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How to Measure Carbon Emission Reduction in China's Public Building Sector: Retrospective Decomposition Analysis Based on STIRPAT Model in 2000–2015

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Abstract: Productive building energy efficiency (BEE) work is an approved factor in the progress of sustainable urbanization in China, with the assessment of carbon emission reduction in China's public buildings (CERCPB) being an essential element of this endeavor. Nevertheless, such evaluation has been hampered by inadequate and inefficient approaches; this is the first study to utilize the Logarithmic Mean Divisia Index Type I (LMDI-I) to decompose the equation of China's public building carbon emissions (CPBCE) with the connected driving factors (population in China, floor areas of China's existing public buildings, building service level index of China's existing public buildings, and the comparable CPBCE intensity), and this equation was established by the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model. The LMDI and STIRPAT approaches subsequently assessed the CERCPB values from 2001 to 2015. The results indicated that: (1) Only the contribution of the comparable CPBCE intensity to CPBCE was negative during 2001–2015; this represents the CERCPB value for the period. (2) The assessment results indicated that CERCPB has accumulated considerably with the swift progress of BEE work in China in 2001–2015. The CERCPB values in 2001–2005, 2006–2010, and 2011–2015 were 69.29, 158.53, and 277.86 million tons of carbon dioxide, respectively. (3) This study demonstrated that the positive effect of implementing public BEE work in China had led to significant results in 2001–2015, which can be regarded as a prerequisite for producing the considerable accumulation of CERCPB over this period. Overall, this study illustrated the feasibility of employing the LMDI and STIRPAT approaches for assessing the CERCPB value. Accordingly, we believe the results of this study are a significant driving force in the next phase of the development of the carbon emission control strategy of public buildings and sustainable urbanization in China.

Keywords: sustainable urbanization; carbon emission reduction; China's public building carbon emissions; LMDI-I decomposition analysis; STIRPAT model

1. Introduction

Worldwide, the building sector is considered to be a major contributor to global carbon emissions, requiring and consuming vast amounts of energy [1–3]. Fruitful building energy efficiency (BEE) work is a prerequisite for establishing sustainable urbanization. China has become the world's main producer of carbon emissions, with the building sector of the country producing the second most carbon emissions nationwide. Accordingly, the BEE work in China is being confronted by important challenges [1,4]. As a typical part of building carbon emissions (BCE), China's public building carbon emissions (CPBCE) accounted for approximately 40% of the BCE in China in 2015 [5–8]. Several studies have forecasted that CPBCE would exceed 1,200 million tons of carbon dioxide ($MtCO_2$) by the 2030s if the Chinese government failed to immediately implement a carbon emission control strategy (CECS) relevant to public buildings [2,9–11]. Obviously, this would increase CPBCE significantly and hamper the progress of sustainable urbanization in China [2,3,12,13]. As the potential for carbon emission reduction (CER) in public buildings in China is greater than in residential buildings, the CECS relevant to buildings must be adopted nationwide by the public building sector [14]. This implies that the carbon emission reduction in China's public buildings (CERCPB) must be assessed to ensure that the public buildings' CECS is being implemented [8].

The authoritative quantification of CPBCE in China has fallen behind substantially, thereby severely influencing the assessment of CERCPB, as such quantification requires dependable and specific CPBCE data. In the statistics system of China relevant to carbon emissions, BCE has been allocated to an autonomous carbon emissions department, but the carbon emission data are dispersed in various social divisions [6,8]. Consequently, at present, authoritative BCE data are still lacking. However, since 2007, sustainable and comparatively systematic calculation models have been established by several researchers in China to compensate for the lack of BCE data (as shown in Figure 1). Tsinghua University constructed the China Building Energy Model (CBEM) in 2007 [15]. This was the first bottom-up-type model in China to evaluate BCE data nationwide, indicating a BCE value of 2246.40 $MtCO_2$, accounting for 20.00% of the total national carbon emissions (TNCE) in 2015. The CPBCE (excluding the heating-related BCE in northern China) amounted to 676 $MtCO_2$, accounting for 30.09% of the BCE [7]. Chongqing University established the China Macroscopic Building Energy Consumption Statistical System (CMBECSS) in 2010 [16]. The original data sources of the CMBECSS were the energy balance sheets of the China Energy Statistical Yearbook. As a typical bottom-up-type model to evaluate the BCE data nationwide, this system estimated the BCE in China for the period 1985–2009 effectively [2]. The updated data of the second-generation system (i.e., CMBECSS Ver. 2.0) indicated a BCE value of 2,233.40 $MtCO_2$, which accounted for 19.98% of the TNCE in 2015 in China. Furthermore, the CPBCE amounted to 863.2 $MtCO_2$, accounting for 38.65% of the BCE in China [5,6,10,17].

Currently, studies on the effective assessment of CERCPB are inadequate, owing to the lack of authoritative CPBCE data. Nevertheless, several relevant published studies have presented feasible methods of assessing the CER in the existing civil building sector of China. These include derivative versions of the Human Impact, Population, Affluence, and Technology (IPAT) equation and index decomposition analysis (IDA), such as the Logarithmic Mean Divisia Index (LMDI), based on the BCE data from the CMBECSS database. With the extended version of the IPAT equation, Ma et al. [2] proposed the concept of comparable BCE intensity and, thereto established an equation. This equation involves the BCE of China and several of its driving factors to calculate the CER in existing buildings nationally by employing LMDI decomposition analysis for the period from 2001 to 2014. Subsequently, the CMBECSS Ver. 2.0 published a series of updated BCE data for China [17]. Ma et al. [5] applied the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model and the additive mode of the LMDI Type I (LMDI-I) method to present an improved calculation model and to further explore the mechanism of the CER in existing civil buildings during 2001 to 2015. Relevant to the residential building sector level, Yan et al. [10] utilized the IPAT equation and performed LMDI decomposition analysis to estimate the CER in existing residential buildings in China for the period 2001 to 2015.

Two comparatively credible and mature estimation approaches to CPBCE data and several similar methods to calculate the CER in existing civil buildings were introduced by the literature review. In comparison with CBEM, the data issued in the CMBECSS are comparatively credible, as this systematic estimation approach provides sustainable, complete, and comparable time-series data involving CPBCE, which is an essential requirement for assessing CERCPB in 2001–2015. Moreover, these BCE data have been accepted widely by various other studies [2,5,6,10,17–20]. Furthermore, the

IPAT equation, including its derivative versions (e.g., the STIRPAT model) and LMDI decomposition analysis are appropriate for identifying and evaluating the different effects on the factors that affect carbon emissions in specific industries [20–24]. As CPBCE is typical of carbon emissions, the methods discussed above can be employed also to assess the CER in the public building sector [6,21].

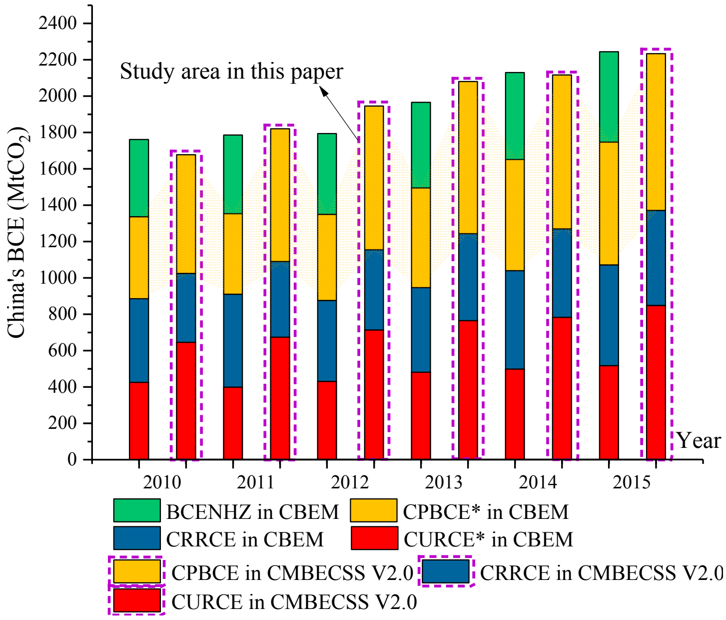

Figure 1. Building carbon emissions (BCE) data comparison between China Building Energy Model (CBEM) and China Macroscopic Building Energy Consumption Statistical System (CMBECSS) Ver. 2.0 in 2010–2015. CPBCE: China's public building carbon emissions; CPBCE*: CPBCE (excluding the heating-related BCE in northern China); BCENHZ: Heating-related BCE in northern China; CURCE: China's urban residential carbon emissions; CRRCE: China's rural residential carbon emissions; CURCE*: CURCE (excluding the heating-related BCE in northern China); CRRCE*: CRRCE (excluding the heating-related BCE in northern China).

Although several studies have assessed and evaluated effectively the CER in the existing civil and residential buildings, the CERCPB assessment approach remains inadequate because believable and mature data involving CPBCE published by CMBECSS prototype are not available, which further influences the establishment of driving factors affecting CPBCE for assessing the value of CERCPB. Namely, the research gap in this study means that the studies mentioned above have pointed out that research on the individual appraisal of CERCPB could be inadequate, indicating that formulating an effective approach to evaluating CERCPB is a crucial task. In order to support the Chinese government in drafting and applying focused policies and targets for enhancing the CECS of public buildings, CERCPB would need to be assessed quantitatively based on specific CPBCE data. Moreover, the progress of BEE work and sustainable urbanization in China would be supported and promoted by such work. Accordingly, conducting further analysis based on CERCPB assessment results is an important and urgent task.

With respect to the overall contribution and innovation of this study, and in view of the inadequacy of other studies on the effective assessment of CERCPB, the aim of this study is to set up an efficient approach to bridging the research gap relevant to effective CERCPB assessment. This study established the CPBCE equation, considering connected driving factors (i.e., population in China, floor areas of China's existing public buildings, building service level index of China's existing public buildings, and the comparable CPBCE intensity) based on the STIRPAT model and through the CPBCE data referenced by the database of CMBECSS Ver. 2.0, thereinto the new driving factor (the comparable

CPBCE intensity) which reflects the actual BEE benefit was highlighted for the assessment of the value of CERCPB. An IDA (i.e., LMDI-I decomposition analysis) was performed afterwards to further explore the distinct effects on these driving factors that affect the CPBCE and to appraise the values of the negative contributions of such driving factors (i.e., CERCPB values) over the past fifteen years (2001–2015). Furthermore, an overview of the public BEE work in China from the late 1990s to 2015 is included to demonstrate the internal cause of the considerable accumulation of CERCPB for the period 2001–2015.

The rest of this study is prepared as shown below. Section 2 reveals the theories of the LMDI and STIRPAT approaches; the method to assess CERCPB is then introduced in the same section. Section 3 guides the sources of data. Section 4 indicates and deeply analyzes the outcomes of LMDI-I decomposition analysis, especially the values of CERCPB from 2001 to 2015. Section 5 discusses the development of China's public BEE work from the late 1990s to 2015, and points out a shortcoming in this study. The conclusions and implications involving energy policies are presented in Section 6.

2. Methodology

2.1. STIRPAT Model and LMDI-I Decomposition Analysis

The STIRPAT model determines the different contributions of three types of driving factors (i.e., population level, P, affluence level, A, and technology level, T) that affect natural or man-made environmental pressures (I) [25]. Furthermore, the STIRPAT model is essentially a revised version of the IPAT model established in the 1970s [26], as indicated in Equations (1) and (2).

$$I = P\ A\ T \tag{1}$$

$$I = \alpha P^b A^c T^d \varepsilon \tag{2}$$

In this case, α and ε represent the model coefficient and the random error of the STIRPAT model, respectively; b, c, and d are the exponentials of P, A, and T, respectively. Numerous studies have been conducted involving the application and development of the STIRPAT model in the fields of energy, environment, sustainability development, etc. [5,23,27,28].

The LMDI-I decomposition analysis is a classic LMDI method, of which Ang and Choi [29] designed the prototype, based on the Divisia index method (i.e., a classic type of IDA). The LMDI is a well-known form of IDA. Compared with other decomposition analysis such as structure decomposition analysis (SDA), LMDI employs a simple decomposition process without too many constraint conditions, and produces effective outputs without any residual values [30–32]. Through the LMDI decomposition analysis, an explained variable is decomposed into a group of driving factors. Subsequently, analysis can be conducted on the contribution of the factors at a quantitative level, and the key driving factors can be marked for further exploration [5,33–36]. Equation (3) indicates the general framework of the LMDI-I decomposition analysis in the additive mode.

$$\Delta V_{x_i} = L(V|_T, V|_0) \times ln\left(\frac{x_i|_T}{x_i|_0}\right) \quad (i = 1, 2, 3, \ldots, n) \tag{3}$$

Note: x_i—The explanatory variable x_i; $x_i|_T$—The value of x_i in reporting period; $x_i|_0$—The value of x_i in baseline period; V—The explained variable V; $V_i|_T$—The value of V in reporting period; $V_i|_0$—The value of V in baseline period; ΔV_{x_i}—The contribution of x_i to V.

In addition, LMDI is an effective approach for the identification of the leading driving factors that affect carbon emissions in different industries [10,37,38].

2.2. Assessment Approach of CERCPB

CERCPB is definable as the CER relevant to the operational phase of existing public buildings in China, related to several driving factors (e.g., development of policies, advancement of technologies, user behavior in public buildings, etc.) [2]. Given that the growth of CPBCE is being maintained at the current stage, CERCPB could be regarded essentially as the negative contributions of the mentioned driving factors that restrict the rapid growth of CPBCE [17].

As indicated in Figure 2, the CPBCE intensity (i.e., CPBCE per floor area) is affected by the public building energy efficiency level and the public building service level [6,16,39], which increases annually because of the comprehensive influence of the two driving factors. As mentioned in the Introduction, various studies have assessed the CER in existing civil buildings through the comparable BCE intensity. For instance, Ma et al. [2] have developed an effective approach to assessing the CER in existing civil buildings. In their approach, the building service level (established by Cai, Ren, and Cao [16] at the national level) was assumed constant from a baseline period to a reporting period, and the comparable BCE intensity—which was calculated based on the constant building service level and the building energy efficiency level—was regarded as the key to further quantifying the CER in existing civil buildings. This approach is also suitable for assessing the value of CERCPB, as the public building sector is considered a typical example of the civil building sector. Figure 3 indicates the variation trend of the comparable CPBCE intensity under the influence of the constant public building service level and the public building energy efficiency level.

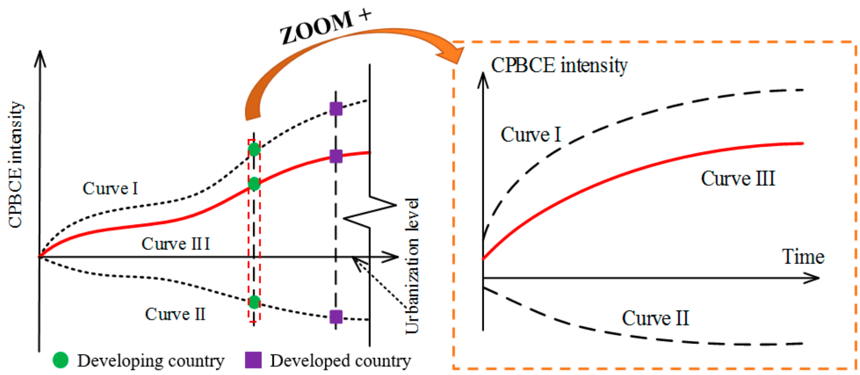

Figure 2. Schematic of the CPBCE intensity (Curve III) with the public building service level (Curve I) and the public building energy efficiency level (Curve II).

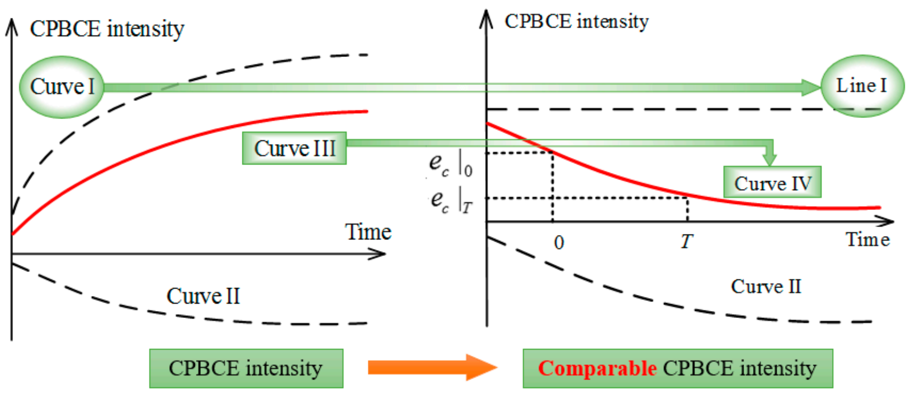

Figure 3. Schematic of the comparable CPBCE intensity (Curve IV) with the constant public building service level (Line I) and the public building energy efficiency level (Curve II).

Figure 3 indicates an intuitive approach to assessing CERCPB, as shown in Equation (4).

$$\text{CERCPB}|_{0\to T} = \Delta e_c|_{0\to T} \times F|_T = -(e_c|_T - e_c|_0) \times F|_T \quad (4)$$

where $F|_T$ is the floor area of China's existing public buildings for the reporting period; $e_c|_0$ and $e_c|_T$ denote the values of the comparable CPBCE intensity for the baseline and reporting periods, respectively. As e_c is an unquantifiable variable at the current phase, assessing the CERCPB directly by using Equation (4) is difficult. Therefore, the mechanism of e_c should be analyzed further. It reflects the changes of the CPBCE intensity of the actual public building energy efficiency level, which is calculated based on the building service level index of China's existing public buildings (I_s) at an invariant level. The varying value of the building service level of existing public buildings during a time period in China is indicted by I_s. This study presents an equation for e, e_c, and I_s, as shown in Equation (5).

$$e = e_c \times I_s \tag{5}$$

$$I_s = \varphi \times I_p \tag{6}$$

As expressed in Equation (6), a mathematical process was employed, namely, a variable coefficient (i.e., φ, $\varphi > 0$) exists between I_s and the CPBCE per capita index (I_p) at different times, because I_s is too abstract to evaluate at a quantitative level. Furthermore, I_p has different values in the baseline and reporting periods compared with I_s. The basis of the assumption about Equation (6) is that I_p largely reflects the changes in I_s, and they have the same trends of change. I_p is a reflection of the changing trends of CPBCE per capita in different periods, which is represented by a ratio of CPBCE per capita in the reporting period to CPBCE per capita in the baseline period, as indicated in Equation (7). Equation (7) shows the relationship between $I_p|_0$ (I_p in the baseline period) and $I_p|_T$ (I_p in the reporting period). In this instance, E represents CPBCE and P is the population of China. In this case, $I_p|_0 = 1$ and $I_p|_T = \frac{E|_T \times P|_0}{E|_0 \times P|_T}$. Given that the rate of changes in I_s and I_p is not exactly the same, the value of φ may differ in different years. Considering the feasibility of LMDI-I decomposition analysis at the upcoming phase, this study assumed that the φ is a constant from the baseline period to the reporting period (i.e., within one year) [2], as indicated in Figure 4.

$$I_p|_T = I_p|_0 \times \frac{e|_T}{e|_0} = I_p|_0 \times \frac{E|_T / P|_T}{E|_0 / P|_0} = 1 \times \frac{E|_T \times P|_0}{E|_0 \times P|_T} \tag{7}$$

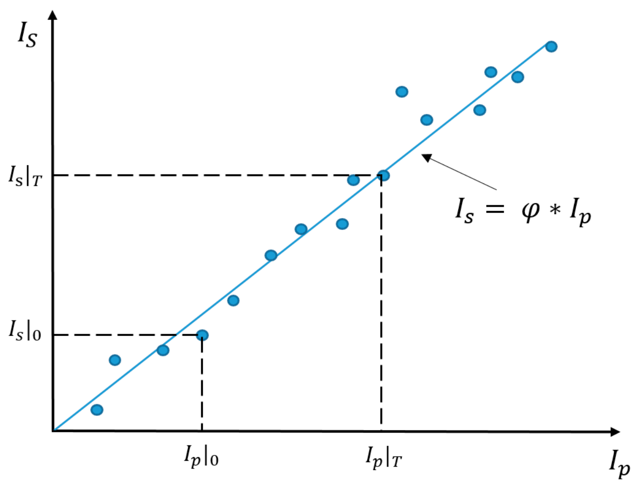

Figure 4. The relationship between I_s and I_p.

As the values of φ at different times are unquantifiable, e_c cannot be quantified in the same period. Through further analysis, an effective CERCPB assessment method was developed that combines the STIRPAT model and LMDI-I decomposition analysis.

$$E = P \times F \times I_s \times e_c \quad (8)$$

As indicated in Equation (8), a STIRPAT-model-based equation of CPBCE was established by obtaining the sum of several driving factors that affect CPBCE. Considering the feasibility of LMDI-I decomposition analysis at the upcoming phase, this study utilized the STIRPAT prototype introduced in Section 2.1. Subsequently, the LMDI-I decomposition analysis was applied to the driving factors of CPBCE in Equation (8). During a period, E changed from $E|_0$ to $E|_T$, and the incremental quantity (i.e., ΔE_{tot}) could be defined as the aggregate of the contributions of the mentioned driving factors that affect CPBCE, as shown in Equation (9). Table 1 indicates the detailed decomposition process and results.

Table 1. Core equations of the carbon emission reduction in China's public buildings (CERCPB) assessment model. LMDI-I: Logarithmic Mean Divisia Index Type I.

CPBCE Decomposition Analysis			
	ΔE_{tot}	$E\|_T - E\|_0 = \Delta E_P + \Delta E_F + \Delta E_{I_s} + \Delta E_{e_c}$	(9)
Method (Additive mode of LMDI-I) Sources: Ang [33], Ang [40]	ΔE_P	$L(E\|_T, E\|_0) \times ln\left(\frac{P\|_T}{P\|_0}\right)$	(10)
	ΔE_F	$L(E\|_T, E\|_0) \times ln\left(\frac{F\|_T}{F\|_0}\right)$	(11)
	ΔE_{I_s}	$L(E\|_T, E\|_0) \times ln\left(\frac{I_s\|_T}{I_s\|_0}\right) = L(E\|_T, E\|_0) \times ln\left(\frac{I_p\|_T}{I_p\|_0}\right)$	(12)
	ΔE_{e_c}	$L(E\|_T, E\|_0) \times ln\left(\frac{e_c\|_T}{e_c\|_0}\right) = L(E\|_T, E\|_0) \times \ln\left(\frac{e\|_T \times I_p\|_0}{e\|_0 \times I_p\|_T}\right)$	(13)
Result	CERCPB	$\sum \| \Delta E_i\|_{0\to T}\| (\Delta E_i\|_{0\to T} \in \{\Delta E_P, \Delta E_F, \Delta E_{I_s}, \Delta E_{e_c}\}, \Delta E_i\|_{0\to T} < 0)$	(14)

Note: (a) Equation (12): $\Delta E_{I_s} = L(E|_T, E|_0) \times ln\left(\frac{I_s|_T}{I_s|_0}\right) = L(E|_T, E|_0) \times ln\left(\frac{\varphi \times I_p|_T}{\varphi \times I_p|_0}\right) = L(E|_T, E|_0) \times ln\left(\frac{I_p|_T}{I_p|_0}\right)$; (b) Equation (13): $\Delta E_{e_c} = L(E|_T, E|_0) \times ln\left(\frac{e_c|_T}{e_c|_0}\right) = L(E|_T, E|_0) \times ln\left(\frac{e|_T \times I_s|_0}{e|_0 \times I_s|_T}\right) = L(E|_T, E|_0) \times ln\left(\frac{e|_T \times \varphi \times I_p|_0}{e|_0 \times \varphi \times I_p|_T}\right) = L(E|_T, E|_0) \times ln\left(\frac{e|_T \times I_p|_0}{e|_0 \times I_p|_T}\right)$; (c) Sources of the prototype model: Ma et al. [2], Cai et al. [16], Cai et al. [41].

In order to improve the understanding of the methodology, a fundamental framework of the CERCPB assessment model is shown in Figure 5. Furthermore, the definitions of leading variables in the CERCPB assessment model are presented in Table 2.

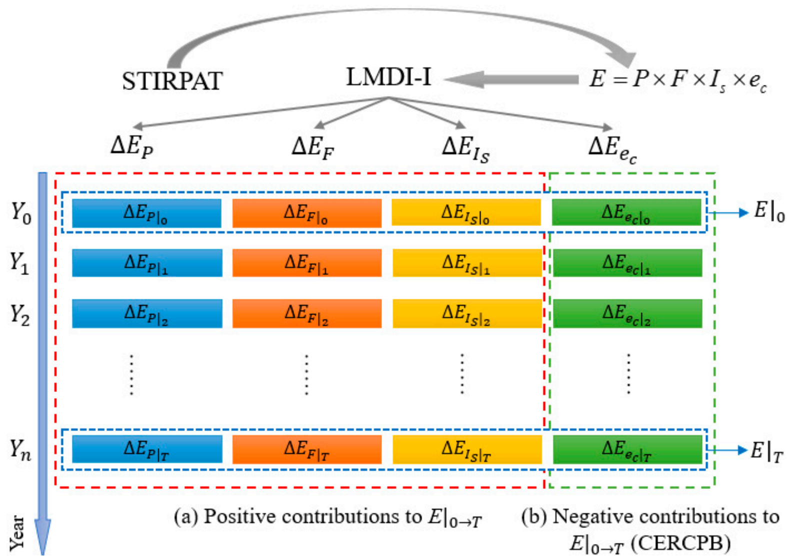

Figure 5. Fundamental framework of CERCPB assessment model. STIRPAT: Stochastic Impacts by Regression on Population, Affluence, and Technology model.

Table 2. Definitions of leading variables.

Nomenclature	Variable	Unit
E	CPBCE	$MtCO_2$
P	Population in China	10^7 persons
F	Floor areas of China's existing public buildings	10^8 m^2
I_s	Building service level index of China's existing public buildings	-
I_p	CPBCE per capita index	-
φ	A variable coefficient	-
e	CPBCE intensity	kg CO_2/m^2
e_c	Comparable CPBCE intensity	kg CO_2/m^2
ΔE_{tot}	The varying value of E during a period	$MtCO_2$
ΔE_P	The contribution of P affecting E	$MtCO_2$
ΔE_F	The contribution of F affecting E	$MtCO_2$
ΔE_{I_s}	The contribution of I_s affecting E	$MtCO_2$
ΔE_{e_c}	The contribution of e_c affecting E	$MtCO_2$

3. Data Sources

Considering that CPBCE's statistics system is still an uncompleted task, official data involving CPBCE are unavailable. Therefore, this study utilized the data from CABEE [17] (i.e., CMBECSS Ver. 2.0) which has been widely accepted by a variety of existing works [2,5,6,10,17–20]. Moreover, the data sources of P and F were accessed from the China Statistical Yearbook. These data are demonstrated in Figures 6 and 7 (the raw data list is indicated in Table A1 of Appendix A).

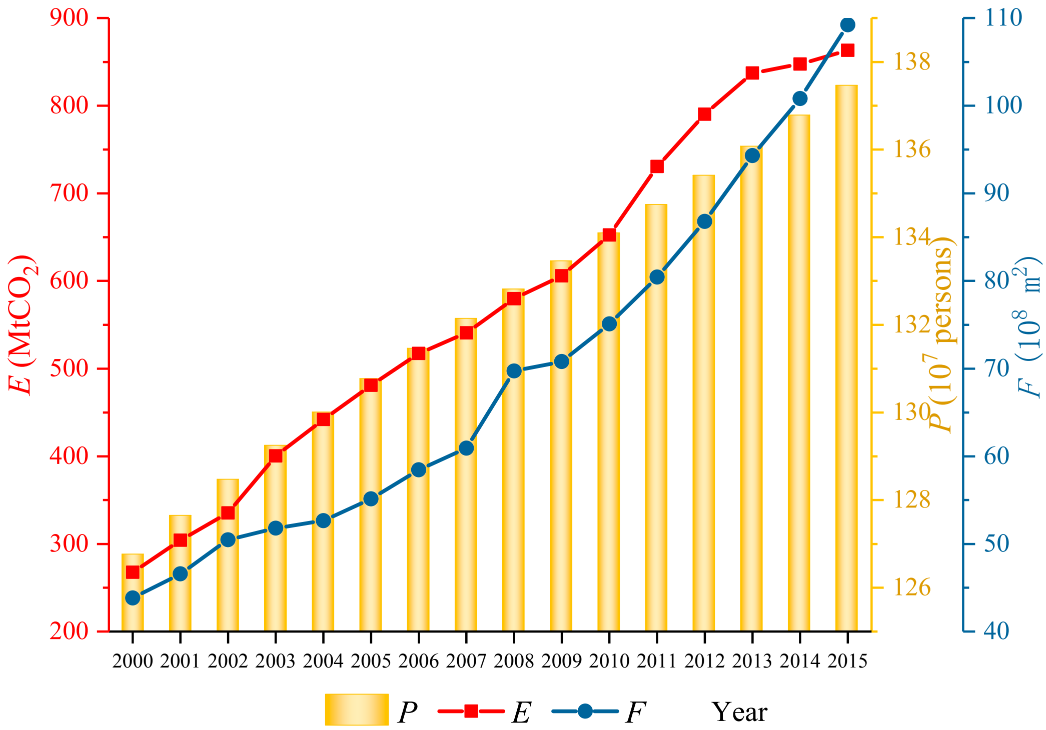

Figure 6. Growth trends of CPBCE (E), floor areas of China's existing public buildings (F), and population in China (P) in 2000–2015.

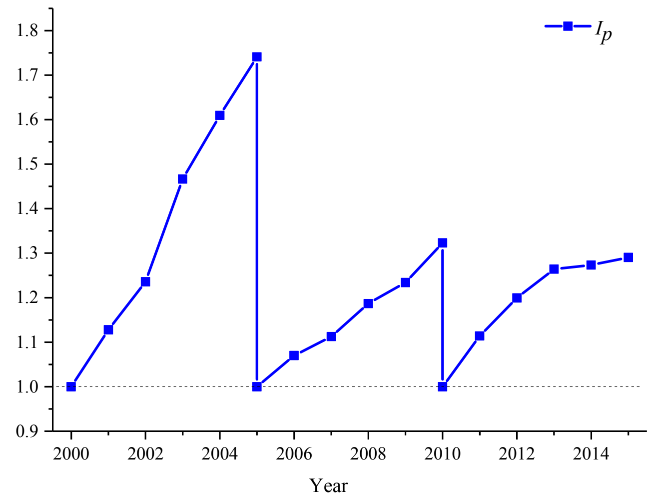

Figure 7. Variation trend of CPBCE per capita index (I_p) in 2000−2015.

4. Results

4.1. Decomposition Results of CPBCE and Values of CERCPB in 2001–2015

Through the detailed calculation, the outputs of the LMDI-I decomposition analysis are reflected in Figure 8 (the detailed decomposition results are indicated in Table A2 of Appendix A). The results demonstrate that only ΔE_{e_c} satisfies the requirement of Equation (14) (i.e., less than 0 in 2001–2005, 2006–2010, and 2011–2015), which reflects that only the contribution of e_c to CPBCE was significantly negative during the period 2001–2015.

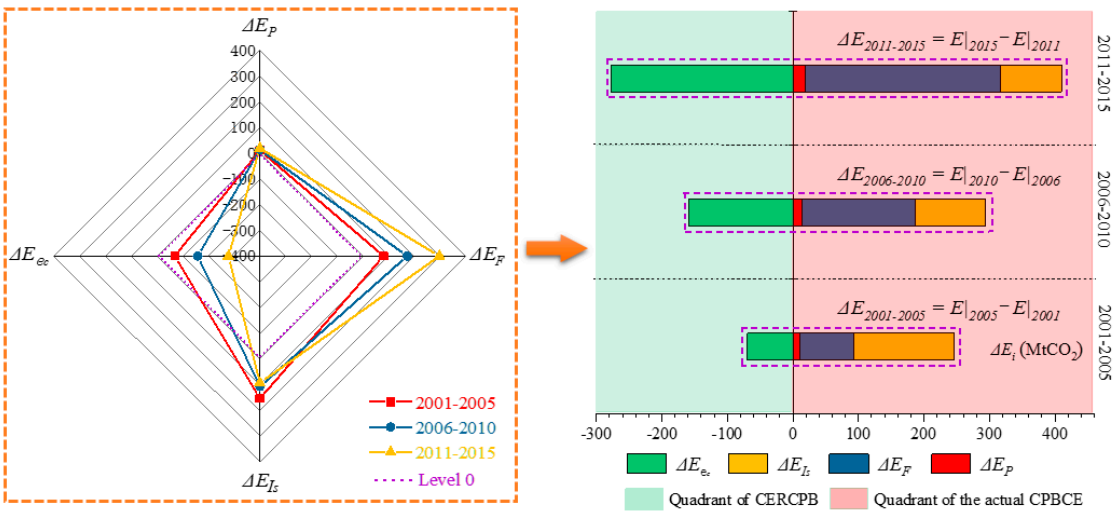

Figure 8. Decomposition results of CPBCE in 2001-2015.

Therefore, $|\Delta E_{e_c}|$ indicates the value of CERCPB for the above-mentioned period. Figure 9 shows the results of CERCPB from 2001 to 2015. The CERCPB values in 2001–2005, 2006–2010, and 2011–2015 were 69.29, 158.53, and 277.86 $MtCO_2$, respectively. In Figure 9, a fluctuation in the growth trend of CERCPB should be observed. This partly affected the stability of the assessment results.

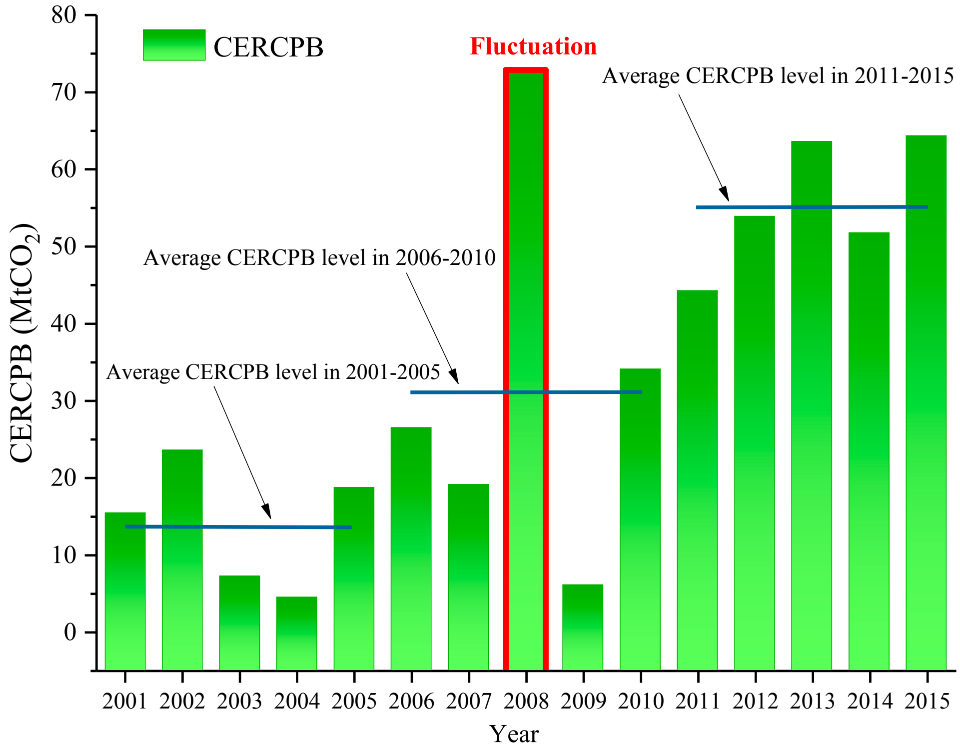

Figure 9. Assessment results of CERCPB in 2001–2015.

4.2. Comparison Analysis between Actual CERCPB and Official Planned CERCPB

The Chinese government had implemented effective measures to assess CER nationwide since 2007 [42]. The official planned values of CERCPB in the periods 2006–2010 and 2011–2015 were approximately 109.38 and 120.19 $MtCO_2$, respectively [42,43]. Figure 10 indicates that the actual values of CERCPB calculated by LMDI-I decomposition analysis were higher than the official planned values during these two periods. It should be noted that the comparison analysis between the actual and official planned values of CERCPB from 2001 to 2005 could not be completed, as no detailed plans for CER at the national level had been established by the Chinese government for this period. Generally, the comparison analysis showed that CER work in the public building sector was accomplished successfully, based on the initiatives of the Chinese government for the period 2001–2015. This implies that the public BEE work was implemented with favorable effect during 2001–2015.

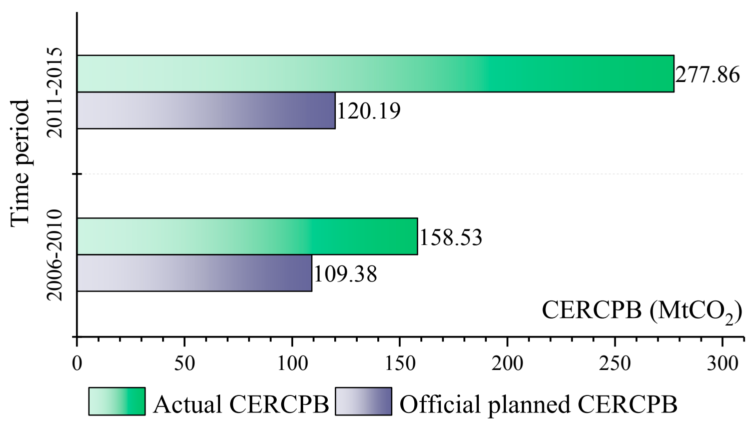

Figure 10. Actual and official planned values involving CERCPB in 2001–2015.

5. Discussion

5.1. Overview of China's Public BEE Work from theLate 1990s to 2015

As indicated in Figure 9, CERCPB had accumulated significantly from 2001 to 2015, reflecting that the effectiveness of BEE work in China had risen rapidly during that time. The Chinese government supported and promoted BEE work in various fields during this phase. Based on official information [8,43–45], this study summarized the leading policies and goals for public BEE works for the period, as shown in Figures 11 and 12, respectively.

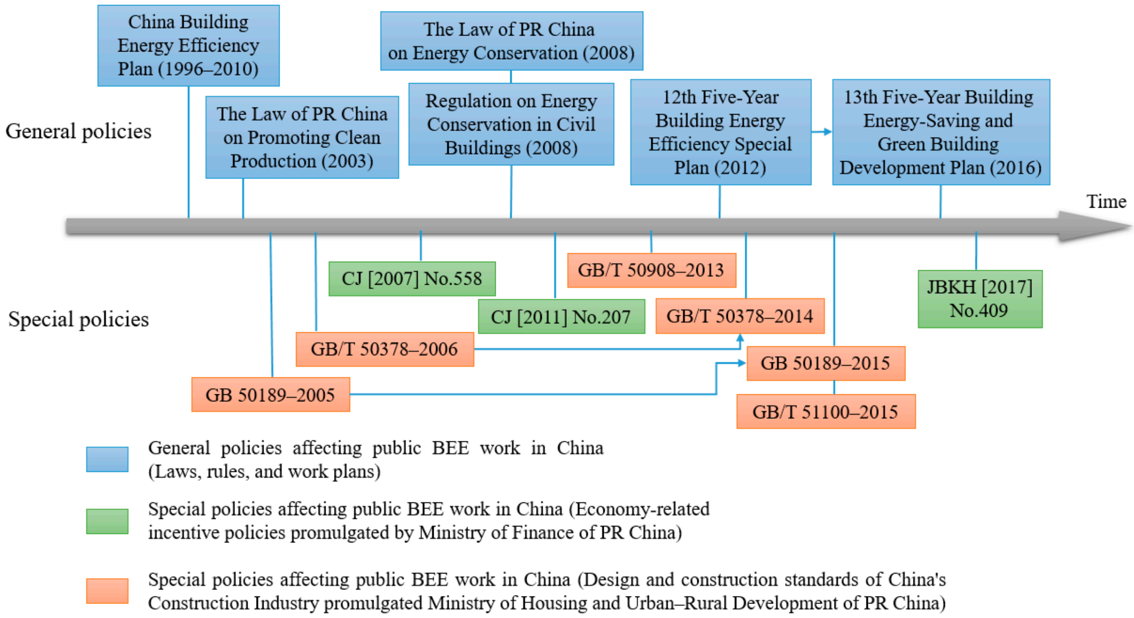

Figure 11. Leading policies affecting public building energy efficiency (BEE) work in China from the late 1990s to 2017.

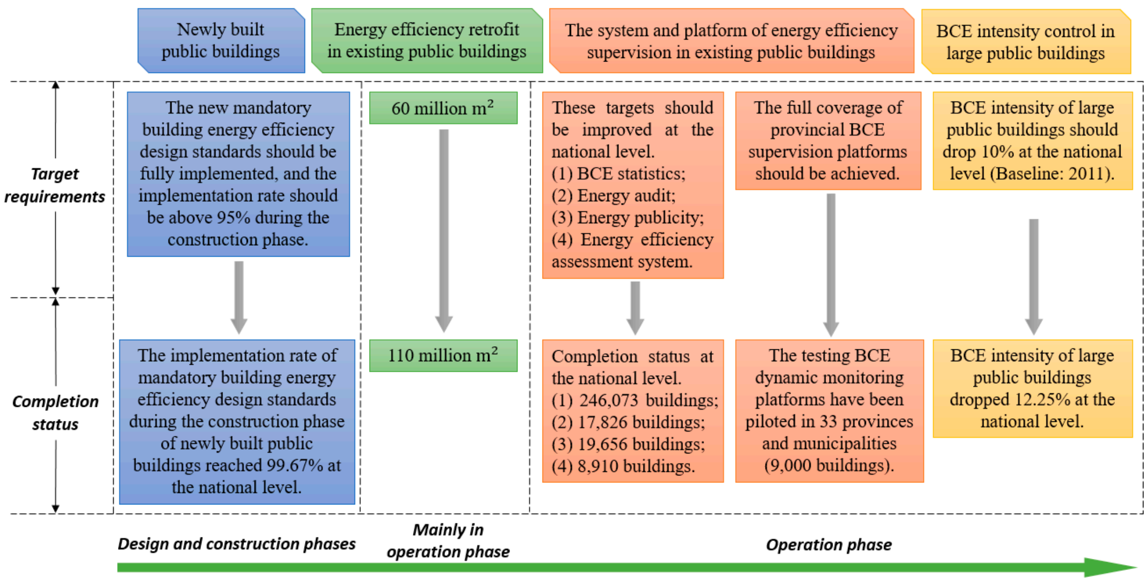

Figure 12. Leading goals of public BEE work in China from 2001 to 2015.

Figures 11 and 12 indicate that public BEE work in China achieved substantial outcomes, and these achievements led to a rapid increase in CERCPB in 2001–2015. However, there are significant delays in the demonstrable effects of the policies on building energy efficiency [1]. Demonstrating the benefits of CER is expected to take a long time, even in newly built public buildings regulated by stringent design standards for energy efficiency in the design and construction phases, as well as in retrofitting existing public buildings for energy efficiency. The BEE work of China from the late 1990s to 2000 has also borne fruit. For example, the *China Building Energy Efficiency Plan (1996–2010)* established in the 1990s was the only specific mid- to long-term work planned during 1990–2010. This significant policy has been beneficial to the development of China's BEE work for approximately 15 years, establishing a strong foundation for the accomplishment of rapid CERCPB accumulation from 2001 to 2015.

5.2. Shortcomings of this Study

Although this study produced significant findings, one shortcoming must be pointed out. The growth trend of CERCPB in Figure 9 showed fluctuation, which partly affected the stability of the assessment results. The values of the floor areas for 2007 and 2008 were not comparable at the same level (as shown in Figures 6 and 13), as the scope of statistics for the floor areas of existing civil buildings in China (including public buildings) was changed for the period 2007–2008 [17,39]. This directly affected the values of e_c for these years. According to the LMDI-I decomposition analysis framework (as shown in Equation (13) and Figure 5), the variation trend of the decomposition results of ΔE_{e_c} for the period 2007–2009 was uneven. Consequently, there was fluctuation in the growth trend of CERCPB in Figure 9, which was expressed further in Figure 13.

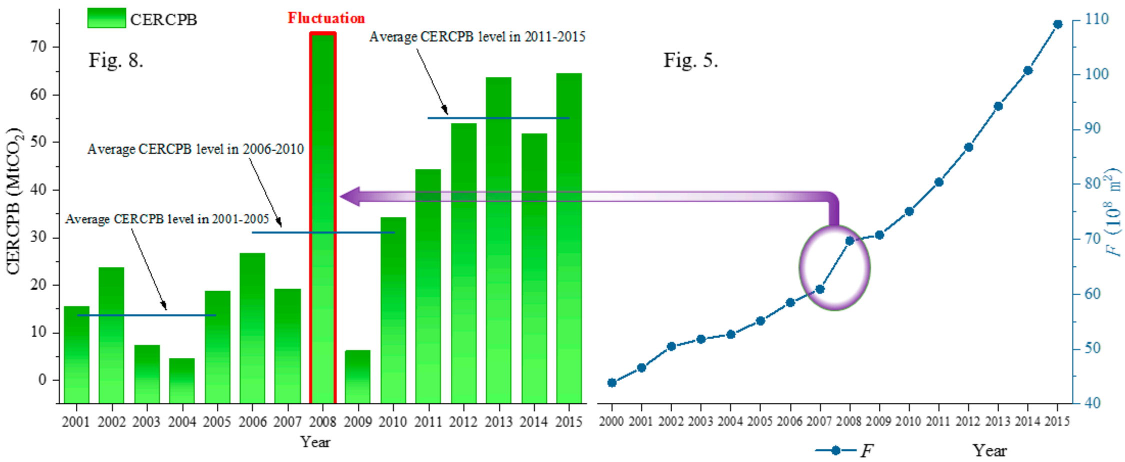

Figure 13. Fluctuation in growth trends involving F and CERCPB in 2001–2015.

The data relevant to CER in the existing civil buildings form the foundation for BEE work in China. Although several studies have effectively assessed and evaluated the CER in the existing civil and residential buildings, the CERCPB assessment approach remained inadequate. Therefore, the Chinese government accordingly has to initiate a system of performance assessment based on the load of the building energy efficiency (e.g., examining the floor areas of existing public and residential buildings relevant to the task of energy efficiency retrofitting) [17]. This initiative has forced the authorities to focus on increasing the value of floor areas of building energy efficiency retrofit, instead of on decreasing the carbon emissions from existing civil buildings [14]. Consequently, the potentiality of CER is expected to decline. However, in view of the potentiality of CER in the public buildings in China being greater than that in the residential buildings, a method for evaluating the current CERCPB should be developed. This would encourage the government to draft and apply focused policies and targets relevant to enhancing the CECS of public buildings. Such an initiative would encourage and support the progress and development of the next stage of BEE work in China. As successful BEE work is a critical factor in sustainable urbanization, the findings of this study are considered significant for such development in China.

6. Conclusions and Policy Implications

The CERCPB values ought to be assessed to enhance the CECS of public buildings in China and to drive the progress of sustainable urbanization and BEE work. This study presented a method based on the LMDI and STIRPAT approaches for the effective assessment of the CERCPB values for the period 2001 to 2015. An overview of public BEE work in China is included in the study, and a shortcoming is mentioned. The main conclusions of this study are as follows:

(1) The outputs of the LMDI-I decomposition analysis demonstrated that only the contribution of comparable CPBCE intensity to CPBCE was negative during the period 2001–2015, and this contribution indicated the CERCPB value for the period.
(2) The assessment results indicated that CERCPB had accumulated considerably with the rapid development of BEE work in China during 2001–2015. The CERCPB values in 2001–2005, 2006–2010, and 2011–2015 were 69.29, 158.53, and 277.86 $MtCO_2$, respectively. Furthermore, the actual CERCPB values derived by this study were obviously higher than the official planned values for the periods. This illustrates the positive effect of implementing public BEE work in China during 2001–2015.
(3) After summarizing the leading policies and goals of China relevant to public BEE works over the past fifteen years, this study demonstrated that public BEE work achieved significant results during 2001–2015, which could be regarded as a prerequisite to attaining the considerable accumulation of CERCPB over this period.

This study revealed the feasibility of assessing CERCPB values by employing the LMDI and STIRPAT approaches. However, at the data level, although BEE work in China has advanced in various respects, a few shortcomings remain in assessing BCE data nationwide. Relevant to both the residential and public building sectors, detailed and accurate BCE data issued by the government are required to determine precise CER values for these sectors. In addition, these data should be also treated to significant indexes for measuring the progress of BEE work in China. Generally, the Chinese government should make a substantial effort to establish a statistics system relevant to nationwide BCE data. We believe that our study represents a most significant task relevant to the next stage of BEE work in China.

This study focused on public building sector in China. In order to achieve the double reduction (i.e., CERCPB and the reduction of CPBCE intensity) of existing public buildings, the Chinese government should further publish effective and targeted BEE policies for public buildings at the upcoming phase, such as the new versions of Design Standard for Energy Efficiency of Public Buildings (GB 50189), Assessment Standard for Green Buildings (GB/T 50378), and guide rules for energy efficiency retrofit of public buildings. Furthermore, considering that the building sector has an acknowledged role in the TNCE of China, the carbon trading market of the building sector can be further developed to promote the progress of China's BEE work in the next phase. Given that it is easier to measure and assess the potential and values of CER in public buildings than residential buildings at regional and provincial levels, public buildings should be regarded as playing an important part in effectively promoting the development of the carbon trading market. This effort can further drive the developments of BEE work and sustainable urbanization in China.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Raw data list of CERCPB assessment model.

Year	E (MtCO$_2$)	P (10^7 persons)	F (10^8 m^2)	E/P (10^2 kg CO$_2$/person)	I_p	E/F (kg CO$_2$/m^2)
Baseline: 2000						
2000	267.80	126.74	43.84	2.11	1.00	61.09
2001	304.20	127.63	46.59	2.38	1.13	65.29
2002	335.40	128.45	50.48	2.61	1.24	66.44
2003	400.40	129.23	51.79	3.10	1.47	77.31
2004	442.00	129.99	52.65	3.40	1.61	83.95
2005	481.00	130.76	55.15	3.68	1.74	87.22
Baseline: 2005						
2005	481.00	130.76	55.15	3.68	1.00	87.22
2006	517.40	131.45	58.46	3.94	1.07	88.50
2007	540.80	132.13	60.92	4.09	1.11	88.77
2008	579.80	132.80	69.74	4.37	1.19	83.14
2009	605.80	133.45	70.80	4.54	1.23	85.56
2010	652.60	134.09	75.10	4.87	1.32	86.90
Baseline: 2010						
2010	652.60	134.09	75.10	4.87	1.00	86.90
2011	730.60	134.74	80.45	5.42	1.11	90.81
2012	790.40	135.40	86.79	5.84	1.20	91.07
2013	837.20	136.07	94.31	6.15	1.26	88.77
2014	847.60	136.78	100.81	6.20	1.27	84.08
2015	863.20	137.46	109.23	6.28	1.29	79.03

Table A2. Detailed decomposition results of CPBCE in 2001–2015.

Year	ΔE_P (MtCO$_2$)	ΔE_F (MtCO$_2$)	ΔE_{I_s} (MtCO$_2$)	ΔE_{e_c} (MtCO$_2$)
2001	1.99	17.38	32.43	−15.39
2002	2.06	25.62	27.08	−23.56
2003	2.20	9.40	60.59	−7.20
2004	2.47	6.93	36.66	−4.46
2005	2.72	21.40	33.57	−18.68
2006	2.63	29.08	31.13	−26.45
2007	2.73	21.81	17.93	−19.07
2008	2.85	75.73	33.31	−72.88
2009	2.89	8.94	20.23	−6.06
2010	3.01	37.08	40.77	−34.07
2011	3.31	47.54	71.38	−44.23
2012	3.76	57.66	52.27	−53.89
2013	4.00	67.60	38.79	−63.60
2014	4.38	56.15	1.63	−51.76
2015	4.24	68.62	7.12	−64.37

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