 2016; Wu et al., 2016), we decomposed the CCBCE into two driving forces (i.e., the CCBCE intensity and the GFA of existing commercial buildings in China) with an index value of one at Phase I.
- As the commercial building energy consumption is a typical type of living energy consumption, rather than industrial energy consumption (Lin and Liu, 2015; McNeil et al., 2016), it is meaningful to explore the driving forces from Tertiary Industry: the index value of one was further decomposed into two driving forces (i.e., GDP per capita of Tertiary Industry in China and its reciprocal value) at Phase II.
- Furthermore, taking into consideration the characteristics of the commercial buildings, the GDP per capita of Tertiary Industry in China would be decomposed again into two driving forces (i.e., the GFA per capita of existing commercial buildings in China and the economic activity intensity of existing commercial buildings in China) at Phase III. Compared with CCBCE intensity, the two driving forces at Phase III are also significant indexes to reflect the growth trend of CCBCE at the unit level (Ge et al., 2017; Ma et al., 2017a; McNeil et al., 2016).

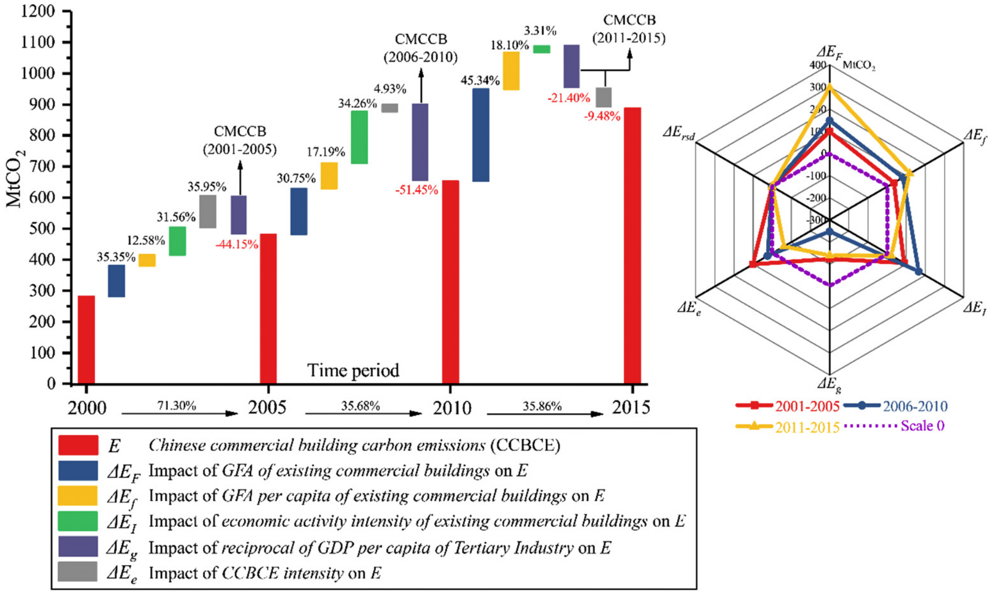


Fig. 9. LMDI-I decomposition results of CCBCE during 2000–2015.

To facilitate understanding of the above decomposition process, Fig. 4 demonstrates the schematic of the decomposition analysis of the Kaya identity of CCBCE. Specifically, Fig. 4 reflects the relationships among the five driving forces affecting CCBCE, as shown in Eq. (8). Let $CCBCE = E$, $f = \frac{F}{P}$, $I = \frac{G}{F}$, $g = \frac{1}{\frac{G}{P}}$, $e = \frac{E}{F}$, Eq. (8) can be transformed into Eq. (9).

$$CCBCE = F \times \frac{F}{P} \times \frac{G}{F} \times \frac{1}{\frac{G}{P}} \times \frac{E}{F} \qquad (8)$$

$$E = F \times f \times I \times g \times e \qquad (9)$$

The LMDI-I was employed to evaluate the different contributions of the driving forces shown in Eq. (9). The value of E changes during a period (i.e., $\Delta E_{tot} = E|_T - E|_0$) and is equal to the sum of the contribution values, as shown in Eq. (10) (Ang, 2015; O'Mahony, 2013). Table 1 demonstrates the process and outcomes of the LMDI-I. Meanwhile, the relevant key variables are explained in Table 2.

To facilitate understanding of our methodology, Fig. 5 demonstrates the schematic of our CMCCB assessment model.

3.3. Data quality control involving CMCCB values

Various studies have used different approaches to verify the data quality in respect of the values of energy savings/carbon mitigation calculated by the LMDI. Combining the effective approach proposed by Ma et al. (2017d) (i.e., comparative analysis between the levels of the energy consumption contribution and the energy efficiency contribution to verify the credibility of the energy savings assessed by the IPAT and LMDI methods) with the specific situation in our study (i.e., the carbon-emission and carbon-mitigation contribution levels), the framework of data quality control, involving the assessment results of CMCCB from 2001 to 2015, is shown in Fig. 6.

To improve the credibility of the results involving data quality control, we have employed two different data sources (i.e., Data source A: CBEM; Data source B: CDBECCE) to establish the carbon-emission contribution level of the commercial building sector in China. Accordingly, the values of the two carbon-emission contribution levels in 2001–2005, 2006–2010, and 2011–2015 constitute two control lines with which to compare the values of the carbon-mitigation contribution level in the previously mentioned three periods, respectively, as shown in Fig. 12.

4. Data source – *China Database of Building Energy Consumption and Carbon Emissions* (CDBECCE)

Taking into consideration that the official statistical system of building carbon emissions remains incomplete, official data on CCBCE are unavailable. Thus, we utilised the time-series data involving CCBCE (E) and the GFA of existing commercial buildings in China (F) from the CDBECCE (CABEE, 2017), which has been recognised by numerous scholars [e.g., Liang et al., 2017; Ma et al., 2017b, 2017c, 2017d; Shuai et al., 2018; L. Wang et al., 2017; Y. Wang et al., 2017; Wei and He, 2017; Yan et al., 2017]. Furthermore, a brief introduction to the CDBECCE is demonstrated in Appendix D. In addition, the data sources of the employed population of Tertiary Industry in China (P) and the GDP of Tertiary Industry in China (G) were accessed from the *China Statistical Yearbook of the Tertiary Industry (2016)* (NBOS_of_PRC, 2016). These time-series data during 2000–2015 are shown in Figs. 7 and 8.

5. Results

5.1. Outputs of CMCCB assessment model

Fig. 9 demonstrates the outputs of the LMDI-I decomposition analysis, from a detailed calculation by MATLAB 9.0. Through Table 3 and Fig. 9, we observe that only the values of $\Delta E_g|_{2001 \to 2005}$, $\Delta E_g|_{2006 \to 2010}$, $\Delta E_g|_{2011 \to 2015}$, and $\Delta E_e|_{2011 \to 2015}$ meet the requirement of the discriminant shown in Table 1 [i.e., Eq. (11)], which proves that only the contribution of the reciprocal of GDP per capita of Tertiary Industry in China re_{m_i} to CCBCE was negative during the periods of 2001–2005 and 2006–2010, and two driving forces (i.e., the reciprocal of GDP per capita of Tertiary Industry in China and the CCBCE intensity) negatively affected the growth of CCBCE in 2011–2015.

Table 3
Rank of driving forces.

Period	Driving force	Contribution level (absolute value)
2001–2005	ΔE_g	|−44.15%|
	ΔE_e	35.95%
	ΔE_F	35.35%
	ΔE_I	31.56%
	ΔE_f	12.58%
2006–2010	ΔE_g	|−51.45%|
	ΔE_I	34.26%
	ΔE_F	30.75%
	ΔE_f	17.19%
	ΔE_e	4.93%
2011–2015	ΔE_F	45.34%
	ΔE_g	|−21.40%|
	ΔE_f	18.10%
	ΔE_e	|−9.48%|
	ΔE_I	3.31%

According to Eq. (11), the annual values of CMCCB in 2001–2015 are indicated in Fig. 10. Specifically, the CMCCB values in 2001–2005, 2006–2010, and 2011–2015 were 123.96, 252.83, and 249.07 MtCO$_2$, respectively. It should be noted that three data fluctuation points exist in the trace of the annual CMCCB values; this phenomenon affected the stability of the assessment results to a certain extent.

5.2. Comparative analysis between the actual and official expected CMCCB

As mentioned in MOHURD_of_PRC (2012, 2014), the official expected CMCCB values in the 11th Five-year Plan Period (2006–2010) and the 12th Five-year Plan Period (2011–2015) were 143 and 150.8 MtCO$_2$, respectively. Thus, it is meaningful to develop a comparative analysis between the official expected and actual values, as shown in Fig. 11.

Fig. 11 demonstrates that the actual values from the CMCCB assessment model were much higher than were the official expected values

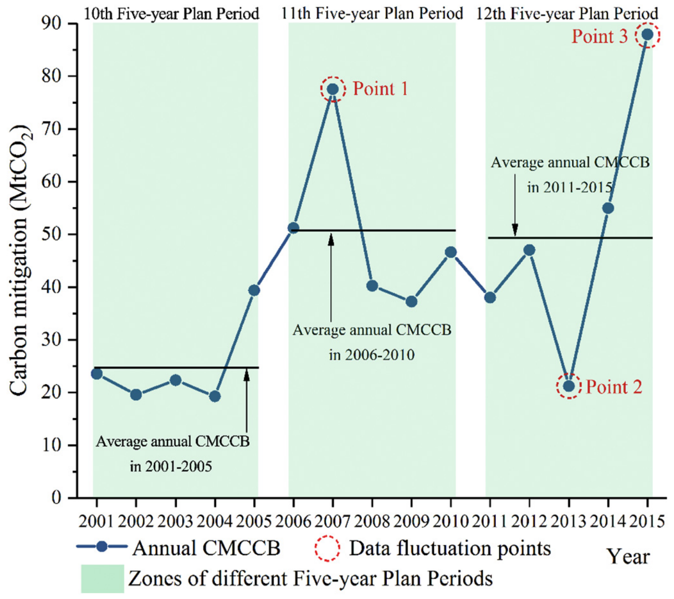


Fig. 10. Annual CMCCB during 2001–2015.

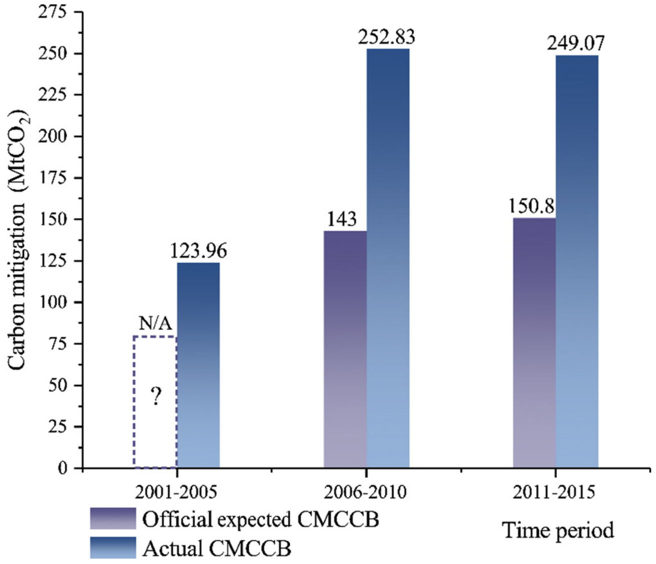


Fig. 11. Actual and official expected values of CMCCB during 2001–2015.

during 2006–2015. As effective actions had been launched by the central government to appraise the carbon mitigation at the national level since the mid-2000s (State_Council_of_PRC, 2007), few official plans for nationwide carbon mitigation had been established for the 10th Five-year Plan Period (2001–2005), and the official expected CMCCB values were lacking during the same period. Thus, the actual values of CMCCB in 2001–2005 faced the dilemma of data comparative analysis. The aforementioned comparative analysis illustrates that the EEP in the commercial building sector was achieved by the central government's positive initiatives during 2001–2015.

5.3. Results of data quality control involving CMCCB values

Through the schematic of CMCCB data quality control (Fig. 6) in Section 3.3, the nationwide carbon mitigation values of China were required for establishing the carbon-mitigation contribution level of the commercial buildings. The nationwide carbon mitigation values were determined by employing the official data published in the *China Statistical Yearbook of the Tertiary Industry (2016)* (NBOS_of_PRC, 2016); we then calculated the values of the carbon-mitigation and carbon-emission contribution levels in the commercial building sector for the period 2001–2015. These values are shown in Table 4, and the comparative analysis between the carbon-mitigation contribution level and the carbon-emission contribution level during 2001–2015 is shown in Fig. 12.

Table 4 and Fig. 12 show that the carbon-mitigation contribution level of the commercial building sector was clearly higher than was the carbon-emission contribution level during 2001–2005 (124.01% > max[8.55%, 7.47%]), 2006–2010 (13.76% > max[7.62%, 6.89%]), and 2011–2015 (11.07% > max[7.92%, 7.60%]), respectively. Significantly, the value of the carbon-mitigation contribution level in 2001–2005 was 124.01%, which was much higher than were the variables in 2006–2010 (13.76%), and 2011–2015 (11.07%). It should be noted that, despite there being no official nationwide carbon mitigation initiative in China in 2001–2005, the civil building sector (including the commercial buildings) managed to achieve the carbon mitigation without supervision from the central government (Lin and Liu, 2015; Zhang et al., 2015). However, various other sectors, such as the industry and transportation sectors, had to contend with high carbon emissions in the absence of carbon mitigation (Cai et al., 2017; Cai et al., 2016;

Table 4
Assessment results of nationwide carbon mitigation, and the values of the carbon-mitigation and carbon-emission contribution levels of the Chinese commercial building sector for 2001–2015.

Year	Nationwide carbon emissions in China (MtCO$_2$)	GDP in China (10^8 CNY, baseline: 2000)	Nationwide carbon intensity in China (kgCO$_2$/CNY)	Nationwide carbon mitigation in China (MtCO$_2$)	Carbon-mitigation contribution level (2001–2005)	Carbon-emission contribution level$_A$ (2001–2005)	Carbon-emission contribution level$_B$ (2001–2005)
2000	3821.06	100,280.10	0.381	–	124.01% $(\frac{123.96}{99.96}\%)$	8.55%	7.47%
2001	4044.22	108,639.20	0.372	95.36			
2002	4409.00	118,561.90	0.372	4.60			
2003	5124.16	130,463.20	0.393	−272.58			
2004	5987.31	143,657.80	0.417	−344.91			
2005	6795.59	160,027.00	0.425	−126.06			
Nationwide carbon mitigation in China (2001−2002)				99.96			
Nationwide carbon mitigation in China (2001–2005)				−643.59 → 0			
Year	Nationwide carbon emissions in China (MtCO$_2$)	GDP in China (10^8 CNY, baseline: 2005)	Nationwide carbon intensity in China (kgCO$_2$/CNY)	Nationwide carbon mitigation in China (MtCO$_2$)	Carbon-mitigation contribution level (2006–2010)	Carbon-emission contribution level$_A$ (2006–2010)	Carbon-emission contribution level$_B$ (2006–2010)
2005	6795.59	187,318.90	0.363	–	13.76%	7.62%	6.89%
2006	7448.14	211,147.70	0.353	211.92			
2007	8097.49	241,195.80	0.336	410.58			
2008	8335.89	264,472.80	0.315	543.07			
2009	8739.28	289,329.90	0.302	380.08			
2010	9376.85	320,102.60	0.293	291.92			
Nationwide carbon mitigation in China (2006–2010)				1837.57			
Year	Nationwide carbon emissions in China (MtCO$_2$)	GDP in China (10^8 CNY, baseline: 2010)	Nationwide carbon intensity in China (kgCO$_2$/CNY)	Nationwide carbon mitigation in China (MtCO$_2$)	Carbon-mitigation contribution level (2011–2015)	Carbon-emission contribution level$_A$ (2011–2015)	Carbon-emission contribution level$_B$ (2011–2015)
2010	9376.85	413,030.30	0.227	–	11.07%	7.92%	7.60%
2011	10,063.12	452,429.90	0.222	208.20			
2012	10,455.59	487,976.20	0.214	398.16			
2013	10,839.74	525,835.40	0.206	427.04			
2014	11,070.96	564,194.40	0.196	559.53			
2015	11,180.00	603,212.10	0.185	656.58			
Nationwide carbon mitigation in China (2011–2015)				2249.51			

*Notice: (a) Data source of carbon-emission contribution level$_A$: CBEM; (b) Data source of carbon-emission contribution level$_B$: CDBECCE.

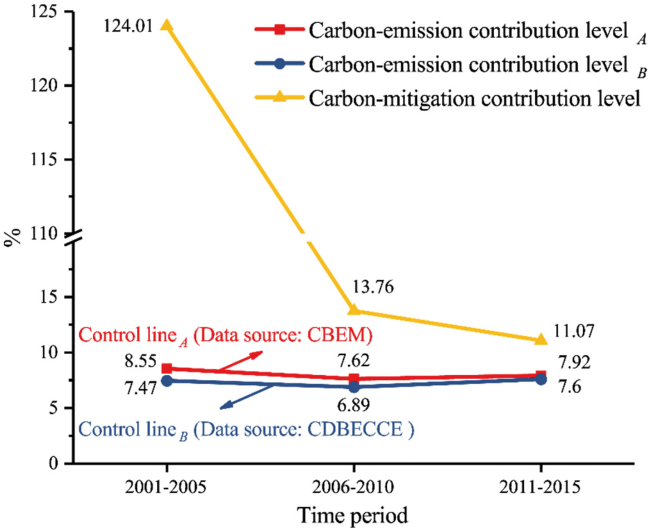


Fig. 12. Comparative analysis between the carbon-mitigation contribution level and the carbon-emission contribution level in the Chinese commercial building sector for 2001–2015.

Fang et al., 2017; Shao et al., 2016b; Zhao et al., 2016), which led to a negative carbon mitigation value in China for the period (i.e., −643.59 $MtCO_2$). It appears that no nationwide carbon mitigation was achieved in China during the entire period of 2001–2005. However, as Table 4 indicates, there was slight carbon mitigation at the national level in 2001 and 2002, causing an extremely high carbon-mitigation contribution level for the commercial building sector in 2001–2005. Overall, the above comparative analysis demonstrates effectively that the results shown in Figs. 9 and 10 are relatively credible and reasonable. This proves that the results of the proposed CMCCB assessment model discussed in Section 3.2 can be considered reliable.

6. Discussion

6.1. CMCCB assessment model: advantages, shortcomings, and universal applicability

As indicated in Section 3.2, the comparable building carbon intensity is an effective indicator to reflect the actual energy efficiency index at the building operation phase, and a few existing studies have treated this indicator as a prerequisite to assessing the energy savings/carbon mitigation in the building sector. However, the most significant weakness of the aforementioned approach is that the comparable building carbon intensity is an unquantifiable variable through the whole process of LMDI-I decomposition; without any further reliable assumptions, it is impossible to utilise Eq. (7) to assessing the carbon mitigation directly. To solve this problem, we have improved the previous approach and proposed a CMCCB assessment model based on the Kaya and LMDI methods. Furthermore, we have launched a comparative analysis of the different approaches for assessing the energy savings/carbon mitigation at the building operation phase in the Chinese building sector, as shown in Table 5 and Fig. 13. To conduct an equitable comparative analysis for the assessment results of different studies, all the results shown in Fig. 13 have been recalculated based on the data source of the CDBECCE (CABEE, 2017).

As indicated in Table 5 and Fig. 13, the most significant advantage of our CMCCB assessment model is that no assumption exists in the Kaya identity of CCBCE and the process of the LMDI-I. All the factors shown in the CCBCE equation are quantifiable through the whole process of LMDI-I decomposition, and these reliable driving forces have ensured the validity of our CMCCB assessment model and the authenticity of the CMCCB values.

Although our CMCCB assessment model has provided significant findings, a shortcoming should be pointed out. As indicated in Fig. 10, three data fluctuation points in the growth trace of the annual CMCCB values can be observed; to a certain extent, this phenomenon has affected the stability of the assessment results. Section 5.1 demonstrated that only the contributions of the reciprocal of the GDP per capita of Tertiary Industry in China (g) and the CCBCE intensity (e) caused the occurrence of CMCCB in 2001–2015. After a cross analysis among the variation traces of g, e, and CMCCB in 2001–2015 (as shown in Fig. 14), we found that the obvious decrease of e led to the significant change of the CMCCB values from 2013 to 2015. Moreover, under the impact of the obvious double-decrease of g and e in 2006–2007, a fluctuation involving the annual CMCCB happened in 2007. To sum up, the annual CMCCB values may be impacted by the sharp changes of the data involving the negative driving forces of CCBCE, although the total values of CMCCB in three Five-year Plan Periods are reliable, which passes the data quality control mentioned in Section 5.3.

Universal applicability is also a key indicator to evaluate the quality of an assessment model. Through our CMCCB assessment model, the equation of CCBCE was decomposed into five driving forces, and these driving forces required just four kinds of variables at the data collection phase (i.e., carbon emissions in the commercial building sector, the GFA of existing commercial buildings, the employed population of Tertiary Industry, and the GDP of Tertiary Industry). The official data involving the Tertiary Industry are available at both the national and provincial levels in most countries and regions. Although the official process of collecting statistical data on energy consumption and carbon emissions in Chinese building sector has fallen behind considerably, the CDBECCE can provide detailed and comparable time-series data involving energy consumption, carbon emissions, and the GFAs of different kinds of civil buildings at both the provincial and national levels (CABEE, 2017). The aforementioned information demonstrates the feasibility of using the assessment model introduced in Section 3.2 for further studies assessing carbon mitigation in the commercial building sector either at the provincial level or in different building climate zones of China. Furthermore, our assessment model can be extended to analyse carbon mitigation in the commercial building sector at the global level if reliable data on energy consumption, carbon emissions, and GFA in the commercial building sector exist in different countries and regions (Berardi, 2017).

Table 5
Different assessment approaches for energy savings/carbon mitigation at the building operation phase in the Chinese building sector.

Study	Target	Scope	Time periods	Methods	Data source	Assumptions in methodology	Results
Ma et al. (2017d)	Energy savings	Civil buildings	2001–2014	IPAT, LMDI	Cai et al. (2014)	Comparable building carbon intensity	Indicated in Fig. 13
Yan et al. (2017)	Energy savings	Residential buildings	2000–2015	IPAT, IDA	Cai et al. (2014)		
Ma et al. (2017c)	Energy savings/carbon mitigation	Existing civil buildings	2001–2005, 2006–2010, 2011–2015	STIRPAT, LMDI	CABEE (2016)		
Our study	Carbon mitigation	Commercial buildings	2001–2015	Kaya, LMDI-I	CABEE (2017)	–	

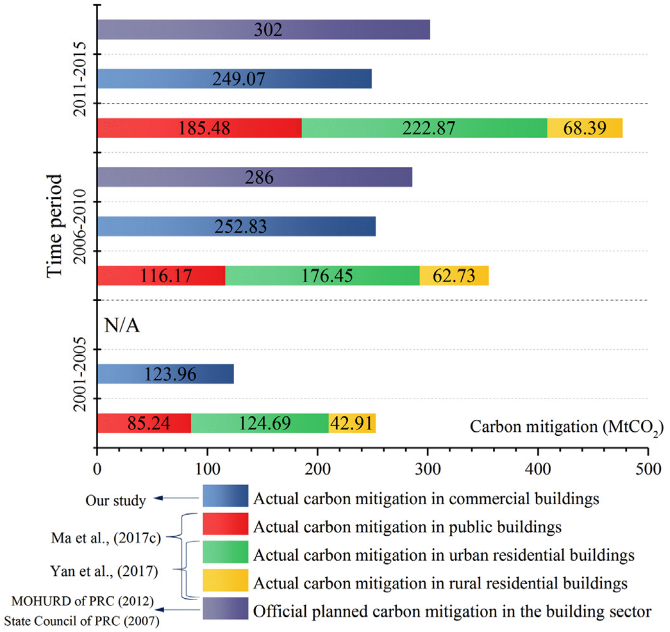


Fig. 13. Assessment results of the energy savings/carbon mitigation at the building operation phase in the Chinese building sector.

6.2. Retrospective assessment of the EEP in the Chinese commercial building sector from the mid-1990s to 2017

Figs. 10 and 11 prove that CMCCB has increased sharply in the past fifteen years, which demonstrates that the efforts of the EEP in Chinese commercial buildings got a positive and strong reply in 2001–2015. As shown in Figs. 15 and 16, through a brief retrospective look at the development of the EEP in Chinese commercial buildings on the basis of official information [e.g., MOHURD_of_PRC, 2012, 2017], we observed that the central government actively promoted the EEP in various ways and achieved substantial outcomes. Overall, we believe that the effective EEP in the commercial building sector was the root cause of the rapidly growing CMCCB during 2001–2015.

Data on carbon emissions and carbon mitigation in the building sector are the foundations for developing the EEP in the building sector of China. Although a few studies have explored carbon mitigation in China's civil and residential buildings, a reliable assessment of carbon mitigation in the commercial building sector is still missing. Thus, the central government faces the challenge of promoting the EEP in the commercial building sector without an effective indicator. At the current phase, the most effective approach for evaluating the quality of the EEP in the building sector is the performance evaluation of the energy-efficiency workloads illustrated in Fig. 16 (Kong et al., 2012; Zuo et al., 2012b). Nevertheless, the values of the decreasing building carbon intensity and the increasing carbon mitigation are the most important indicators to reflect the actual effectiveness of the energy-efficiency workloads (Lin and Liu, 2015; Liu et al., 2017a; McNeil et al., 2016). Therefore, to achieve the maximum potential for carbon mitigation, the EEP in the Chinese commercial building sector should be evaluated based on the reliable CMCCB values. This action would further encourage the central government to launch focused plans and policies for the building energy efficiency strategy in the forthcoming periods.

7. Conclusions

7.1. Main findings

We put forward a method combining the LMDI-I decomposition analysis with the Kaya identity to assess the CMCCB values during 2001–2015. After determining the CMCCB values, a comparative analysis of the actual and official expected values of CMCCB, a data quality control involving the CMCCB values, and a comprehensive evaluation about the CMCCB assessment model, respectively, were launched to identify the reliability of our CMCCB assessment model. Moreover, a retrospective discussion of the EEP in the Chinese commercial building sector was conducted to reveal the root cause of the rapidly growing CMCCB. The main findings of this study are as follows:

- CMCCB values in 2001–2005, 2006–2010, and 2011–2015 were 123.96, 252.83, and 249.07 MtCO$_2$, respectively. Through the LMDI-I decomposition analysis, only two driving forces [i.e., the reciprocal of GDP per capita of Tertiary Industry in China and the CCBCE intensity] from the Kaya identity of the CCBCE contributed negatively re_{m_i} to CCBCE during 2001–2015, and the quantified negative contributions denoted the CMCCB values for the period 2001–2015.
- The CMCCB assessment model provided reliable results and revealed its universal applicability at different regional levels. As the most significant advantage of our CMCCB assessment model, no assumption exists in the Kaya identity of the CCBCE and the process of the LMDI-

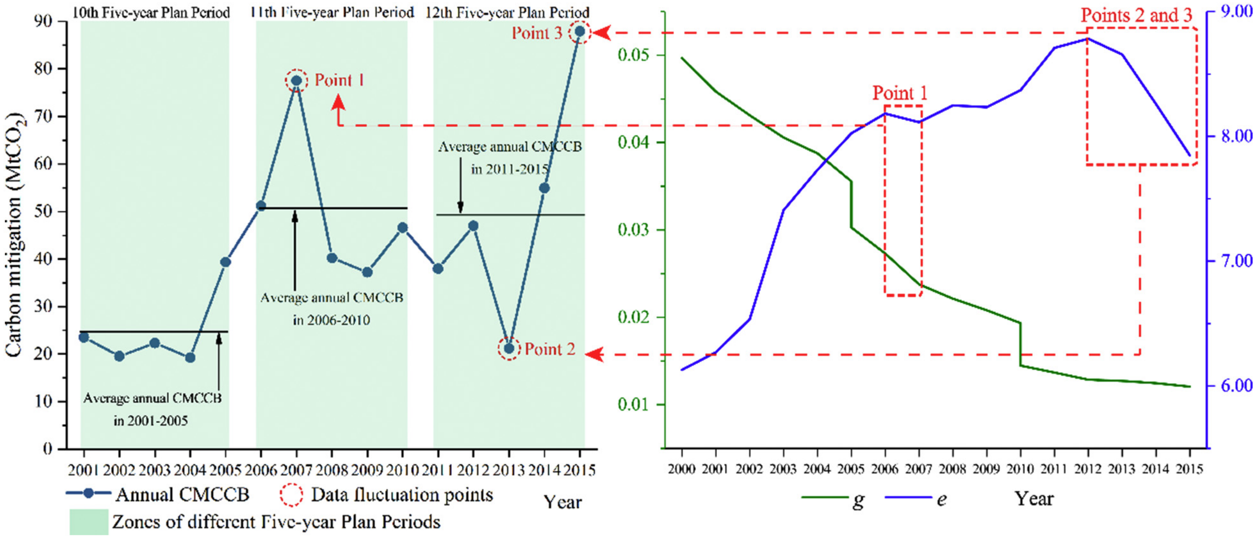


Fig. 14. Cross analysis among the variation traces of *g*, *e*, and CMCCB during 2001–2015.

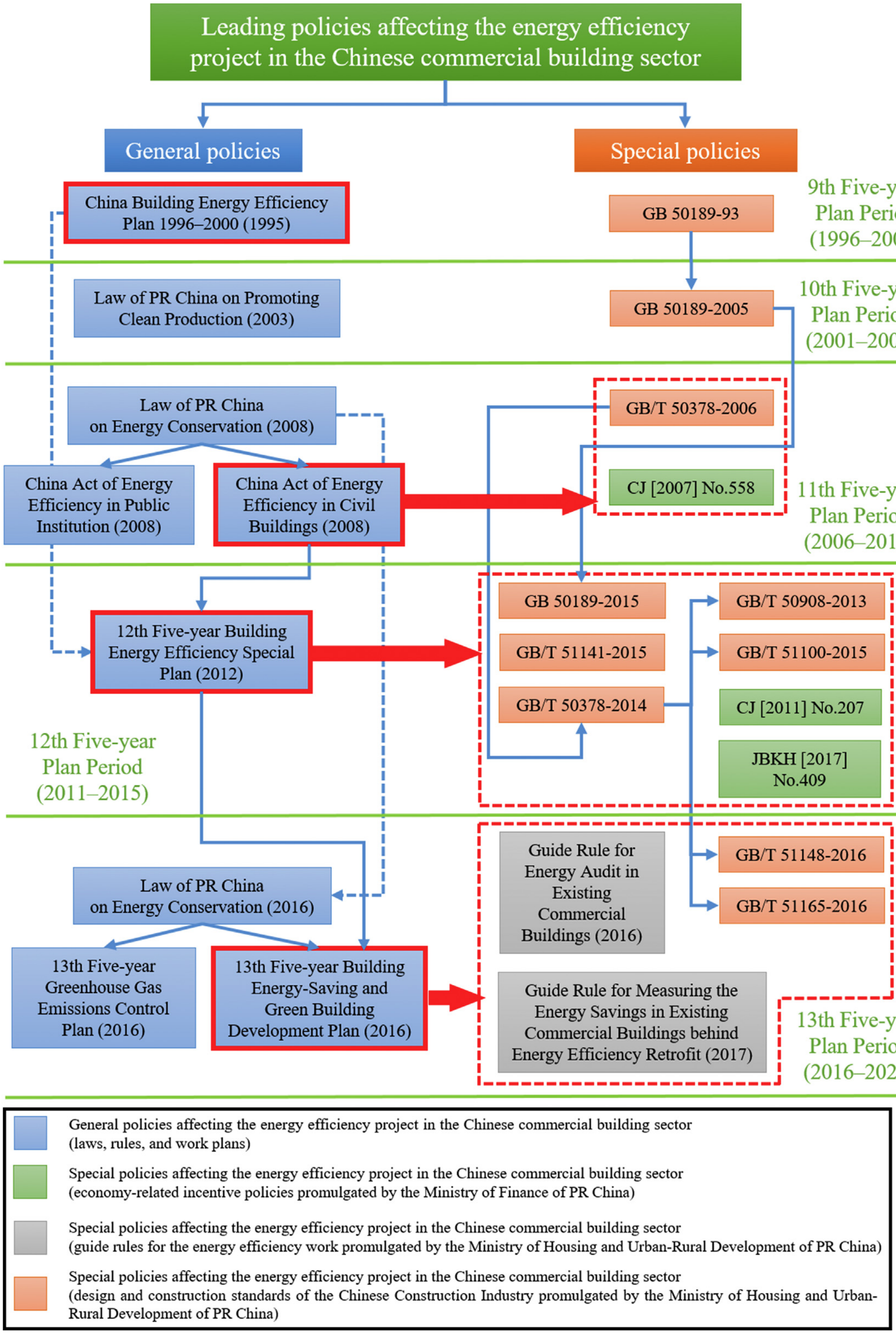


Fig. 15. Leading policies of the EEP in the Chinese commercial building sector from the mid-1990s to 2017.

I. All the five factors shown in the CCBCE equation are quantifiable through the whole process of LMDI-I decomposition, and these reliable driving factors ensured the validity of our CMCCB assessment model and the authenticity of the CMCCB values. Meanwhile, the data quality control analysis involving the CMCCB values also demonstrated that the CMCCB values from the assessment model were relatively credible and reasonable, which proved that the proposed CMCCB assessment model could be considered reliable.

- As for the universal applicability of the CMCCB assessment model, the Kaya identity of the CCBCE only required four kinds of variables at the data collection phase, and all the data were available at both the national and provincial levels by the data source of the CDBECCE and *China Statistical Yearbook of the Tertiary Industry* (CABEE, 2017; NBOS_of_PRC, 2016). Thus, the proposed CMCCB assessment model

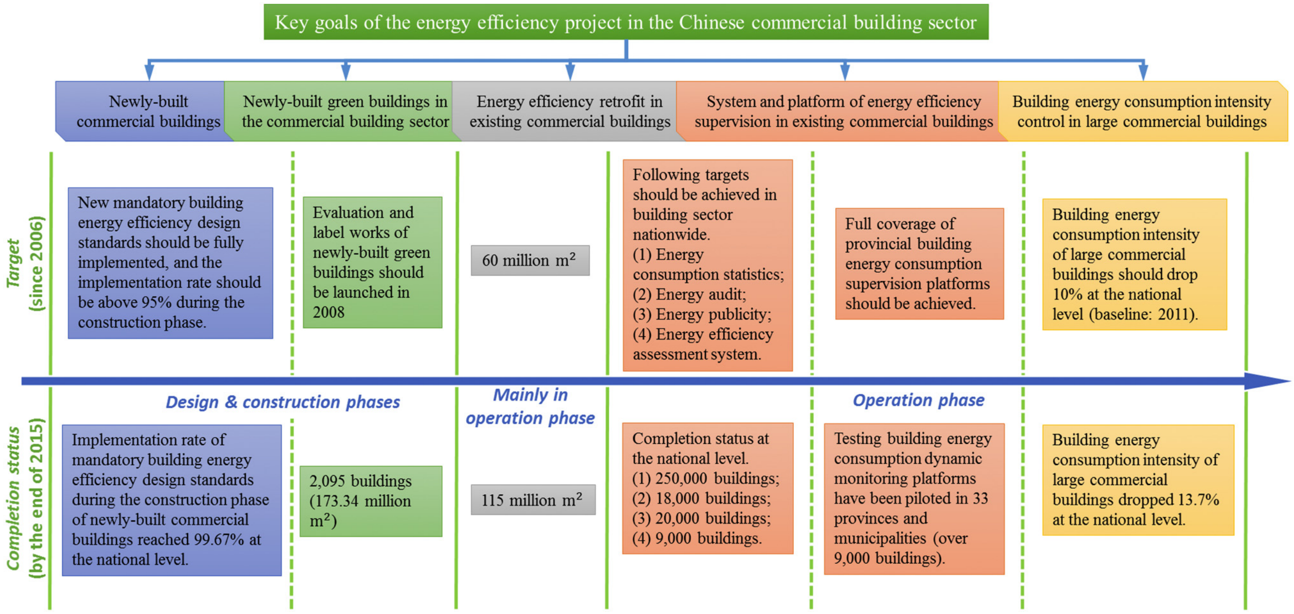


Fig. 16. Key goals of the EEP in the Chinese commercial building sector during 2006–2015.

is also suitable for exploring carbon mitigation in the commercial building sector either at the provincial level or in different building climate zones of China. Moreover, a global-level assessment of carbon mitigation in the commercial building sector based on the Kaya and LMDI approaches is feasible if reliable data involving energy consumption, carbon emissions, and GFA in the commercial building sector exist in different countries and regions.

- Substantial achievements of the EEP in the Chinese commercial building sector were the root cause of the rapidly growing CMCCB. Through a retrospective discussion of the development of the EEP in the Chinese commercial building sector, we have observed that the central government actively promoted the EEP in various ways and achieved substantial outcomes. Moreover, the comparative analysis in Section 5.2 have indicated that the actual CMCCB values were significantly higher than were the official expected values during 2001–2015. The above evidence illustrates that the efforts of the EEP in the Chinese commercial buildings got a positive and strong reply in 2001–2015, and we believe that the effective EEP in the commercial building sector was the root cause of the rapidly growing CMCCB.

7.2. Policy implications

In respect of the policy implications of the current EEP in the Chinese building sector and in view of the limit of the text length, the main policy implications of our study will focus on the official data statistical project of energy consumption and carbon emissions in the Chinese building sector. As mentioned in Section 6.2, in commercial and residential buildings alike, the decreasing building carbon intensity and increasing carbon mitigation values are the most effective indicators to reflect the actual effectiveness of the energy-efficiency workloads of the EEP in the building sector. Hence, reliable data on energy consumption and carbon emissions are the foundations for developing the EEP in the Chinese building sector. To achieve the maximum potential for carbon mitigation in the building sector, the central government should make a substantial endeavour to issue an official statistical yearbook including credible data on building energy consumption and carbon emissions at both the national and provincial levels as soon as possible. This action will go a long way toward helping the central and provincial governments issue targeted policies and special plans for the energy efficiency strategy in the Chinese building sector in the future.

7.3. Further research

Various aspects of this study should be further improved. First, as regards the study area, the current study focused on assessing the CMCCB values at the national level. In view of the influence of unbalanced affluence and development [i.e., aspects such as population and its spatial distribution, economic scale, urbanization level, volume of existing commercial buildings, the universal heating-related energy consumption of commercial buildings in northern China (Zhong et al., 2009)], and the diverse climates in China's different regions, the CCBCE status of the various regions would be significantly different. Therefore, further study is required to assess the CMCCB values at the provincial level or in different building climate zones of China based on the data source of the CDBECCE, and to analyse the CMCCB changes with the different building energy efficiency policies in these areas from a much smaller perspective.

As regards the framework of the CMCCB assessment model, the different energy consumption structures and prices relevant to the different commercial buildings in different regions obviously contribute to the CCBCE. In addition, the driving forces disregarded in the current Eq. (9) must be covered in further research to enhance the precision of the CMCCB values, after determining sensible and appropriate approaches to quantifying the detailed effects of such driving forces on the CCBCE. Overall, future research should consider appropriate approaches to overcoming the unresolved aspects mentioned above.

Acknowledgements

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Appendix A

- Civil buildings in this study, if not specified, include two sectors (i.e., commercial and residential building sectors) (McNeil et al., 2016)
- The commercial building sector in this study, if not specified, means both private commercial buildings and public buildings (Ge et al., 2017).
- Building carbon emissions in this study, if not specified, mean the carbon emissions in the operation phase of existing civil buildings (Berardi, 2017).

Appendix B

In our methodology, the Kaya identity of CCBCE is expressed as follows

$$\mathrm{CCBCE} = F \times \frac{F}{P} \times \frac{G}{F} \times \frac{1}{\frac{G}{P}} \times \frac{E}{F} \tag{B–1}$$

Meanwhile, Eq. (B–1) can be further simplified as:

$$E = F \times f \times I \times g \times e \tag{B–2}$$

Through the guidance of the LMDI-I decomposition (Ang, 2015; Ang, 2005), the CCBCE changes (i.e., ΔE_{tot}) in Eq. (B–2) during a period of T are shown below.

$$\Delta E_{tot} = E|_T - E|_0 = \Delta E_F + \Delta E_f + \Delta E_I + \Delta E_g + \Delta E_e + \Delta E_{rsd} \tag{B–3}$$

where

$$\Delta E_F = W \times \ln\left(\frac{F|_T}{F|_0}\right) \tag{B–4}$$

$$\Delta E_f = W \times \ln\left(\frac{f|_T}{f|_0}\right) = W \times \ln\left(\frac{F|_T \times P|_0}{F|_0 \times P|_T}\right) \tag{B–5}$$

$$\Delta E_I = W \times \ln\left(\frac{I|_T}{I|_0}\right) = W \times \ln\left(\frac{G|_T \times F|_0}{G|_0 \times F|_T}\right) \tag{B–6}$$

$$\Delta E_g = W \times \ln\left(\frac{g|_T}{g|_0}\right) = W \times \ln\left(\frac{P|_T \times G|_0}{P|_0 \times G|_T}\right) \tag{B–7}$$

$$\Delta E_e = W \times \ln\left(\frac{e|_T}{e|_0}\right) = W \times \ln\left(\frac{E|_T \times F|_0}{E|_0 \times F|_T}\right) \tag{B–8}$$

$$\Delta E_{rsd} = W \times \ln\left(\frac{rsd|_T}{rsd|_0}\right) \tag{B–9}$$

where W denotes the $W(E|_T, E|_0)$, expressing the log-mean of two variables (Ang, 2015), as illustrated in Eq. (B–10).

$$W(\alpha,\beta) = \begin{cases} \dfrac{\alpha - \beta}{ln\alpha - ln\beta}, & \alpha \neq \beta \ (\alpha > 0,\ \beta > 0) \\ 0 \quad , & \alpha = \beta \ (\alpha > 0,\ \beta > 0) \end{cases} \tag{B–10}$$

Furthermore, the following mathematical derivation proves that the value of ΔE_{rsd} is 0 during the LMDI-I decomposition (Ang, 2005).

$$\begin{aligned} &\because \Delta E_F + \Delta E_f + \Delta E_I + \Delta E_g + \Delta E_e \\ &= W \times \left[\ln\left(\frac{F|_T}{F|_0}\right) + \ln\left(\frac{f|_T}{f|_0}\right) + \ln\left(\frac{I|_T}{I|_0}\right) + \ln\left(\frac{g|_T}{g|_0}\right) + \ln\left(\frac{e|_T}{e|_0}\right) \right] \\ &= W \times \ln\left(\frac{F|_T}{F|_0} \times \frac{f|_T}{f|_0} \times \frac{I|_T}{I|_0} \times \frac{g|_T}{g|_0} \times \frac{e|_T}{e|_0}\right) = \frac{E|_T - E|_0}{\ln\left(\frac{E|_T}{E|_0}\right)} \times \ln\left(\frac{E|_T}{E|_0}\right) \\ &= E|_T - E|_0 = \Delta E_{tot} = \Delta E_F + \Delta E_f + \Delta E_I + \Delta E_g + \Delta E_e + \Delta E_{rsd} \\ &\therefore \Delta E_{rsd} = 0. \end{aligned}$$

To sum up, Eqs. (B–11) to (B–12) indicate the improved approach to assessing CMCCB values during a period of T based on Eq. (7).

$$\mathrm{CMCCB} = \sum |\Delta E_i|_{0 \to T}| \tag{B–11}$$

where

$$\Delta E_i|_{0 \to T} \in \{\Delta E_F, \Delta E_f, \Delta E_I, \Delta E_g, \Delta E_e\}, \text{and } \Delta E_i|_{0 \to T} < 0 \tag{B–12}$$

Appendix C

Since China is a large country with a land area of 9.6 million square kilometres and complex terrain, the climate differs considerably from the north to the south. Thus, the energy efficiency design approaches of civil buildings in different regions of China are very different. To clarify the scientific relationship between building and climate, China issued the national standard (i.e., Code for Design of Civil Buildings, GB 50352-2005) in 2005 (MOHURD_of_PRC, 2005), which officially divided China into five main building climate zones and twenty sub building climate zones. In different divisions of China Building Climate Zones, the central government put forward different requirements for the energy efficiency design of civil buildings. Fig. C-1 illustrates the schematic of China Building Climate Zones.

Appendix D**Brief introduction to** *China Database of Building Energy Consumption and Carbon Emissions* **(CDBECCE) and** *Chinese Building Energy Consumption Report*

The official process of collecting statistical data on building energy consumption in China has fallen behind significantly, as building energy consumption data have been not considered independently in the data statistical system of energy consumption in China. Thus, official data of building energy consumption in China are still lacking. Meanwhile, the values of different estimation approaches involving the energy consumption in the Chinese building sector are very different (ranging from constituting 15–50% of the nationwide energy consumption in China). In this case, the *Special Committee of Building Energy Consumption Statistics*, which was established by the *China Association of Building Energy Efficiency* (CABEE—a separate division belongs to Ministry of Housing and Urban-Rural Development of PR China), has, since 2016, launched special studies involving energy consumption and carbon emissions in the Chinese building sector. The studies have the technological support of Chongqing University (CQU, PR China) and Lawrence Berkeley National Laboratory (LBNL, USA).

As one of the leading achievements of CABEE, the up-bottom-type building energy consumption statistical model named the *China Database of Building Energy Consumption and Carbon Emissions* (CDBECCE), which was established on the basis of data mining tools and processing methods involving building energy consumption, provided detailed Chinese building energy consumption data at both the national and provincial levels during the period of 2000–2015; this database also provided a series of statistical indexes involving the Chinese building sector (e.g., GFAs of different types of civil buildings and policy

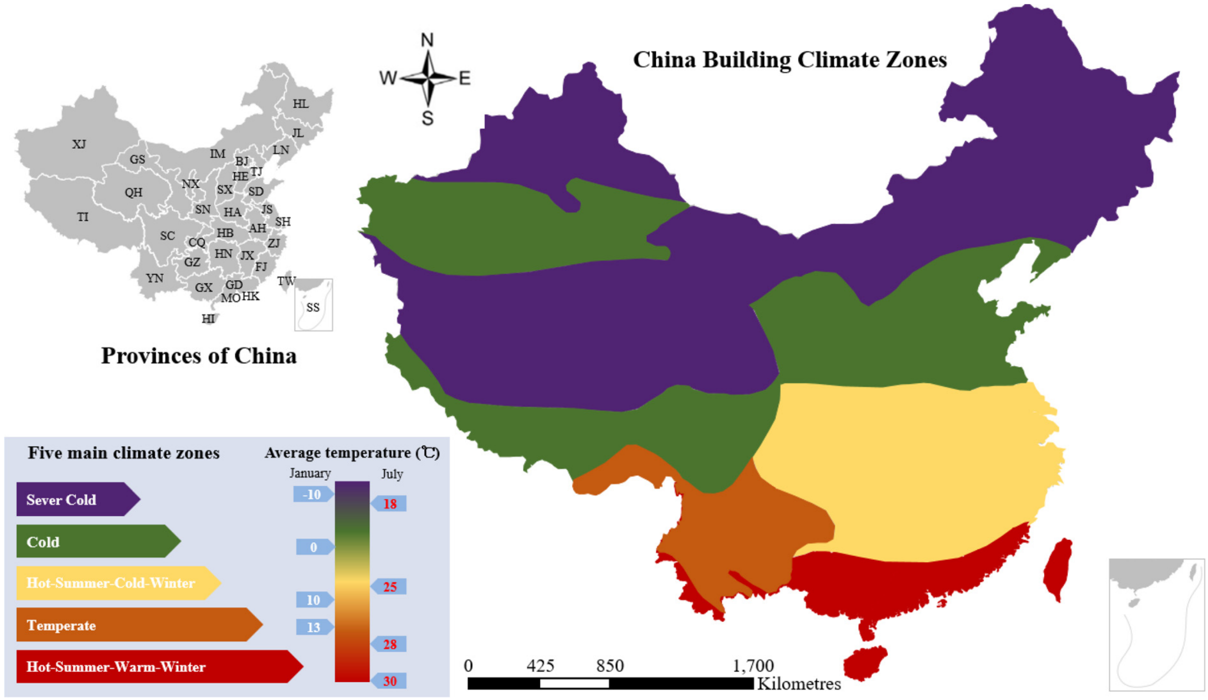

Fig. C-1. Schematic of China Building Climate Zones.

implementation involving the building energy efficiency project). Specifically, CDBECCE indicated a national building energy consumption value of 857 Mtce in 2015, which accounted for 19.89% of the nationwide energy consumption in China during the same period.

Furthermore, CABEE has published an annual research report (i.e., *Chinese Building Energy Consumption Report*) based on the data source of CDBECCE since 2016. The official e-print of the *Chinese Building Energy Consumption Report (2017)* will be online in June 2018.

- For more information, please either contact the project leader (Dr. Weiguang Cai, the corresponding author of this paper) of CDBECCE and the *Chinese Building Energy Consumption Report* or access the following URLs.

Dr. Weiguang Cai, Email: cquwgcai@gmail.com; wgcai@cqu.edu.cn
Homepage: http://www.cmre.cqu.edu.cn/info/1145/3629.htm
Secretary General, Special Committee of Building Energy Consumption Statistics, China Association of Building Energy Efficiency, Beijing, 100835, PR China

- China Database of Building Energy Consumption and Carbon Emissions (CDBECCE)

http://www.cabee.org/site/term/63.html
https://doi.org/10.1016/j.jclepro.2018.02.283 (CDBECCE prototype)

- Chinese Building Energy Consumption Report (2017)

http://mp.weixin.qq.com/s/YHw8cOpDvqJXWqYpDdttDA (e-print version)
http://china.cnr.cn/gdgg/20171101/t20171101_524008893.shtml?from=singlemessage&isappinstalled=0

- Chinese Building Energy Consumption Report (2016)

http://www.efchina.org/Reports-zh/report-20170710-1-zh (official e-print version)
http://www.cabee.org/site/content/22542.html

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