RESEARCH ARTICLE

The impacts of driving variables on energy-related carbon emissions reduction in the building sector based on an extended LMDI model: a case study in China

Boya Jiang[1] · Lin Sun[1] · Xiaoxiao Zhang[1] · Hong Xian Li[2] · Baolin Huang[3]

Abstract

As China's main contributor to energy-related carbon emissions, the building sector in Jiangsu Province generates around 13.58% of the national carbon emissions. However, the influential variables of the energy structure in Jiangsu Province have been little investigated during the past decade. With the increasing emphasis on China's investment in technological innovation and adjustment of its industrial structure, research and development (R&D) has become an inevitable area for carbon emissions reduction. Nevertheless, its role in carbon emissions has rarely been examined. In this research, based on the logarithmic mean Divisia index (LMDI) model, the variables affecting the fluctuation of carbon dioxide emissions in the building sector (CEBS) in Jiangsu Province during 2011–2019 were restructured by introducing technological factors related to the construction industry, including energy structure, energy intensity, R&D efficiency, R&D intensity, investment intensity, economic output, and population engaged in the construction industry. From the results, it can be inferred that (1) energy structure, energy intensity, R&D efficiency, and investment intensity operate as inhibitors in increasing CEBS, and investment intensity exerts a more prominent impact on suppressing the growth of CEBS; (2) R&D intensity, economic output, and population engaged have a promotional effect on the fluctuations of CEBS, among which the first factor most actively promoted the increase in carbon emissions, although its role was negligible for economic output and the population; and (3) R&D efficiency, R&D intensity, and investment intensity are the three most critical variables for influencing the CEBS, but they are volatile. The numerical fluctuation caused by the three factors might be correlated to national and local policy interventions. Finally, policy recommendations are put forward for strengthening the management and minimizing the CEBS in Jiangsu Province.

Keywords Carbon dioxide emissions in the building sector (CEBS) · Logarithmic mean Divisia index (LMDI) · R&D efficiency · R&D intensity · Investment intensity

Introduction

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) confirmed that greenhouse gas emissions caused by human activities have led to increasingly severe global warming. Priyadarshi Shukla, the co-chair of IPCC Working Group III, said that in order to achieve sustainable development, all industries need to implement technical measures for energy conservation and emission reduction, which could reduce carbon dioxide from global energy consumption by 40 to 70% by 2050 (IPCC 2022).

China has pledged to take steps to reduce its carbon emissions over the past decade. During the international summit on climate change held in Paris in 2015, China declared a goal to decrease its carbon intensity by 60 to 65% by 2030, relative to 2005 levels. In September 2020, during the 75th session of the UN General Assembly, the Chinese government explicitly stated that it intended to achieve carbon peaking by 2030 and carbon neutrality by 2060 (the Double Carbon Plan). These targets require the provincial

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✉ Boya Jiang
jiangboya@njtech.edu.cn

1   School of Architecture, Nanjing Tech University, Nanjing 211816, China

2   School of Architecture and Built Environment, Deakin University, Locked Bag 20001, Geelong, VIC 3220, Australia

3   School of Architecture, Southeast University, Nanjing 210096, China

governments' promulgation and implementation of carbon emission-related policies to make energy conservation and emissions reduction in various industries binding goals and lay the solid groundwork for achieving peak carbon emissions and carbon neutrality.

Jiangsu Province is situated in the Yangtze River Delta region and along the eastern coastal center of the Chinese mainland. It covers 1.06% of China's total land area and accounts for around 13.32% of China's gross domestic product (GDP). By 2021, Jiangsu Province will possess the highest overall output value in China's building sector, at 4,164.2 billion yuan, with 7.5% growth year-on-year. Jiangsu Province could therefore be considered the leader of the building sector in China. In 2022, the "Implementation Suggestions on the Double Carbon Work" and the "Work Plan for Promoting the Double Carbon in 2022" were released by the Jiangsu provincial government as a response to the national government's objectives and tasks. The papers provide substantial backing for the implementation of the double carbon plan.

The assessment of carbon dioxide emissions in the building sector (CEBS) encompasses both direct and indirect carbon emissions. Direct carbon emissions result from the building sector's production process consuming energy directly; indirect carbon emissions refer to the carbon emissions generated by other sectors due to the building sector's drawing effect (Zhang et al. 2013). The scope of this paper is limited to the direct carbon emissions produced by the building sector. To minimize the CEBS, scientific and technological innovation in building material production, on-site construction, operation processes, and demolition is one strategy. A consensus is emerging about the role of technological innovation and green buildings in R&D. This consensus is reflected in the encouragement of the use of renewable energy, the enhancement of building energy efficiency, and the achievement of sustainable and high-quality development. It is therefore of both theoretical and practical relevance to explore the impact of R&D investment on CEBS in Jiangsu. Exploring the impact of R&D investment on CEBS in Jiangsu is therefore both theoretically and practically relevant.

In terms of research methods, index decomposition analysis (IDA) and structural decomposition analysis (SDA) are two extensively used carbon emissions decomposition methods (Ang 2005, 2000). Compared with the SDA method based on the I-O table, the IDA method requires fewer data and can be used to carry out time series analysis (Ma et al. 2019). There are two categories of IDA methods: the arithmetic mean division index (AMDI) method and the logarithmic mean division index (LMDI) method. The latter may be used to decompose multiple factors with a simple formula and no residual (Men et al. 2019).

Owing to its advantage of completely eliminating residual error in the top-down LMDI index decomposition approach, it has found widespread application in many fields of research, including transportation and industry. Recently, domestic and foreign scholars from both China and other countries have conducted research on the variables that drive the fluctuations in carbon emissions for transportation, industry, and other sectors. As an example, Wang et al. (2011) examined the trend of carbon emissions in China's transportation sector between 1985 and 2009 and established the LMDI model to decompose the forces that contribute to carbon emissions in China's transportation sector into six impacts. Among these, the principal cause of growing carbon emissions is per capita economic activity, whereas the key cause of lowering carbon emissions is transportation intensity. Tian et al. (2014) evaluated the amount of carbon dioxide emissions by China's agriculture sector from 1995 to 2010 and applied the LMDI approach to assess the variables that influence carbon emissions. They concluded that the industrial structure effect, labor effect, and efficiency effect placed significant restraints on China's agricultural carbon emissions, while the economic effect promoted the carbon emissions of the agriculture sector in China. Based on an extension of the Kaya-LMDI model, Ouyang et al. (2015) assess the primary determinants governing emissions of carbon dioxide produced by Chinese industries from 1991 to 2010. Their findings demonstrated that industrial activities accounted for the bulk of the increase in carbon emissions in China's industrial sector, while the biggest contributor to the decline was energy intensity. Han et al. (2018) additionally extended the Kaya identity and established an LMDI framework to investigate the driving effects of industrial carbon dioxide emissions in Jiangsu Province from 2002 to 2015. Based on the results of their analysis, they recommended remedies and provided solutions for reducing carbon emissions from the industrial sector in Jiangsu Province.

Several researchers have also conducted a number of investigations on the CEBS, mainly based on the input–output (I-O) method in the last 20 years. Nassen et al. (2007) evaluated and analyzed the CEBS in Sweden using the top-down I-O approach. From the perspectives of direct and indirect carbon emissions, Qi et al. (2013) established a model of the construction industry's carbon footprint by using the I-O approach and used the Kaya identity to decompose the CEBS into four driving factors. Taking the construction industry in thirty Chinese provinces as the research object, Feng et al. (2014) calculated and analyzed the energy efficiency of the construction industry in each province using the data envelopment analysis (DEA) approach, and they developed the CEBS calculation model. To inquire into the connection between CEBS and GDP in China, Du et al. (2015) used the Kuznets curve and decoupling method by applying the

I-O method. Huang et al. (2018) utilized the I-O approach to investigate the carbon emissions caused by construction activities in 40 countries around the world and put forward measures and prospects for global CEBS reduction.

However, the I-O method for the measurement of CEBS has some disadvantages, such as calculated time delay, the discontinuous time span in the calculation, and an imprecise result. Compared with the I-O method, the benefit of the LMDI decomposition approach is the flexible processing of fluctuant data. In recent years, therefore, academics from both China and other countries have sought to apply the LMDI approach to the investigation of driving variables about national or regional CEBS. Hu et al. (2015) built the Tapio decoupling model and utilized the LMDI approach to examine the decoupling of CEBS and its affecting variables in China between 1996 and 2012. Lin et al. (2015) calculated the overall energy-related carbon dioxide emissions of residential and commercial buildings in China and constructed an LMDI decomposition model to restructure the motivating forces of CEBS into ten variables. Using an LMDI model, Lu et al. (2016) decomposed the driving factors of the construction sector into seven conventional effects based on the estimated CEBS in China between 1994 and 2012. The majority of the increase in carbon emissions was attributable to building materials, whereas energy intensity was the key component in hindering carbon emissions. According to the characteristics of CEBS, Du et al. (2017) calculated and analyzed the direct and indirect CEBS in various provinces of China. According to their findings, there was a distinct disparity in CEBS between provinces, with eastern provinces emitting more than western provinces. Moreover, the national carbon emission intensity exhibits a notable decline. Li et al. (2017) expanded the STIR-PAT model with the Kaya identity and additional urbanization characteristics and utilized the ridge regression approach to examine the CEBS-related driving variables. Using the data from China's CEBS between 2000 and 2014, Song et al. (2018) conducted an LMDI decomposition analysis in order to reach the conclusion that indirect carbon emission intensity significantly contributes to the expansion of CEBS, while indirect CEBS is mainly affected by building materials. According to the research, cement was found to play the largest role, while wood actually slowed the rise of carbon emissions. He et al. (2020) set up an LMDI model to decompose the CEBS in China between 2000 and 2015 into five driving components and came to the conclusion that the two primary influences on CEBS were the per capita steel accumulation and the economic output. Based on these two elements, several practical recommendations for reducing CEBS were proposed.

In summary, most scholars have focused on the driving effects of national and regional carbon emissions, while provincial carbon emissions have been the subject of comparatively few studies, most of which have concentrated on industry, agriculture, and transportation. The literature on CEBS has mostly been subject to the limitation of the industry characteristics, such as energy consumption, energy structure, and population engaged in the building sector, and has given little consideration to its integration over time. Moreover, the influencing factors of scientific and technological innovation have rarely been included in the study of CEBS.

Accordingly, in this paper, data on the CEBS in Jiangsu Province are collected, sorted, and calculated. To analyze the trend of CEBS in Jiangsu Province between 2011 and 2019, the LMDI decomposition model is established to decompose the driving variables into R&D efficiency, R&D intensity, investment intensity, economic output, population engaged in the building industry, energy structure, and energy intensity. Finally, on the basis of the CEBS analysis, suggestions are offered for strengthening carbon emission management to help minimize carbon dioxide emissions from the building industry.

Methodology

Calculation methods of CEBS

The CEBS in Jiangsu Province was calculated according to the carbon emission coefficient method provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. However, the consumption of all kinds of energy is measured by physical quantity in the China Energy Statistical Yearbook, and this calculation method should be converted to standard quantity, being capable of measuring carbon emissions. The CEBS can be calculated according to Eq. (1):

$$C = \sum C_i = \sum F_i \times H_i \times E_i \qquad (1)$$

where C denotes the cumulative energy-related CEBS; C_i refers to the CEBS emitted by energy i; F_i denotes the carbon emission coefficient of energy i; H_i denotes the standard coal coefficient of energy i; and E_i denotes the consumption of energy i.

Table 1 and Fig. 1 detail the specific standard coal coefficient and carbon emission coefficient for each form of energy. Electricity, natural gas, fuel oil, diesel oil, kerosene, gasoline, crude oil, coke, and coal were all taken into account as the main sources of energy.

LMDI decomposition method

In 1998, Ang and colleagues developed the LMDI utilizing the exponential technique. In contrast with other decomposition approaches, the LMDI approach offers the benefits of full decomposition, absence of residual, strong adaptability, and straightforward interpretation. It is therefore widely used by scholars across the globe. The decomposition approach could

Table 1 Standard coal coefficient H_i and carbon emission efficient F_i of various types of energy

Energy	Standard coal coefficient (unit: kgce/kg)	Carbon emission efficient (unit: t/tce)	Energy	Standard coal coefficient (unit: kgce/kg)	Carbon emission efficient (unit: t/tce)
Electricity	0.1229	2.2132	Gasoline	1.4714	0.5532
Natural gas	1.3300	0.4479	Crude oil	1.4286	0.5854
Fuel oil	1.4286	0.6176	Coke	0.9714	0.1128
Diesel oil	1.4571	0.5913	Coal	0.7143	0.7476
Kerosene	1.4714	0.3416			

Data source: China Energy Statistics Yearbook 2020; General Rules for Calculation of Comprehensive Energy Consumption (GB/T 2589–2008)

Fig. 1 Carbon emission factors of the regional power grid in China. (Data source: Carbon emission factors of China's regional grid baseline for emission reduction projects from 2006 to 2017)

Region	Electric power carbon emission factor (kg-CO$_2$/kWh)
North China power grid	0.4578
Northeast China power grid	0.331
East China power grid	0.4923
Central China power grid	0.3112
Northwestern China power grid	0.3232
South China power grid	0.2476

restructure the influencing factors of CEBS, which is suitable to quantify the contribution of each selected factor to the growth of CEBS.

This paper uses the LMDI additive decomposition approach combined with the Kaya identical equation developed by the Japanese academician Yoichi Kaya (1989). This approach is used to split the elements that contribute to carbon emissions into four indicators: (1) carbon intensity, measured by the ratio of carbon emissions to energy usage (C/E); (2) energy intensity, measured by the ratio of overall energy usage to gross domestic product (E/GDP); (3) GDP per capita (GDP/P); and (4) population (P). The model can be stated using the following equation:

$$C = \frac{C}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P \tag{2}$$

where C is the carbon emission; E is the overall energy usage; GDP is the gross domestic product; and P is the total population.

By extending Eq. (2) and integrating new variables, the CEBS changes can be further divided into eight factors, expressed by the following carbon emission equation:

$$C = \sum_i \frac{C_i}{E_i} \times \frac{E_i}{E} \times \frac{E}{GDP_a} \times \frac{GDP_a}{R} \times \frac{R}{I} \times \frac{I}{GDP_a} \times \frac{GDP_a}{P} \times P$$
$$= EI \cdot RE \cdot RI \cdot II \cdot G \cdot P \sum_i F_i \cdot S_i \tag{3}$$

Based on the extension of Kaya identity, the driving factors that may affect the growth of CEBS are added to the right side of the equation, and the changes in the impact of factors on CEBS growth in year t relative to year 0 (the base period) might be obtained based on the additive formula of the LMDI decomposition method.

Given the availability of data, the eight influencing factors are selected. The decomposition method operates on the principle that the LMDI model is employed to systematically restructure the factors using a time-series approach in order to differentiate the impact of each factor on the growth of CEBS. Ultimately, this method enables the determination of the contribution rate of each factor and facilitates the selection of the factors that exert the most significant influence on CEBS.

The definitions of the different variables in Eq. (3) are summarized in Table 2.

The variation in CEBS from year 0 to year t can be restructured into the eight driving factors listed below:

$$\Delta C = \Delta C_t - \Delta C_0 = \Delta F_i + \Delta S_i + \Delta EI + \Delta RE + \Delta RI + \Delta II + \Delta G + \Delta P \tag{4}$$

In Eq. (4), Δ reflects the variation in each driving factor. The effects of each factor on the CEBS variations are as follows:

$$\Delta F_i = \sum_i W(C_i^t, C_i^0) ln \frac{F_i^t}{F_i^0} \tag{5}$$

$$\Delta S_i = \sum_i W(C_i^t, C_i^0) ln \frac{S_i^t}{S_i^0} \tag{6}$$

$$\Delta EI = \sum_i W(C_i^t, C_i^0) ln \frac{EI^t}{EI^0} \tag{7}$$

$$\Delta RE = \sum_i W(C_i^t, C_i^0) ln \frac{RE^t}{RE^0} \tag{8}$$

$$\Delta RI = \sum_i W(C_i^t, C_i^0) ln \frac{RI^t}{RI^0} \tag{9}$$

$$\Delta II = \sum_i W(C_i^t, C_i^0) ln \frac{II^t}{II^0} \tag{10}$$

$$\Delta G = \sum_i W(C_i^t, C_i^0) ln \frac{G^t}{G^0} \tag{11}$$

$$\Delta P = \sum_i W(C_i^t, C_i^0) ln \frac{P^t}{P^0} \tag{12}$$

$$W(C_i^t, C_i^0) = \frac{C_i^t - C_i^0}{ln C_i^t - ln C_i^0} \tag{13}$$

where the carbon emission coefficient of each energy form is a fixed value, and so $\Delta F_i = 0$. The calculations for the remaining seven factors are displayed in Table 4, and it should be noted that no consideration was given to the influence of the carbon emission coefficient.

Current status of Jiangsu construction industry and data source

Jiangsu construction industry's economic development

Between 2011 and 2019, the economy of the Jiangsu construction industry developed rapidly (see Fig. 2). Within these nine years, the provincial GDP grew at an equilibrium

Table 2 Definition of each variable in Eq. (3)

Variable	Definition
C	Total energy-related CEBS in Jiangsu Province
C_i	CEBS of energy form i in Jiangsu Province
E_i	Consumption of energy form i in Jiangsu Province's building sector
E	Total energy consumption in Jiangsu Province's building sector
GDP_a	Gross domestic product in Jiangsu Province's building sector
R	R&D expenditure in Jiangsu Province's building sector
I	Fixed-asset investment in the building sector of Jiangsu Province
P	Population engaged in the building sector of Jiangsu Province
$F_i (C_i/E_i)$	Carbon emissions coefficient: CO_2 emission from the building industry per unit of energy form i in Jiangsu Province
$S_i (E_i/E)$	Energy structure: percentage of usage of energy form i to overall energy consumption in Jiangsu Province's building sector
$EI(E/GDP_a)$	Energy intensity: Jiangsu Province's total building energy consumption per unit of the gross construction product
$RE(GDP_a/R)$	R&D efficiency: ratio of gross domestic product to R&D expenditure of the Jiangsu building sector
$RI(R/I)$	R&D intensity: ratio of R&D expenditure to the investment in fixed assets of the Jiangsu building sector
$II(I/GDP_a)$	Investment intensity: share of total investment in fixed assets to the gross construction output in Jiangsu Province
$G(GDP_a/P)$	Economic output: gross domestic product per capita in Jiangsu Province's building sector

yearly growth rate of 10.29%, increasing from 1512 to 3310 billion yuan, much more than the domestic average for the same time period. Statistics indicate that the progress of Jiangsu Province's construction sector is robust and has a significant amount of untapped potential, but there have been fluctuations, as mentioned in the "Data sources" section. The equilibrium yearly growth rate of GDP from Jiangsu Province's construction sector decreased from 17.60% in 2011–2014 to 2.41% in 2014–2016 and then increased to 8.68% in 2016–2019.

Structure of energy-related CEBS in Jiangsu Province

The CEBS from the consumption of each form of energy in Jiangsu Province can be calculated according to Eq. (1). According to Fig. 3 and Table 3, the structure of CEBS due to energy consumption in Jiangsu Province changed from 2011 to 2019. Prior to 2015, the primary contributor to the comparatively substantial volumes of CEBS was the usage of

diesel energy, while after 2015, the CEBS generated by electric energy exceeded those of diesel energy, which exhibited a significant downward trend. Other energy forms, in descending rank of carbon emissions, included gasoline, raw coal, fuel oil, natural gas, and kerosene. It is worth mentioning that the building sector in Jiangsu Province does not consume coke or crude oil; hence, CEBS are not affected by either. The total energy-related CEBS in Jiangsu Province exhibited periodic fluctuations. The value decreased from 48.260×10^4 tons of carbon dioxide in 2011 to 30.944×10^4 tons in 2019. Moreover, the two periods during 2012–2014 and 2017–2019 reflected a trend of increasing emissions, with corresponding average yearly growth rates of 8.93% and 3.81%. The total CEBS decreased the most during 2014–2015, with an average rate of reduction of around 38.84% each year, as shown in Table 3. The Ministry of Housing and Urban–Rural Development of China (2014) selected Jiangsu Province as one of the comprehensive pilot areas for construction market supervision and building sector modernization. This measure may partly explain the sharp decline in CEBS growth in Jiangsu

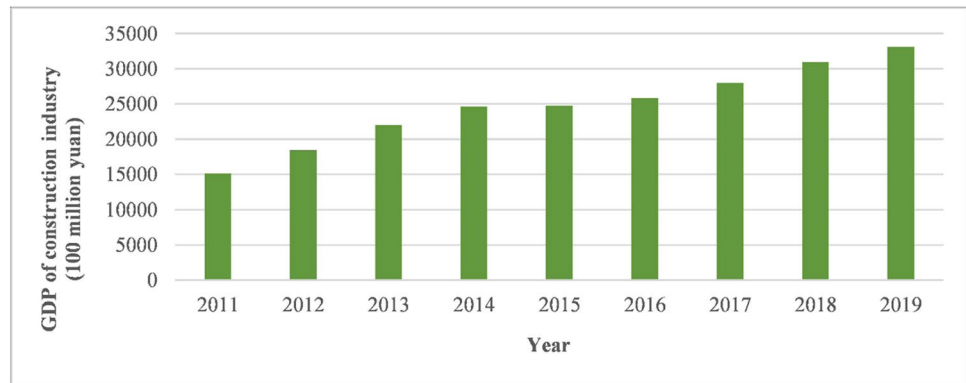**Fig. 2** The trend of Jiangsu Province's construction industry GDP from 2011 to 2019

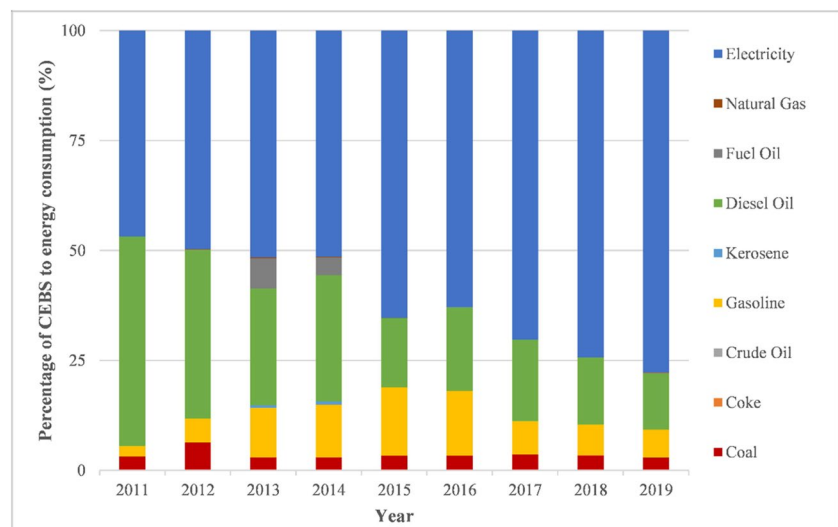**Fig. 3** Proportion of energy-related CEBS in Jiangsu Province between 2011 and 2019

Table 3 Energy-related CEBS in Jiangsu Province from 2011 to 2019 (unit: 10^4 tons)

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Coal	1.399	2.926	1.517	1.629	1.324	1.276	1.287	1.33	1.207
Coke	0	0	0	0	0	0	0	0	0
Crude oil	0	0	0	0	0	0	0	0	0
Gasoline	1.685	3.801	8.962	10.126	9.467	8.612	4.087	4.209	4.119
Kerosene	0	0	0.281	0.352	0	0	0	0	0
Diesel oil	34.446	28.699	22.306	25.675	10.184	11.752	10.615	9.684	8.736
Fuel oil	0	0.071	5.894	3.67	0	0	0	0	0.115
Natural gas	0	0.048	0.119	0.119	0.006	0.006	0.006	0.0119	0.0119
Electricity	10.73	11.721	13.679	14.511	13.317	12.275	12.722	14.876	16.755
Total	48.260	47.266	52.758	56.082	34.298	33.921	28.717	30.111	30.944

Province from 2014 to 2015. As a pilot province, Jiangsu Province took the lead in modernizing the building sector by analyzing and studying the enterprise technology and management mode process, enhancing the government's oversight system, summarizing and promoting mature advanced technology and management experience, and directing and promoting the nationwide development of building sector modernization. In addition, corresponding to its call for "national energy structure adjustment," the building sector in Jiangsu Province had adjusted and upgraded its energy structure, which may have largely reduced the use of diesel fuel, thus curbing the growth of CEBS.

Data sources

Given the consideration of data availability, the annual data during 2011–2019 are utilized in this study. The China Energy Statistical Yearbook (2012–2020) provides data about energy consumption, carbon emission coefficient, and gross energy consumption in the Jiangsu building sector. The standard coal coefficients for diverse energy sources were obtained from the General Guidelines for Calculation of Integrated Energy Consumption (GB/T 2589–2008). The fixed-asset investment in the building sector of Jiangsu Province comes from the China Statistical Yearbook on Construction (2012–2020). The R&D expenditure of the Jiangsu building sector comes from the Jiangsu Science and Technology Yearbook (2012–2020). The data including the GDP of the Jiangsu building sector and the population engaged in the building sector of Jiangsu Province are derived from the Jiangsu Statistical Yearbook (2012–2020).

Results and discussion

Analysis of CEBS driving factors in Jiangsu Province

According to the LMDI model, the CEBS in Jiangsu Province from 2011 to 2019 was restructured into seven influencing factors. The annual variation and cumulative changes of the factors were calculated. These factors include energy structure (ΔS_i), energy intensity (ΔEI), R&D efficiency (ΔRE), R&D intensity (ΔRI), investment intensity (ΔII), economic output (ΔG), and population engaged in the construction industry (ΔP).

According to Table 4 and Fig. 4, the cumulative change of CEBS in Jiangsu during 2011–2019 was -37.43×10^4 tons. The periods 2011–2012, 2014–2015, and 2016–2017 saw negative change stages for carbon emissions growth (-24.43×10^4 tons, -17.77×10^4 tons, and -5.64×10^4 tons, respectively), revealing a trend of carbon emission reduction compared with the baseline (emissions in 2011). The value in 2011–2012 showed a clear inhibitory effect on carbon emissions fluctuation. The five periods 2012–2013, 2013–2014, 2015–2016, 2017–2018, and 2018–2019 saw positive change stages for carbon emissions growth (5.40×10^4 tons, 3.26×10^4 tons, 0.05×10^4 tons, 1.54×10^4 tons, and 0.16×10^4 tons, respectively). In contrast to the emissions in 2011, CO_2 emissions have remained at a relatively modest increase during 2012–2019. Carbon emissions fluctuation was given a strong boost during 2012–2013. In general, the cumulative increase of the Jiangsu CEBS exhibited a downward trajectory, and the influence of any individual driving force on the evolution of CEBS was less significant year by year.

As shown in Table 4 and Fig. 5, energy structure (ΔS_i), energy intensity (ΔEI), R&D efficiency (ΔRE), and investment intensity (ΔII) were negative change factors; they all had an inhibitory effect on the CEBS in Jiangsu Province. Ranked from high to low by their inhibitory effects, the variables were $\Delta II > \Delta S_i > \Delta EI > \Delta RE$. R&D intensity ($\Delta RI$), economic output ($\Delta G$), and population engaged in the construction industry (ΔP) were positive change factors; they all promoted the CEBS in Jiangsu Province. Ranked from high to low by their promotion effects, the variables were $\Delta RI > \Delta P > \Delta G$.

Energy structure

The energy structure reflects the impact of changes in the proportion of energy use in various categories on carbon

Table 4 The annual variation and cumulative changes of the decomposed factors for CEBS in Jiangsu Province from 2011 to 2019 (unit: 10^4tons)

	$\triangle Si$	$\triangle EI$	$\triangle RE$	$\triangle RI$	$\triangle II$	$\triangle G$	$\triangle P$	$\triangle C$
2011–2012	− 5.08	− 5.58	− 25.85	29.78	− 27.05	2.50	6.86	− 24.43
2012–2013	− 2.00	− 1.53	− 7.72	12.49	− 4.26	3.19	5.24	5.40
2013–2014	1.35	− 3.57	− 9.28	13.46	− 4.76	2.98	3.08	3.26
2014–2015	− 13.78	− 4.31	1.18	− 3.50	2.31	0.07	0.25	− 17.77
2015–2016	2.26	− 4.00	5.37	− 4.76	− 0.17	0.85	0.51	0.05
2016–2017	− 5.89	− 1.81	17.77	− 17.17	− 0.96	0.66	1.75	− 5.64
2017–2018	− 0.36	− 1.24	− 1.57	1.25	0.48	3.31	− 0.32	1.54
2018–2019	− 1.06	− 0.25	− 0.76	3.58	− 3.40	1.14	0.90	0.16
Total	− 24.55	− 22.29	− 20.85	35.13	− 37.83	14.70	18.27	− 37.43

emissions, such as coal, gasoline, diesel oil, and electricity (Xu et al. 2016). From 2012 to 2019, the overall energy consumption structure was dominated by electricity; in 2011, diesel was more dominant than electricity (see Fig. 6). In general, electricity energy consumption is gradually increasing, and diesel energy consumption decreased significantly in 2015, which may have been somewhat connected to the conclusion of the 12th Five-Year Program in China. As illustrated in Table 4 and Fig. 6, the CEBS in Jiangsu

Province caused by the energy structure effect in 2011–2019 was − 24.55 × 10^4 tons, showing a strong negative change in general, which was a crucial factor for inhibiting the overall growth of CEBS in Jiangsu Province. However, the changes in 2013–2014 and 2015–2016 were positive, 1.35 × 10^4 tons and 2.26 × 10^4 tons, respectively. The negative change of energy structure reached the maximum in 2014–2015 when the overall inhibition of CEBS was the largest at − 13.78 × 10^4 tons. In 2015, the diesel fuel consumption of

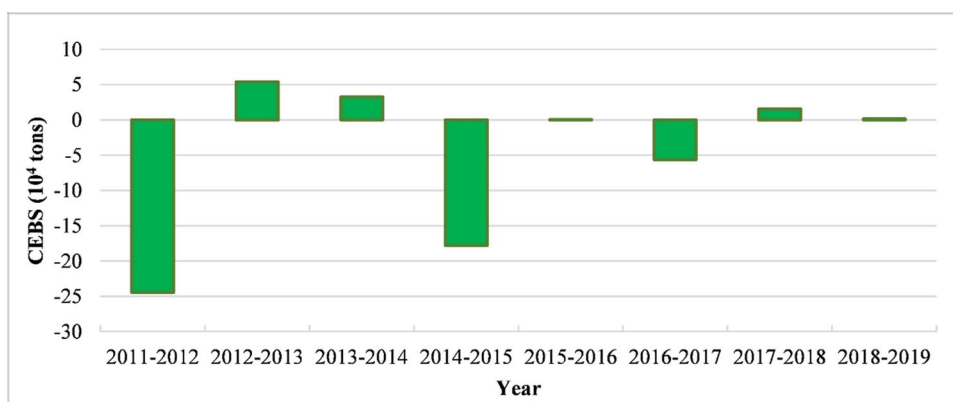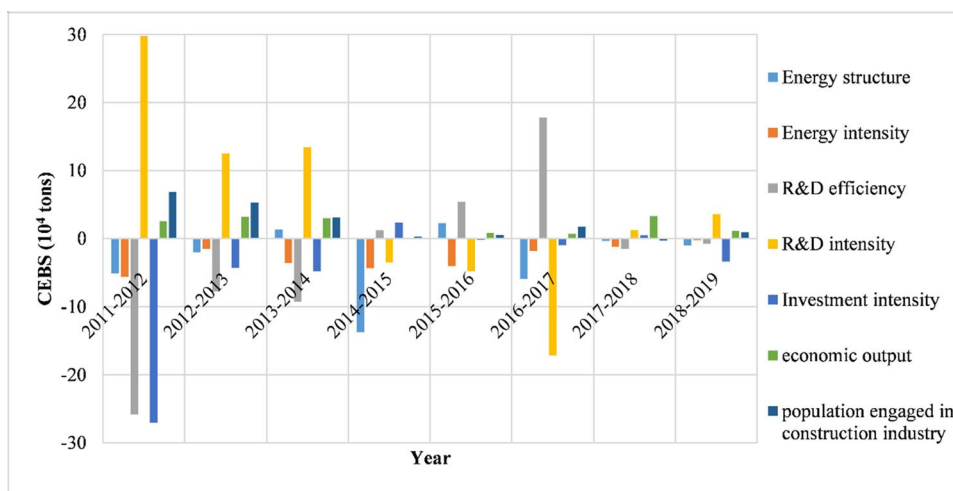**Fig. 4** Variation of CEBS in Jiangsu Province from 2011 to 2019

Fig. 5 Annual variation of influencing factors of CEBS in Jiangsu Province from 2011 to 2019

the building sector in Jiangsu Province decreased by 60.34% compared with the previous year, suggesting that the variation in CEBS was significantly influenced by this change, which may have been related to the Jiangsu Green Building Design Standard issued that year, promoting the optimization and rebalancing of the energy consumption pattern and to some extent inhibiting the growth of CEBS.

The building sector of Jiangsu Province relies heavily on fossil fuel energy, resulting in a substantial quantity of CEBS. Therefore, the reduction of fossil fuel energy consumption can greatly inhibit CEBS. Optimizing the energy structure and expanding the usage of novel, renewable, and non-fossil energy sources may aid in reducing the CEBS in Jiangsu Province.

Energy intensity

The ratio of the building sector's gross energy use to its total gross product can be represented by energy intensity, which measures the energy usage efficiency and relates to the energy consumption fraction of the output. As shown in Table 4 and Fig. 7, the change in Jiangsu Province CEBS attributable to the influence of energy intensity was always negative between 2011 and 2019, with the total change at -22.29×10^4 tons, demonstrating that CEBS was substantially inhibited by energy intensity. In 2011–2012, the inhibition of energy intensity on CEBS reached its maximum at -5.58×10^4 tons. The negative trend slowed in 2012–2013, gradually recovered in 2013–2015, and then stabilized in 2015–2019. Table 3 shows that the carbon emission reduction in 2011–2012 and 2014–2015 is the most obvious, indicating that the suppression of energy intensity on the CEBS in Jiangsu Province may have been caused by government-issued emission reduction regulations, owing to the greatest negative fluctuation in the energy intensity impact in these two phases. For instance, the Opinions of Jiangsu Provincial Government on Further Strengthening Energy Conservation, issued by the Jiangsu Provincial Government in 2011, advocated for enterprises to vigorously promote the transformation of existing energy-saving technologies, introduce new energy-saving technologies, and improve the efficiency of their energy utilization, thus

Fig. 6 Annual variation in CEBS driven by energy structure in Jiangsu Province from 2011 to 2019
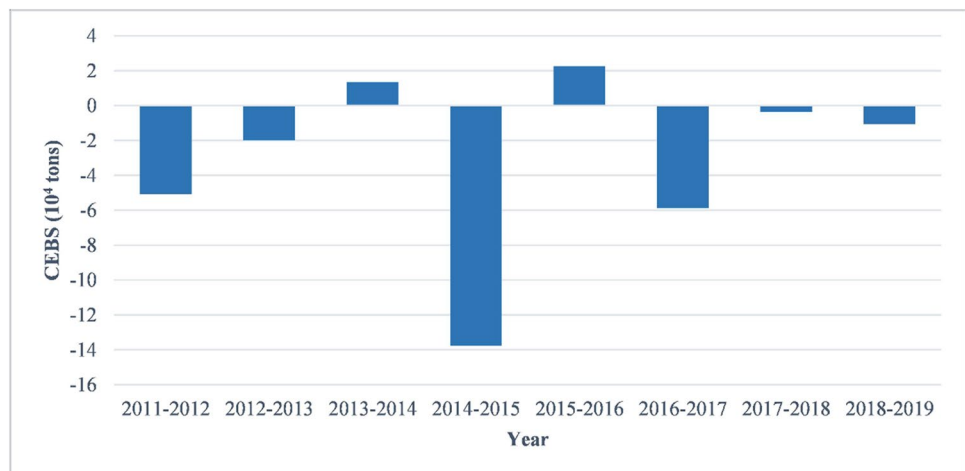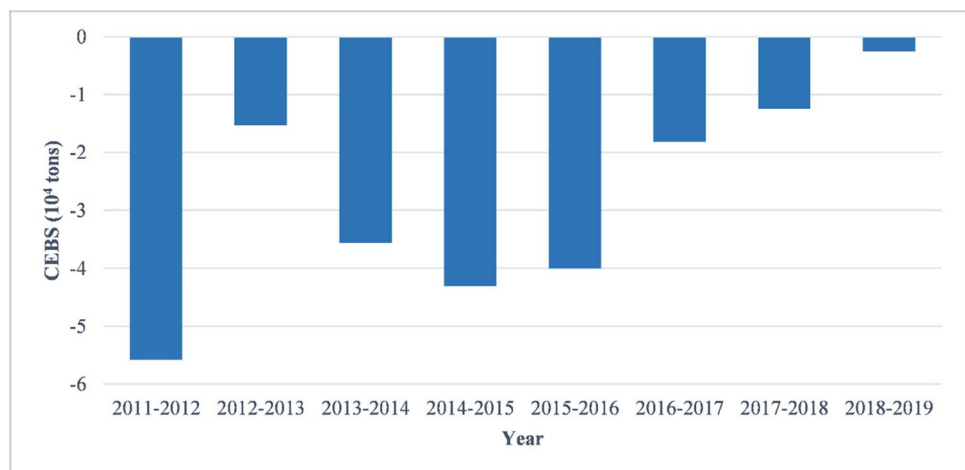

Fig. 7 Annual variation in CEBS driven by energy intensity in Jiangsu Province from 2011 to 2019

accelerating the sustainable development of Jiangsu building sector. In the same way, this policy carried out the quota management of building energy consumption, strictly controlled the production activities with excessive energy usage and strengthened the supervision of law enforcement related to energy conservation.

The construction enterprises in Jiangsu Province should therefore strengthen their investment in technology R&D to improve the energy efficiency of their operations.

R&D efficiency

The ratio between gross product and the expenses of research and development can be used to measure R&D efficiency. As is shown in Table 4 and Fig. 8, the change of CEBS in Jiangsu Province caused by the R&D efficiency effect in 2011–2019 was -20.85×10^4 tons, indicating that R&D efficiency restrained the growth of carbon emissions. The effect varies greatly at each stage, however, indicating significant volatility. For example, the change in the impact of R&D efficiency on CEBS between 2011 and 2014 was negative, and the strongest inhibitory effect on carbon emissions was -25.85×10^4 tons in 2011–2012. The negative trend slowed significantly from 2012 to 2013 and increased slightly from 2013 to 2014. From 2014 to 2017, the variation in R&D efficiency was positive, which had a significant promoting influence on CEBS, and the trend of positive variation is visible year by year. The most significant improvement in R&D efficiency occurred in 2016–2017, and the promotion of carbon emissions was the largest among all factors in the same period at 17.77×10^4 tons. The variation of R&D efficiency in 2017–2019 was negative, although the inhibition on the rise of CEBS was not readily apparent.

It follows that the connection between the influence of R&D efficiency and the increase of CEBS in Jiangsu Province is not stable. This finding shows a strong correlation with the emphasis that construction enterprises place on R&D. R&D expenditures are normally categorized as traditional R&D expenditures and green R&D expenditures. Among them, the primary purpose of traditional R&D expenditure is to improve production efficiency and expand competitive advantages to gain more profits. Due to the lack of consideration for long-term green construction, however, the adverse effect of traditional R&D on resources and the environment could be significant. The purpose of green R&D expenditure is to tackle resource and environmental issues, alleviate the pressure on resources and the environment caused by economic activities, and earn both financial benefits and green ecological profits simultaneously so as to achieve sustainable development.

When enterprise R&D expenditure emphasizes enhancing energy efficiency, the growth of CEBS might be effectively mitigated. For example, the model results show that in the period of 2011–2014, the effect of the R&D efficiency factor on the growth of CEBS was inhibitory, so it is supposed that the green R&D expenditures of the building sector in Jiangsu Province account for a larger proportion of the overall R&D expenditures. The implementation of the following policies would help promote increased green R&D expenditure in the Jiangsu building sector. In 2011, the Jiangsu Provincial People's Government (2011) issued the Opinions of the Provincial Government to Further Enhancement the Work of Energy Conservation, which promoted building energy savings and green building development. In 2012, the Jiangsu Department of Housing and Urban–Rural Development (2012) identified 91 innovative technologies for popularization and 6 outdated technologies for restriction. In 2013, the Jiangsu Provincial Thermal Environment and Energy Saving Design Standard for Residential Buildings was revised, making the 65% energy saving mandatory.

Fig. 8 Annual variation in CEBS driven by R&D efficiency in Jiangsu Province from 2011 to 2019
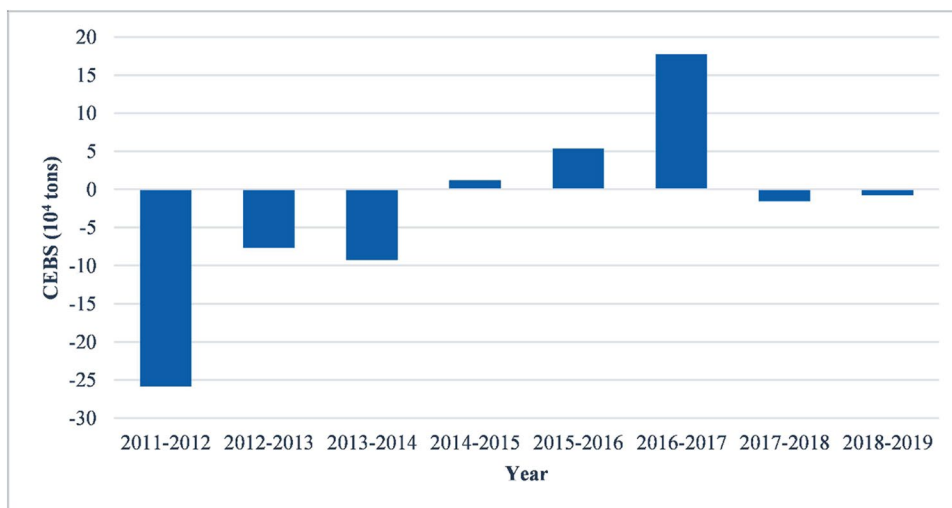
However, when more spending on R&D is required for the advancement of the production efficiency of the construction industry, enterprises will have an incentive to further expand the volume of production, which will result in an increase in the CEBS (Shao et al. 2016), as happened in 2014–2017. Jiangsu People's Government (2014) issued a policy paper to expedite the modernization of the construction sector, foster the transformation and restructuring of the construction sector, and give strong support to the modernization of the construction industry. In general, higher R&D expenditure is not always better. Blindly improving the R&D efficiency of construction enterprises would easily lead to overcapacity, resulting in counterproductive results.

R&D intensity

R&D intensity can be determined by comparing the overall amount of R&D expenditure to the total amount of investment in fixed assets. According to Table 4 and Fig. 9, the change in the CEBS in Jiangsu Province caused by the R&D intensity impact between 2011 and 2019 was 35.13×10^4 tons, indicating that R&D intensity exerted the greatest influence in promoting the growth of CEBS, despite the fact that it varied greatly at different stages. The CEBS exhibited a trend of positive change from 2011 to 2014, and the positive change momentum of R&D intensity from 2011 to 2012 was the largest among all factors in the same period at 29.78×10^4 tons. It exhibited a negative variation from 2014 to 2017, which had a strong inhibitory effect on the CEBS in Jiangsu Province. Compared with other factors in the same period, the negative variation of R&D intensity from 2016 to 2017 was the largest at -17.17×10^4 tons. From 2017 to 2019, the change in R&D intensity was positive, but the promoting effect on CEBS was not obvious.

R&D activity is a double-edged sword, and the impact of R&D intensity on CEBS is predominantly determined by the R&D objective. R&D activities are often categorized as either green R&D or traditional R&D (Zhang et al. 2019). If the purpose of R&D is to promote emission reduction and energy conservation, then technological progress will be reflected in the expansion of the use of clean energy sources and the enhancement of energy efficiency. In this case, technological advances with regard to energy structure could be considered green R&D, which is the inexhaustible driving force for emission reduction and energy conservation. However, R&D activities are mainly focused on expanding manufacturing size and enhancing productivity, and technological progress would increase CO_2 emissions and energy consumption, resulting in Jevons' paradox, which British economist William Stanley Jevons initially put forward in his book *The Coal Question* in 1865 (1906). Therefore, the variation of CEBS in Jiangsu Province under the influence of R&D intensity could provide a reference for estimating the proportion and inclination of green R&D in the construction industry. For instance, the significant negative change from 2014 to 2017 could be understood as the result of the unusually high percentage of green R&D compared to the general R&D in the building sector of Jiangsu Province during this time frame.

Between 2014 and 2017, the government in Jiangsu Province issued a number of guidelines and policies, which promoted the development of green R&D to varying degrees. For example, Jiangsu Provincial Department of Housing and Urban-Rural Development (2014) provided technical and regulatory funding for recommending building energy efficiency and environmentally responsible construction; Jiangsu Provincial People's Congress and its Standing Committee (2015) indicated that Jiangsu Province has taken the lead in carrying out local legislation on green buildings nationwide; Jiangsu Provincial People's Government

Fig. 9 Annual variation in CEBS driven by R&D intensity in Jiangsu Province from 2011 to 2019
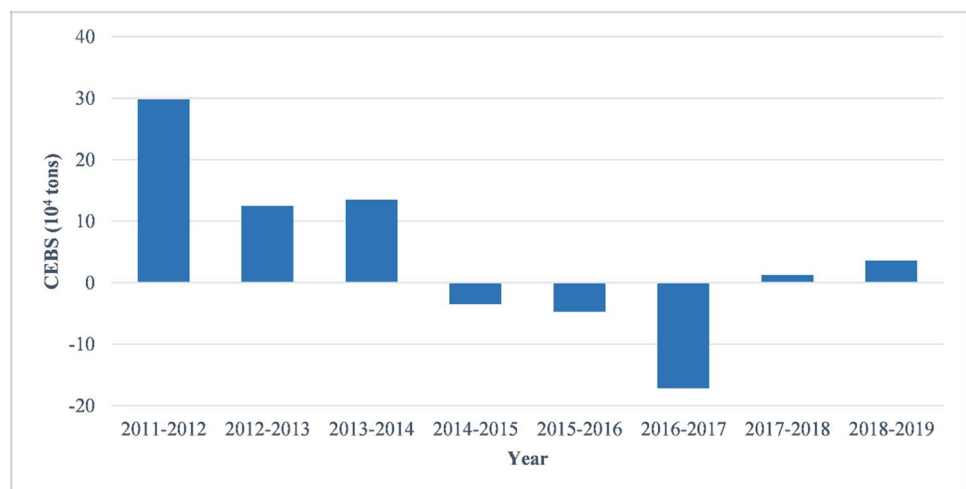
issued Thirteenth Five-Year Strategy for Energy Conservation (2016) required the stringent execution of building energy efficiency criteria throughout the Jiangsu construction industry. The provincial building energy conservation standards will be raised from 50 to 65% in comparison to the building energy consumption between 1980 and 1981. Green buildings would be actively developed, and the utilization of environmentally friendly energy sources in buildings would be promoted.

Investment intensity

The definition of investment intensity is the ratio of total investment in fixed assets to gross construction output. As illustrated in Table 4 and Fig. 10, the change of CEBS in Jiangsu Province caused by the investment intensity effect in 2011–2019 was -37.83×10^4 tons, indicating that investment intensity has the most important inhibitory effect on the growth of CEBS. The negative change caused by investment intensity from 2011 to 2012 was the largest of all factors at -27.05×10^4 tons. Although the changes in 2014–2015 and 2017–2018 were positive, they did not contribute significantly to the growth of CEBS.

Fixed-asset investment refers to the investment in the construction of fixed assets, including building installation, production of components, construction facilities, transportation equipment and operation and maintenance equipment, and scientific research. It covers all stages of building construction, maintenance, and renovation. However, the impact of investment intensity on CEBS must consider the investment scale and structure of the construction industry. Investment intensity is a mixed blessing to the CEBS. Increased investment intensity can not only expand the scale of production, enhance the efficiency of construction machinery and equipment, and increase carbon emissions but also increase the investment in green

buildings and equipment, clean energy, and renewable energy equipment, upgrade construction machinery and equipment, and improve emission reduction, energy efficiency, and energy conservation. In general, except for 2011–2012, changes in CEBS from other phases were not significant. This can be attributed to the government's adoption of a series of policies in the 12th Five-Year Strategy during this time frame, which invested funds in technologies for energy conservation, emission mitigation, and clean energy utilization, thereby curbing CEBS.

Economic output

Economic output refers to the gross domestic product per capita in Jiangsu Province's building sector. As seen in Table 4 and Fig. 11, the change in the CEBS in Jiangsu Province caused by the economic output of the building sector was consistently positive. The overall variation during the study period was 14.70×10^4 tons, indicating that the economic output of the building sector had a promoting impact on CEBS. The influence of economic output was slight, however, compared with other factors, and the positive change from 2017 to 2018 is the largest at only 3.31×10^4 tons. Under the 13th Five-Year Strategy, China's economic growth switched from a focus on fast production to one on quality, aiming at achieving sustainable, high-quality development. At the same time, Jiangsu Province is vigorously strengthening the transformation and innovation of the building industry, intensifying the structural reform on the supply side as part of the national reform of the building sector. The economic output of the building sector therefore only minimally affected CEBS in Jiangsu Province.

Population engaged in the building industry

According to Table 4 and Fig. 12, the variation of CEBS in Jiangsu Province caused by the population engaged in

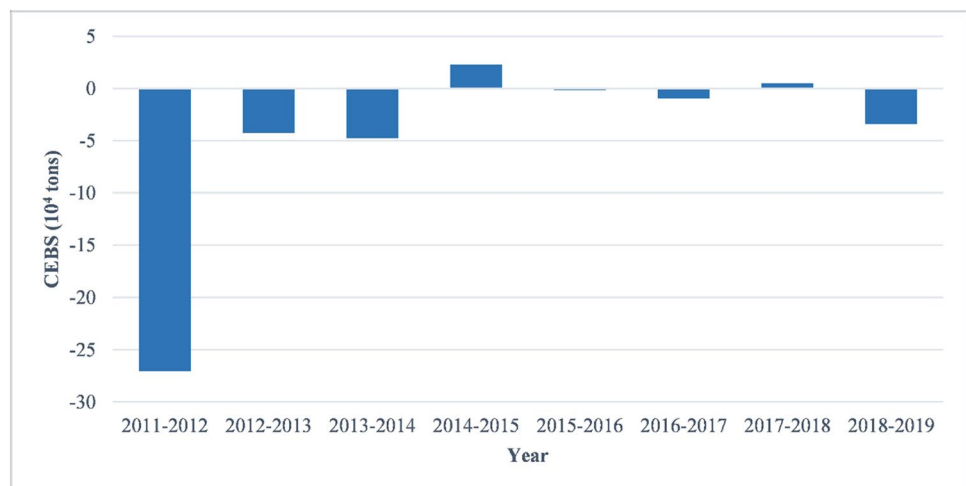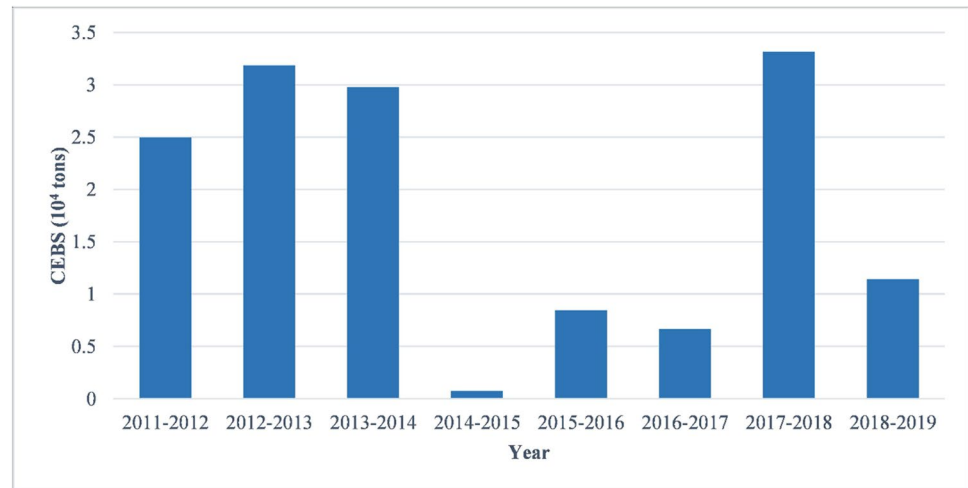**Fig. 10** Annual variation in CEBS driven by investment intensity in Jiangsu Province from 2011 to 2019

Fig. 11 Annual variation in CEBS driven by economic output in Jiangsu Province from 2011 to 2019


the building industry was 18.27×10^4 tons from 2011 to 2019, indicating that this factor had a certain promotion effect on CEBS. The absolute value of the total change of the factor was small, however, indicating that the influence was restrained. From 2017 to 2018, the change was negative, -0.32×10^4 tons, which inhibited CEBS only to a slight degree. From 2011 to 2019, the population engaged in the Jiangsu Province building sector increased at a rate of 5.23% per year on average. The growth of the population engaged in the building industry has led to a rise in the energy requirements for construction equipment and infrastructure, thus driving the growth of CEBS. In addition, the building industry in Jiangsu Province is still a labor-intensive industry, with traditional workers accounting for the majority of the total working population. In the future, with the continuous investment in science and technology, manual labor will gradually be replaced by machines, which may be predicted to have a certain impact on CEBS in the future, such as the energy consumption

generated by the operation of advanced machines will likely lead to more carbon dioxide emissions.

Discussion

Currently, the majority of research conducted on CEBS in China focuses on a national scale, and there is a notable absence of studies at the provincial level. Furthermore, few studies have considered the impact of R&D on the growth of CEBS. Jiangsu Province, being recognized as the province with the most robust building sector in China, should assume a pioneering role in addressing China's dual-carbon plan. This entails undertaking industrial upgrading and transformation initiatives through substantial investments in R&D. By doing so, Jiangsu Province might strive to not only meet but also surpass the national targets for energy conservation and emission reduction. Simultaneously, considering the prevailing circumstances and the growing trend of science and technology

Fig. 12 Annual variation in CEBS driven by the population engaged in Jiangsu construction industry from 2011 to 2019
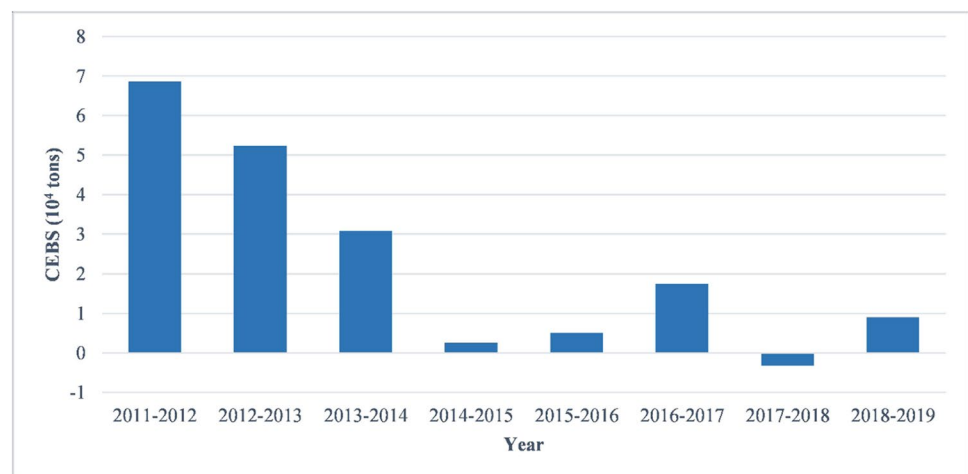
investment in Jiangsu Province, it has practical value to investigate the influence of R&D on the growth of CEBS. Hence, this study incorporates three more indicators, namely R&D efficiency, R&D intensity, and investment intensity, into the examination of CEBS in Jiangsu, building upon the established energy-related effect variables.

The LMDI method is a valuable tool for comprehending the composition and dynamics of energy consumption. It facilitates the examination of the individual contributions of different factors to the overall change in CEBS. Moreover, it aids the building sector in Jiangsu Province by enabling the development of tailored policies aimed at conserving energy and reducing emissions.

The results of the decomposition model allow us to derive the contribution of the impact of the seven influencing factors on the growth of CEBS during the period 2011–2019. The energy structure factor, which in general shows a strong inhibition of CEBS growth, suggests that reducing the use of diesel fuel and increasing the use of new energy sources may be conducive to reducing the growth of CEBS. The energy intensity factor, which measures the efficiency of energy use, has a significant inhibitory effect on the growth of CEBS, so improving energy use efficiency may have a significant effect on carbon emission reduction. The R&D efficiency factor inhibits CEBS growth overall but shows volatility, possibly due to the fact that the structure of R&D expenditures in the building sector varies at each stage. The R&D intensity factor has the greatest effect on CEBS growth but varies widely across stages, depending mainly on the main objectives of R&D activities at different stages. The investment intensity factor is the most important factor inhibiting the growth of CEBS, while its impact needs to take into account the size and structure of investments in the building sector. The economic output factor and the population engaged in the building industry factor have a limited positive effect on CEBS growth.

Nevertheless, there are some constraints. The LMDI method could decompose the total energy carbon emission into the contribution of each factor, but it could not analyze the interaction between all factors. Complex interactions frequently arise among various factors in practice. Therefore, future studies will investigate the relationship and interaction between factors such as R&D efficiency, R&D intensity, and investment intensity in depth, using pertinent theories and methods. Additionally, a comprehensive analysis will be undertaken to assess the collective influence of these factors on CEBS in Jiangsu.

Conclusions and implications

This study calculates the CEBS in Jiangsu Province from 2011 to 2019 and uses an expanded LMDI approach for factor decomposition. The variations in CEBS are decomposed into seven influencing factors: energy structure, energy intensity, R&D efficiency, R&D intensity, investment intensity, economic output, and population engaged in the building industry. The following conclusions and implications may be derived from the examination of the decomposition findings.

Conclusions

(1) From 2011 to 2019, the cumulative increment of CEBS in Jiangsu Province revealed a negative change trend on the whole, and the cumulative change amount was -37.43×10^4 tons. The negative stages of carbon emission growth were 2011–2012, 2014–2015, and 2016–2017, and the year with the greatest carbon emission reduction was 2011–2012. Similarly, 2012–2013, 2013–2014, 2015–2016, 2017–2018, and 2018–2019 were the positive stages of carbon emission growth, and 2012–2013 had the largest carbon emission increase.

(2) The influence of each variable on the alteration of CEBS in Jiangsu Province was weakened year by year. Negative changes occurred in investment intensity, energy structure, energy intensity, and R&D efficiency, which inhibited the growth of CEBS. The changes were -37.83×10^4 tons, -24.55×10^4 tons, -22.29×10^4 tons, and -20.85×10^4 tons, respectively. R&D intensity, the population engaged in the building industry, and the economic output exhibited positive changes, which promoted the growth of CEBS. The changes were 35.13×10^4 tons, 18.27×10^4 tons, and 14.70×10^4 tons, respectively.

(3) Among all the driving factors in this research, investment intensity had the most inhibiting influence on the growth of CEBS, which was mainly due to the negative change in 2011–2012. The effect in other years was not prominent. Energy structure significantly restrained the growth of CEBS, with the strongest negative change in 2014–2015, but positive change in 2013–2014 and 2015–2016. Energy intensity always hurt the growth of CEBS, with the largest inhibitory effect from 2011 to 2012, and the negative effect showed a decreasing trend thereafter. CBES increase was restrained by the R&D efficiency with obvious fluctuation characteristics. The change from 2014 to 2017 was positive, but it promoted the increase of CEBS. R&D intensity had the strongest role in driving the rise of CEBS, but the influence varied across different stages. The change of 2014–2017 was negative, which restrained the increase of CEBS. To some extent, the population engaged in the building sector promoted the increase in CEBS, but the absolute value of the change was small and the influence was limited. There was a slight positive association between the degree of economic output and the rise in CEBS.

Policy implications

(1) Developing low-carbon technologies through scientific and technological innovation, increasing the utilization rate of non-fossil, renewable, and new energy by optimizing the energy structure, and effectively regulating the energy supply and demand structure may be able to reduce CEBS in Jiangsu Province (Liu et al. 2019). The energy system dominated by fossil fuels seems to be an obstacle to low-carbon development, and there is still a large scope for the advancement of non-fossil energy. The building sector of Jiangsu Province must further reduce its dependence on fossil fuels. The government and relevant departments should place great significance on the adjustment and renovation of the building sector's energy structure while vigorously supporting the development of renewable and sustainable energy sources, including photovoltaic power, hydropower, wind power, solar power, and biomass power. At the same time, macro means should be used to supervise and enforce the law on construction enterprises, and environmental carrying capacity ought to be taken into account to boost the policy's benefit and efficiency (Meng et al. 2018).

(2) Green R&D activities are separated from traditional R&D activities in that their primary objective is to encourage energy efficiency and emission reduction, so it is vital to raise the proportion of green R&D to overall R&D spending. Technological progress will increase energy conservation and accelerate the use of environmentally friendly energy, which represents an inexhaustible catalyst for the sustained and healthy expansion of the building sector in Jiangsu Province. Spending on R&D, if used mainly to expand production scale and increase productivity, would result in the growth of CEBS. The government should better provide incentives for the green R&D expenditure of construction activities in Jiangsu Province, establish a green R&D system, and strongly advocate the development of eco-friendly building technologies. The integration of the idea of sustainable development across the whole life cycle of the building sector is important in order to achieve comprehensive low-carbon transformation and green upgrading from a top-down perspective (Li et al. 2023). Examples include carbon capture, utilization, and storage (CCUS), building information modeling (BIM) technology, prefabricated buildings, and green construction.

(3) The building sector in Jiangsu Province would benefit from promoting structural transformation and upgrading, optimizing the structure of the building sector through technological upgrading and innovation, in order to achieve sustainable and superior development. Due to recent advances in the Internet, big data, and artificial intelligence, the construction industry should gradually realize industrial modernization; promote the integration of R&D and the implementation of innovative technologies in the whole lifecycle of architectural design, construction, and operation and maintenance; and drive construction enterprises to transform and upgrade to intelligent construction. (Qi et al. 2021). At the same time, it should place emphasis on the training of R&D personnel in the construction industry, establish various forms of talent training platforms, increase the cultivation and introduction of construction talents, improve the level of architectural design and construction, and encourage enterprises to improve the professional quality of construction employees (Xinhua 2020).

Author contribution Boya Jiang: conceptualization, formal analysis, and writing – original draft; Lin Sun: data curation and writing – original draft; Xiaoxiao Zhang: validation and visualization; Hong Xian Li: supervision and investigation; Baolin Huang: writing – review and editing.

Data availability Data will be made available on request.

Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

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