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Energy savings evaluation in public building sector during the 10th–12th FYP periods of China: an extended LMDI model approach

Minda Ma[1] · Ran Yan[1] · Weiguang Cai[1,2,3]

Abstract Energy savings can be treated as an indicator to reveal the effectiveness of energy efficiency task (EET) in the building sector, especially in the public buildings. However, evaluating the values of energy savings in public buildings (ESPB) was challenged by the missing data sources and inadequate tools in China. To overcome these problems, this study applied an extended Logarithmic Mean Divisia Index model to examine the contributions of different impact factors affecting the public building energy consumption (PBEC) and further evaluated the ESPB values during the 10th–12th Five-Year Plan (FYP) periods in China. Results included three aspects: (1) Absolute values of the contribution of the adjusted PBEC intensity to PBEC denoted the ESPB values in China. (2) Total values of ESPB were 99.9 Mtce during the 10th–12th FYP periods of China. Concretely, the ESPB values during the three FYP periods were as follows: 71.091 Mtce (the 12th FYP period), 19.075 Mtce (the 11th FYP period), and 9.734 Mtce (the 10th FYP period). (3) Effective EET of public buildings was a strong support for the rapidly growing ESPB during the three FYP periods. Furthermore, this study suggested that China should issue the official data on energy consumption in the building sector as quickly as possible, and this action would deeply help the government design targeted plans and policies for the future EET in the building sector.

Keywords Energy savings · Public buildings · Energy data · Extended LMDI model · FYP period

✉ Weiguang Cai
  cquwgcai@gmail.com; wgcai@cqu.edu.cn

1   School of Construction Management and Real Estate, Chongqing University, Chongqing 400030, People's Republic of China

2   Energy Analysis and Environmental Impacts Division, Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

3   Special Committee of Building Energy Consumption Statistics, China Association of Building Energy Efficiency, Beijing 100835, People's Republic of China

List of symbols

PBEC	Public building energy consumption
E	Public building energy consumption (PBEC) in China
ESPB	Energy savings in public buildings
P	Population size in China
U	Urbanization level in China
f	Floor space per capita of public buildings in China
e	PBEC intensity in China
$e_{ad.}$	Adjusted PBEC intensity in China
L_s	Service level of public buildings in China
L_P	Per capita level of PBEC in China
ε	Conversion index between L_s and L_P
LMDI	Logarithmic Mean Divisia Index
ΔE_P	Contribution of P to E
ΔE_U	Contribution of U to E
ΔE_f	Contribution of f to E
ΔE_{L_s}	Contribution of L_s to E
$\Delta E_{e_{ad.}}$	Contribution of $e_{ad.}$ to E

1 Introduction

Public building energy consumption (PBEC) constitutes approximately 40% of the energy consumption in China's building sector, which requires an explosive energy demand (Liang et al. 2014; McNeil et al. 2016; Berardi 2017). Since energy efficiency in the public building sector is expected to provide over 20% of CO_2 reduction for achieving the CO_2 emission peak of China in the mid-2030s (Fujii et al. 2016; Ma et al. 2017; Lynn et al. 2017), the energy efficiency task (EET) of public buildings should be developed in depth to achieve this target. The value of energy savings is an indicator to reveal the effectiveness of EET in the building sector, especially in the public buildings (Lin and Liu 2015; Ma et al. 2017; Cai et al. 2017). Therefore, evaluating the energy savings in public buildings (ESPB) of China is worthy to be regarded as a pressing task to achieve.

Reliable and sustainable data on PBEC are the foundations to evaluate the ESPB values. As for China, the authoritative data collection task of building energy consumption is incomplete (CABEE 2016; Ye et al. 2018). Hence, the official data on building energy consumption (including the PBEC) are still missing. Nevertheless, a few scholars utilized different approaches to estimating the national PBEC data of China. As a typical example, based on the raw energy data of *China Energy Statistical Yearbook*, *China Association of Building Energy Efficiency* (CABEE) developed a data mining tool to collect the time-series data on PBEC (CABEE 2016), and this approach was widely approved by numerous relevant studies (e.g., Ma et al. 2017; Wei et al. 2017; Wang et al. 2017a, b; Liang et al. 2017; Shuai et al. 2018; Liu et al. 2017a, b; Cai et al. 2016). Specifically, CABEE (2016) indicated a national PBEC value of 341 million tons of standard coal equivalent (Mtce) in 2015, which accounted for 39.79 and 7.93% of the building energy consumption and national energy consumption in China during the same period, respectively.

Logarithmic Mean Divisia Index (LMDI) method is a famous approach to analyzing the impacts of different factors to energy consumption in one or more divisions, which was first proposed by Ang (2005). Combining the data support of CABEE (2016) with the

LMDI method, a series of previous studies have evaluated the energy savings in Chinese building sector. For example, Ma et al. (2017) applied the LMDI method to examine five impact factors of energy consumption in Chinese building sector and assessed the energy savings based on the negative factor (i.e., building energy consumption per floor space) during 2001–2014. As for the residential building sector, Yan et al. (2017) employed the LMDI to analyze the identities of residential energy consumption in urban and rural China, respectively. The results indicated that the energy savings of the residential buildings were from the contribution of the residential energy consumption intensity to residential energy consumption. With respect to the carbon reduction in Chinese building sector, Lin and Liu (2015) utilized the LMDI method to identify the leading impact factors involving the carbon reduction in both the residential and commercial building sectors of China during 1995–2012. However, through a careful searching, an individual study on evaluating the energy savings in Chinese public building sector is almost lacking at the current phase.

The abovementioned review demonstrates that the PBEC data issued by the CABEE (2016) are comparatively reliable as they have been widely approved by numerous relevant studies. Meanwhile, the LMDI method is appropriate for exploring the contributions of different impact factors that affect building energy consumption and evaluating the values of energy savings in the building sector. Therefore, the LMDI approach is also effective to evaluate the ESPB values in China. In this case, this study applied an extended LMDI model to explore the contributions of different impact factors to the PBEC and further evaluated ESPB values during the 10th–12th Five-Year Plan (FYP) periods (2001–2015) in China. Through analyzing the trend of ESPB values in the aforementioned periods, the effectiveness of EET in Chinese public buildings can be examined at a quantitative level.

The other parts of this paper are as follows. Section II proposes a methodology of the PBEC identity and extended LMDI model for evaluating the ESPB values of China. Besides, the raw data involving the LMDI are introduced in the same section. Sections 3 and 4 illustrate and discuss the ESPB values and EET of public buildings during the 10th–12th FYP periods in China, respectively. Furthermore, the conclusions and further works are shown in Sect. 5.

2 Methodology

2.1 PBEC identity

At a regional level, the ESPB can be observed by the decrease in the PBEC intensity clearly. As for China, the trend of PBEC intensity (e) was an asymmetric inverted V-shaped trace during the 10th–12th FYP periods, as illustrated in Fig. 1. Given that the values of PBEC intensity were increasing from 2000 to 2012, the ESPB values during the same period were unable to be evaluated. Thus, this study recalculated the actual PBEC intensity (i.e., the adjusted PBEC intensity in China, $e_{ad.}$), which removed the impact of the service level of public buildings in China (L_s). The trend of $e_{ad.}$ is shown in Fig. 1.

Figure 1 reveals a clear road map for evaluating the ESPB values during a period of ΔT, as shown below.

$$\text{ESPB}|_{0 \to T} = \Delta e_{ad.}|_{0 \to T} \times F|_T = (e_{ad.}|_0 - e_{ad.}|_T) \times F|_T \qquad (1)$$

$e_{ad.}|_0$ and $e_{ad.}|_T$ represent the $e_{ad.}$ in the baseline and target periods, severally; $F|_T$ is the target period value of the floor space of public buildings in China. As indicated in Fig. 1,
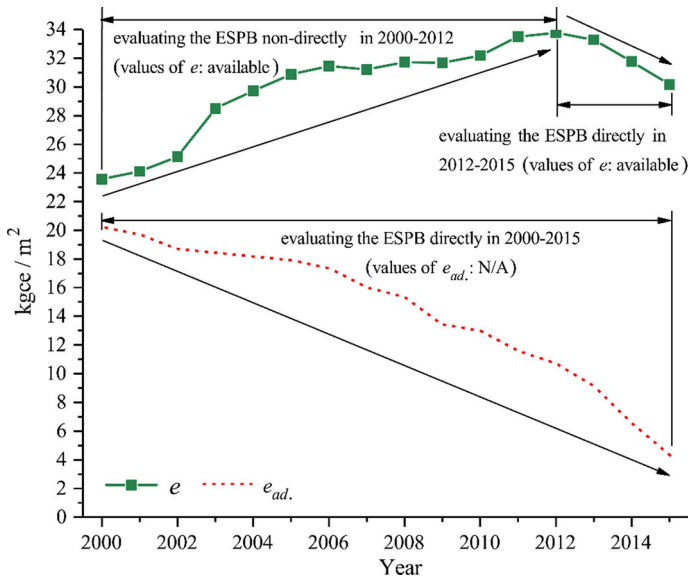
Fig. 1 Trends of PBEC intensity in China (e) and its adjusted value ($e_{ad.}$) in 2000–2015

$e_{ad.}$ is an unquantifiable index. Therefore, this study further analyzed the mechanism of this index for evaluating the ESPB values. Following the guidance of Ma et al. (2017), the relationship among L_s, e, and $e_{ad.}$ is demonstrated in Eq. (2). Thereafter, the L_s can be further decomposed into two variables since the value of L_s is hard to be measured at a quantitative level. In Eq. (3), L_P and ε represent the per capita level of PBEC in China and the conversion index between L_s and L_P, respectively.

$$e_{ad.}|_T = \frac{e|_T}{L_s|_T} \tag{2}$$

$$= \frac{e|_T}{\varepsilon \times L_P|_T} \tag{3}$$

$$= \frac{E|_T/F|_T}{\varepsilon \times \left[L_P|_0 \times \frac{E|_T/(P|_T \times U|_T)}{E|_0/(P|_0 \times U|_0)} \right]} \tag{4}$$

$$= \frac{E|_0 \times P|_T \times U|_T}{\varepsilon \times F|_T \times P|_0 \times U|_0} \tag{5}$$

Based on Eq. (3), the equation can be further developed into Eqs. (4) and (5). In this case, $E|_0$ and $E|_T$ represent the PBEC in China (E) in the baseline and target periods, severally; $P|_0$ and $P|_T$ express the population size in China (P) in the baseline and target periods, respectively; $U|_0$ and $U|_T$ denote the urbanization level in China (U) in the baseline and target periods, respectively. It should be noted that the value of L_P in the baseline period is 1 (i.e., $L_P|_0 = 1$).

In Eq. (5), the data collection of all the variables is available, excluding the ε. However, during a period of ΔT, the impact of ε to $\Delta e_{ad.}|_{0 \to T}$ can be removed by the fraction

reduction (as shown in Eqs. (A–5) and (A–6)). Thus, this study applied the LMDI method to assess the $\Delta e_{\text{ad.}}|_{0 \to T}$ and further evaluated the ESPB values, which would be introduced in Sect. 2.2. Before applying the LMDI method, an identity involving E and $\Delta e_{\text{ad.}}$ should be established. In this study, the IPAT model was used to build the identity.

IPAT model, proposed by Ehrlich and Holdren (1971), was widely applied to analyze the human impact (I) to the environment (e.g., energy consumption, CO_2 emissions, etc.) with a multiplication of three kinds of impact factors (i.e., population size (P), affluence level (A), and technology progress (T)), as shown in Eq. (6).

$$I = P \times A \times T \tag{6}$$

Considering the characteristics of the PBEC in China, this study decomposed the population of IPAT into two variables: the population size (P) and urbanization level (U) in China; as for the affluence level, the floor space per capita of public buildings (f) and service level of public buildings (L_s) in China were involved; Moreover, the adjusted PBEC intensity in China ($e_{\text{ad.}}$), which indicates the actual level of PBEC intensity, represents the technology progress of IPAT. Equation (7) reveals the extended IPAT model which covers the aforementioned five factors.

$$I = P \times A \times T \to (E)_I = (P \times U)_P \times (f \times L_s)_A \times (e_{\text{ad.}})_T \tag{7}$$

Besides, the form of Eq. (7) can be further simplified as Eq. (8).

$$E = P \times U \times f \times L_s \times e_{\text{ad.}} \tag{8}$$

2.2 Extended LMDI model

To explore the contributions of different impact factors mentioned in Eq. (8) and evaluate the ESPB values during the 10th–12th FYP periods, this study utilized an extended LMDI model to decompose Eq. (8). The LMDI method is a widely used tool to analyze the impacts of different factors to energy consumption in one or more divisions, which was first proposed by Ang (2005). Through the LMDI method, an identity of a target involving energy consumption and its several impact factors can be decomposed into a sum of different contributions of the impact factors to the target. Let the IPAT model be an example, and Eqs. (9)–(12) reveal the structure of the LMDI method during a period of Δt.

$$\Delta I = I|_t - I|_0 = \Delta I_P + \Delta I_A + \Delta I_T \tag{9}$$

$$\Delta I_P = \sum_i L \times \ln\left(\frac{P_i|_t}{P_i|_0}\right) \tag{10}$$

$$\Delta I_A = \sum_i L \times \ln\left(\frac{A_i|_t}{A_i|_0}\right) \tag{11}$$

$$\Delta I_T = \sum_i L \times \ln\left(\frac{T_i|_t}{T_i|_0}\right) \tag{12}$$

where L represents the $L(I_i|_t, I_i|_0)$, which indicates the logarithm mean of two positive variables, as demonstrated in Eq. (13).

$$L(x,y) = \begin{cases} \dfrac{x - y}{\ln\left(\dfrac{x}{y}\right)}, & x \neq y \\ 0, & x = y \end{cases} \tag{13}$$

Taking into consideration that a few impact factors were established based on other related factors (e.g., L_s and $e_{ad.}$) in Eq. (8), this study applied an extended version of the LMDI method (Shao et al. 2016; Choi and Oh 2014; Cai et al. 2017) to examine the contributions of the impact factors that affect the PBEC in China and further evaluated the ESPB values. As indicated in Eq. (8), this study considered five impact factors in the PBEC changes. During a period change of ΔT, the change of PBEC (i.e., ΔE) can be expressed as:

$$\Delta E = E|_T - E|_0 = \Delta E_P + \Delta E_U + \Delta E_f + \Delta E_{L_s} + \Delta E_{e_{ad.}}, \tag{14}$$

where ΔE_P, ΔE_U, ΔE_f, ΔE_{L_s}, and $\Delta E_{e_{ad.}}$ represent the contributions of the five impact factors to the PBEC changes, respectively. Following the definition of ESPB, the improved approach to evaluating ESPB values based on Eq. (1) is as follows:

$$\text{ESPB} = -\left[\sum \Delta E_j|_{0 \to T} \right], \tag{15 - 1}$$

where $\Delta E_j|_{0 \to T} \in \left\{ \Delta E_P, \Delta E_U, \Delta E_f, \Delta E_{L_s}, \Delta E_{e_{ad.}} \right\}$, and

$$\Delta E_j|_{0 \to T} < 0 \tag{15 - 2}$$

Furthermore, the detailed process of the extended LMDI decomposition is demonstrated in "Appendix A".

2.3 Data

This study collected the data on E and F from *Chinese Building Energy Consumption Report (2016)* (CABEE 2016). Meanwhile, *China Population and Employment Statistics Yearbook* provided the detailed data of P and U. All the aforementioned data are illustrated in Fig. 2.

3 Results

Following the guidance of Eqs. (A–1)–(A–8) in "Appendix A", this study ran detailed calculation to obtain the decomposition results of the extended LMDI model, as illustrated in Fig. 3. It should be noted that only the contribution of the adjusted PBEC intensity to PBEC ($\Delta E_{e_{ad.}}$) was negative during the 10th–12th FYP periods in China (i.e., -9.01, -10.31, and -28.32%, respectively). Thus, the absolute values of $\Delta E_{e_{ad.}}$ (i.e., the blue blocks shown in Fig. 3) reflect the values of ESPB in China. Concretely, the ESPB values during the three FYP periods in China can be assessed as follows: 71.091 Mtce (the 12th FYP period), 19.075 Mtce (the 11th FYP period), and 9.734 Mtce (the 10th FYP period). Furthermore, the annual ESPB values from 2001 to 2015 are demonstrated in Fig. 4.
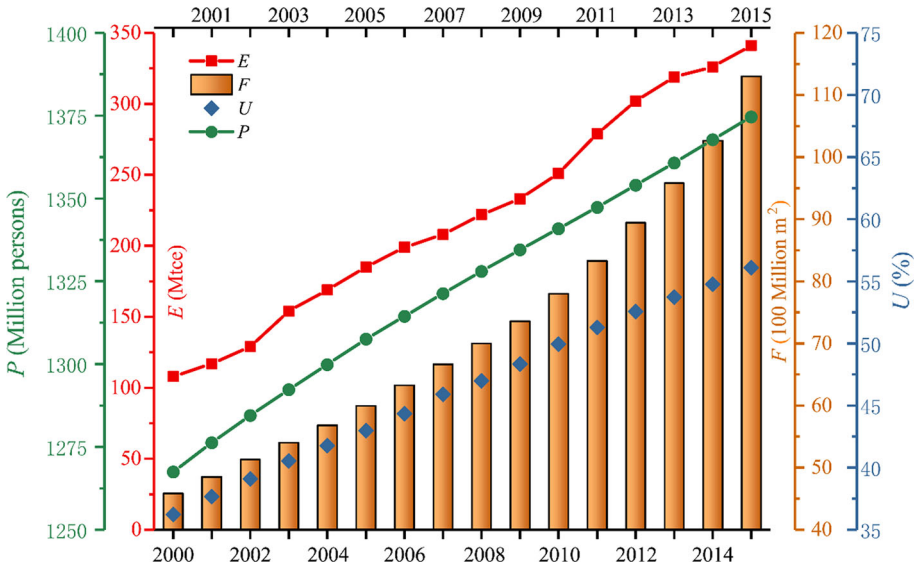
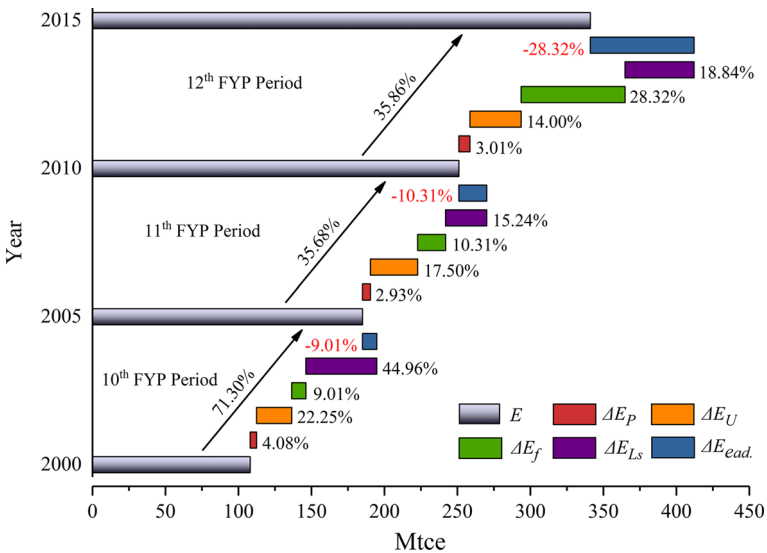**Fig. 2** Trends of *E*, *F*, *P*, and *U* during the 10th–12th FYP periods

Fig. 3 Extended LMDI decomposition results of PBEC in China

4 Discussion

Figures 3 and 4 illustrate that ESPB values in China have increased significantly during the past three FYP periods, which demonstrates that the efforts of EET in Chinese public buildings received a strong and positive response during the same periods. This study made a concise summary about the development of EET in Chinese public building sector during
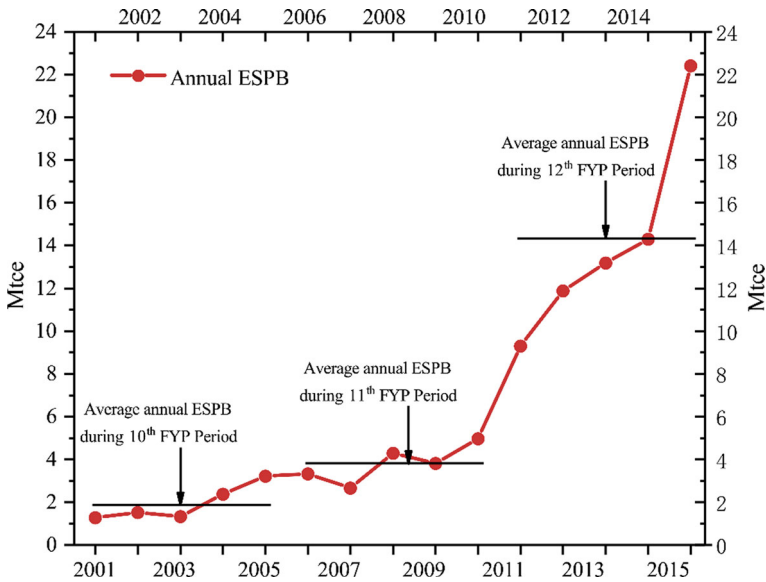
Fig. 4 Annual ESPB values during the 10th–12th FYP periods in China

the 10th–12th FYP periods, as shown in Fig. 5 and Table 1. Based on the achievements of EET in Chinese public buildings, this study believes that the effective EET was a strong support for the rapidly growing ESPB during the three FYP periods.

Data on PBEC and ESPB are the foundations for promoting the EET in Chinese public buildings (Ma et al. 2017; Cai et al. 2018; Mi et al. 2017). Since the reliable values of the
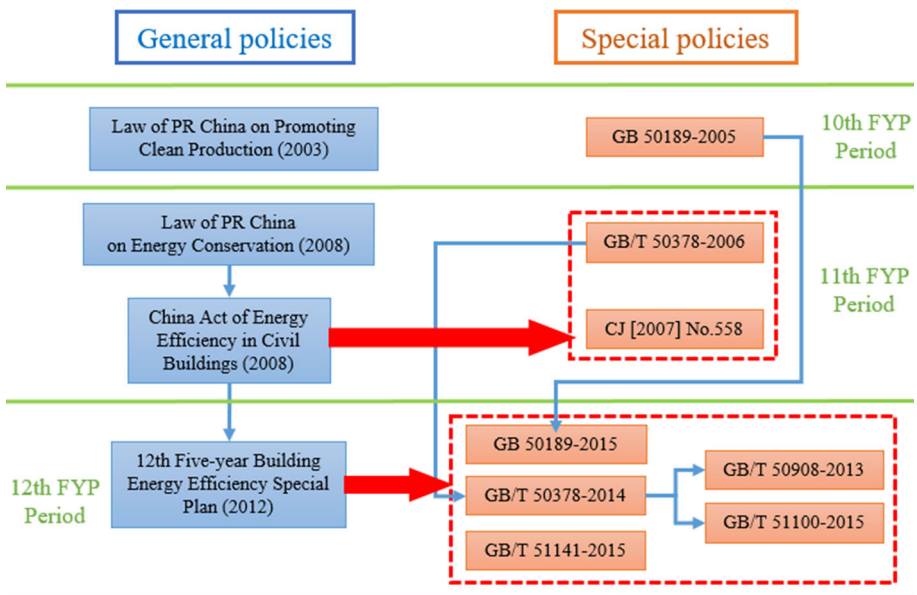

Fig. 5 Policies of EET in Chinese public building sector during the 10th–12th FYP periods

abovementioned data are still lacking at the national level, the Chinese government faces the challenge of evaluating the EET of public buildings without an effective indicator. A general approach to evaluating the effectiveness of EET is to check the workloads shown in Table 1. However, the detailed energy data are non-ignored parts of a reliable EET evaluation in the building sector (Lin and Liu 2015; Kong et al. 2012; Cai et al. 2017). To achieve the maximum potentiality of energy efficiency, the EET in Chinese public buildings should be evaluated with the data support of the PBEC and ESPB. Therefore, a substantive endeavor to publish an official data achievement ought to be made by the Chinese government as soon as possible, which includes the reliable data involving the energy consumption in different types of civil buildings at both the national and provincial levels. This action will deeply help the central and local governments design targeted plans and policies for the EET in the building sector at the forthcoming periods.

As for the weakness of this study, compared with other two FYP periods, the ESPB values faced a sharp increase during the 12th FYP period, as shown in Fig. 4. Given that the extended LMDI model demonstrated that only the impact of $e_{ad.}$ (i.e., the adjusted PBEC intensity) on PBEC caused the accumulation of ESPB, this study used a cross-check to analyze the changes in $e_{ad.}$ and ESPB during the 10th–12th FYP periods, as shown in Fig. 6. The results indicated that the significant decrease in $e_{ad.}$ from 2012 to 2015 caused the sharp increase in the annual ESPB during the same period. In other word, the annual ESPB values may be affected by the uneven changes in the time-series data on $e_{ad.}$, which was hard to be observed in the total values of ESPB during different FYP periods.

Table 1 Achieved goals of EET in Chinese public building sector during the 11th and 12th FYP periods

| 11th FYP period (MOHURD_of_PRC 2012)	12th FYP period (MOHURD_of_PRC 2017)
PBEC data on 33,000 buildings	Set up sub-metered energy monitoring platforms in 33 provinces; 9000 + public buildings were dynamically monitored
Energy audit for 4850 buildings	
Nine provincial level PBEC monitoring platforms	Pilot energy efficiency retrofit for 233 campuses, 44 hospitals, and 19 research institutions
70 + energy efficient campuses	Set 11 cities for public building energy efficiency retrofit. Retrofit 48.64 million m^2, which encouraged other building retrofits to reach 0.11 billion m^2
Sub-metered energy monitoring for 1500 + buildings	
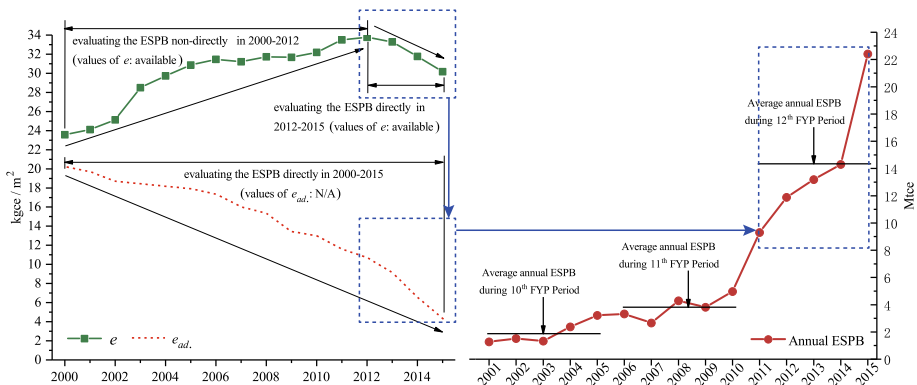
Fig. 6 Changes in $e_{ad.}$ and ESPB during 2000–2015

5 Conclusions and further works

This study proposed an extended LMDI model to examine the contributions of different impact factors affecting the PBEC and further evaluated the ESPB values during the 10th–12th FYP periods in China. Moreover, a discussion about analyzing the development and achievements of EET in Chinese public buildings based on the proof of ESPB values during the 10th–12th FYP periods was also involved. The main findings of this study included three aspects:

- The extended LMDI model revealed that the absolute values of the contribution of the adjusted PBEC intensity to PBEC denoted the ESPB values in China. Since only $\Delta E_{e_{ad.}}$ was negative during the 10th–12th FYP periods in China, the absolute value of this variable represented the ESPB values.
- Total values of ESPB were 99.9 Mtce during the 10th–12th FYP periods of China. Concretely, the FYP period values of ESPB were as follows: 71.091 Mtce (the 12th FYP period), 19.075 Mtce (the 11th FYP period), and 9.734 Mtce (the 10th FYP period). Through analyzing the annual values of ESPB, this study observed that the ESPB values faced a sharp increase during the 12th FYP period, and the cause of this phenomenon could be attributed to the significant decrease in the adjusted PBEC intensity during the same period in China.
- Effective EET of public buildings was a strong support for the rapidly growing ESPB. During the past three FYP periods, the Chinese government developed the EET of public buildings in a series of aspects, and the substantial achievements from the EET promoted the rapid accumulation of ESPB in China.

This study evaluated the national ESPB values in China based on an extended LMDI model and the energy data support of *Chinese Building Energy Consumption Report (2016)* (CABEE 2016). However, many aspects related to this study could be improved by further studies. For example, the study area of this paper focused on the national level, taking into consideration that the impacts of unbalanced affluence level (e.g., population size, economy development, urbanization level, volume of public buildings, etc.), and the different climates in different regions of China, the PBEC condition in the various regions would definitely differ. Therefore, it is meaningful to launch further studies about analyzing the energy saving potential of PBEC at a regional level in China, such as developing the energy saving calculation application for public buildings in different provinces. This work will help the central and local governments design targeted plans and goals for the future EET of public buildings.

Appendix A

On the basis of the original LMDI decomposition proposed by Ang (2015), the value of PBEC changes (i.e., ΔE) during a period of ΔT can be indicated as shown below.

$$\Delta E = E|_T - E|_0 = \Delta E_P + \Delta E_U + \Delta E_f + \Delta E_{L_s} + \Delta E_{e_{\text{ad.}}} \qquad (A-1)$$

$$\Delta E_P = L \times \ln\left(\frac{P|_T}{P|_0}\right) \qquad (A-2)$$

$$\Delta E_U = L \times \ln\left(\frac{U|_T}{U|_0}\right) \qquad (A-3)$$

$$\Delta E_f = L \times \ln\left(\frac{f|_T}{f|_0}\right) = L \times \ln\left(\frac{F|_T \times P|_0 \times U|_0}{F|_0 \times P|_T \times U|_T}\right) \qquad (A-4)$$

$$\Delta E_{L_s} = L \times \ln\left(\frac{L_s|_T}{L_s|_0}\right) = L \times \ln\left(\frac{\varepsilon \times L_P|_T}{\varepsilon \times L_P|_0}\right) = L \times \ln\left(\frac{L_P|_T}{L_P|_0}\right) \qquad (A-5)$$

$$\begin{aligned}
\Delta E_{e_{\text{ad.}}} &= L \times \ln\left(\frac{e_{\text{ad.}}|_T}{e_{\text{ad.}}|_0}\right) = L \times \left[\ln\left(\frac{e|_T}{e|_0}\right) - \ln\left(\frac{L_s|_T}{L_s|_0}\right)\right] \\
&= L \times \left[\ln\left(\frac{e|_T}{e|_0}\right) - \ln\left(\frac{\varepsilon \times L_P|_T}{\varepsilon \times L_P|_0}\right)\right] = L \times \left[\ln\left(\frac{e|_T}{e|_0}\right) - \ln\left(\frac{L_P|_T}{L_P|_0}\right)\right]
\end{aligned} \qquad (A-6)$$

where L represents the $L(E|_T, E|_0)$, which indicates the logarithm mean of two positive variables, as demonstrated in Eq. (A–7).

$$L(x,y) = \begin{cases} \dfrac{x-y}{\ln\left(\dfrac{x}{y}\right)}, & x \neq y \\ 0, & x = y \end{cases} \qquad (A-7)$$

Following the definition of ESPB, the improved approach to evaluating ESPB values based on Eq. (1) is as follows.

$$\text{ESPB} = -\left[\sum \Delta E_j|_{0 \to T}\right], \qquad (A-8-1)$$

where $\Delta E_j|_{0 \to T} \in \{\Delta E_P, \Delta E_U, \Delta E_f, \Delta E_{L_s}, \Delta E_{e_{\text{ad.}}}\}$, and

$$\Delta E_j|_{0 \to T} < 0 \qquad (A-8-2)$$

Appendix B

As indicated in Sect. 2.3, the data on PBEC and floor spaces of public buildings in China were collected from *Chinese Building Energy Consumption Report (2016)* (CABEE 2016), which provided the detailed time-series data on national building energy consumption in China. Furthermore, this report also issued a series of building-related statistical indexes (e.g., floor spaces of different types of civil buildings). The aforementioned data are illustrated in Fig. 7.
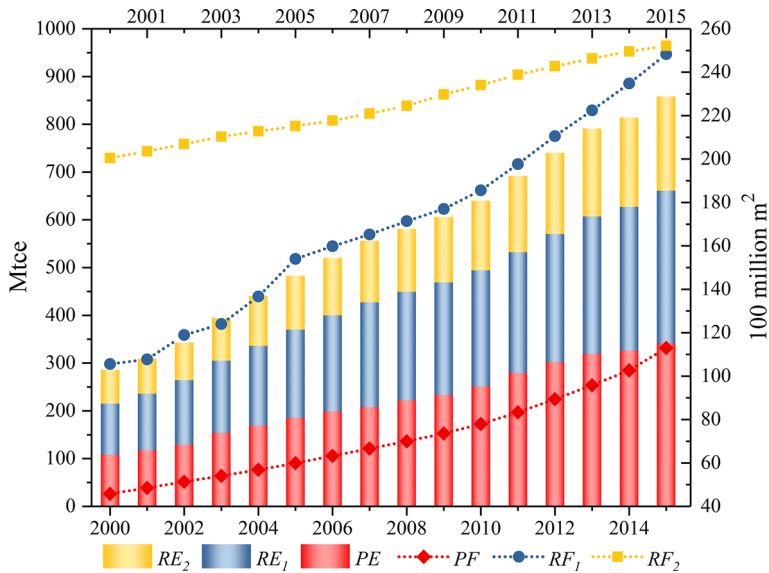
Fig. 7 Trends of civil building energy consumption (PE, RE₁, and RE₂) and floor spaces of civil buildings (PF, RF₁, and RF₂) during the 10th–12th FYP periods in China. Notices: PE—Public building energy consumption in China; RE₁—Residential energy consumption in urban China; RE₂—Residential energy consumption in rural China; PF—Floor spaces of public buildings in China; RF₁—Floor spaces of residential buildings in urban China; RF₂—Floor spaces of residential buildings in rural China. URL: http://www.efchina.org/Attachments/Report/report-20170710-1. *Sources*: CABEE (2016)

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