

CO₂ emissions in China's building sector through 2050: A scenario analysis based on a bottom-up model



Tao Yang^a, Yiqun Pan^{a,*}, Yikun Yang^a, Meishun Lin^b, Bingyue Qin^a, Peng Xu^a, Zhizhong Huang^c

^a School of Mechanical Engineering, Tongji University, Shanghai 201804, China

^b China Aviation International Construction and Investment Co., Ltd., Beijing 100085, China

^c Sino-German College of Applied Sciences, Tongji University, Shanghai 201804, China

ARTICLE INFO

Article history:

Received 1 July 2016

Received in revised form

20 March 2017

Accepted 21 March 2017

Available online 27 March 2017

Keywords:

Carbon emissions

Building sector

China

Scenario analysis

Energy policy

ABSTRACT

Global climate change and energy crises have increasingly impeded the sustainable development of society and economy. With an accelerated process of urbanization and improved standards of living, China has become the largest carbon emitter in the world and therefore has great responsibility and great potential to mitigate global carbon emissions. Accordingly, as the largest source of emissions in China, Chinese buildings should also decrease carbon emissions towards this goal. However, until now, there has been no clear and comprehensive understanding of the carbon emissions in this sector. To fill this gap, we survey the current and future situation. Firstly, we estimate the controlled ceiling of building carbon emission, splitting from the overall reduction goal in China. Then we develop a comprehensive carbon-calculating methodology, the China Building Carbon Emissions Model, using a bottom-up approach, and assess the building carbon emissions based on official statistics. On the basis of that, scenario analysis is used to predict the future trend of carbon emissions in China's building sector. According to our analysis, it is critical to simultaneously control floor space, energy consumption and energy structure to limit the growth of carbon emissions in the building sector. Finally, some relative policy suggestions are also discussed.

© 2017 Published by Elsevier Ltd.

1. Introduction

A building, permanently or temporarily standing in one place, is an artificial structure enclosed within roofs and walls, with all necessary apparatus, equipment and fixtures attached [1]. Over the past several centuries, buildings have provided abundant facilities for various human needs but have also substantially influenced the global environment. According to research, the building sector has become the largest source of greenhouse Gas (GHG) emissions [2] and is responsible for 40% of all energy consumption and one-third of all GHG emissions [3–5].

Including the building sector, the global energy demand and GHG emissions increase with economic development and improved standard of living despite the increasing energy efficiency during the past ten years. Many governments and

organizations in different countries and regions around the world have started to implement various measures to restrain this severe trend. For example, the European Union (EU) [6] announced the 2030 Energy Strategy on January 22, 2014, aiming to promote the development of the EU low-carbon economy, and to improve the competitiveness of energy systems. In this agreement, they promised a 40% cut in GHG emissions compared to 1990 levels, at least a 27% share of renewable energy consumption, and at least 27% energy savings compared with the business-as-usual scenario. Moreover, as the biggest energy consumer and CO₂ emitter in the world [7–9], China plays an essential role in the progress of mitigation efforts and has the due responsibility to adopt a series of practical measures. In 2009, the Chinese State Council promised to decrease CO₂ intensity per GDP by 40–45% in 2020 compared with 2005 levels [10]. In November 2014, agreeing on the U.S.–China Joint Announcement on Climate Change [11], China aimed to achieve its maximum CO₂ emissions in 2030 and to make its best efforts to peak early; China also planned to increase the share of non-fossil fuels in their primary energy consumption to approximately 20%

* Corresponding author. Room A441, No. 4800 Cao'an Road, Department of Mechanical and Energy Engineering, Tongji University, Shanghai 201804, China.

E-mail address: yiqunpan@tongji.edu.cn (Y. Pan).

by 2030. At the 2015 Paris Climate Conference [12], China continued to firmly reiterate their promised actions regarding climate change. Following these policies, the building sector should cooperate with the progress of CO₂ emissions reductions and contribute its own endeavors. For this special position of buildings, the *Fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report* also concluded that “the building sector not only has the largest potential for significantly reducing greenhouse gas emissions, but also that this potential is relatively independent of the cost per ton of CO₂ eq. achieved. With proven and commercially available technologies, the energy consumption of both new and old buildings can be cut by an estimated 30%–50% without significantly increasing investment costs” [13]. Therefore, energy conservation has become one of the primary goals in the development process of the building industry.

In this background, it is critical to analyze various CO₂ emissions scenarios for the building sector in the future and to then accordingly propose several feasible policy advices. Studies related to this scope have been developed over recent years. As early as 1990, the IPCC creatively developed an estimation method for carbon emissions, combining activity level data and emissions factors (carbon emissions = activity level × emissions factor) [14]. In this equation, the activity data quantifies energy consumption caused by urban activities (such as the coal consumed by boiler combustion and the electricity used by residents), and the emissions factor refers to the carbon emissions per unit of activity level (such as a ton of coal or a kilowatt-hour of electricity). Based on the approach proposed by the IPCC, Coondoo et al. [15] analyzed the Granger causality test between carbon dioxide emissions and per capita income and presented different relationships between income and the environment in different countries; Antanasijević et al. [16] estimated the GHG intensity in Europe by the means of general regression neural networks, using the historical data during 2004–2012, and this GHG is also energy-related. In fact, this classical methodology for estimating carbon emissions is still proven practical in use and deduced to further application today. Yeo et al. [17] applied this method to calculate the amount of carbon emissions produced and set this result as the basis for discussing the change in the overshoot ratio after the 2nd Energy Master Plan in the Republic of Korea. Moreover, York et al. [18] built a more advanced model called the STIRPAT model to discuss the relationship between population and carbon dioxide emissions. Ahmad et al. [19] developed an empirical model (considering all of the variables in logarithmic form) to analyze the relationship between carbon emissions, energy consumption, and economic growth in India. Hao et al. [20] established a detailed model to predict the energy consumption and GHG emissions in China's freight transport sector, by subdividing the model into road, rail, water, aviation, and pipeline.

As presented above, the current feasible scientific methods mostly concentrate on estimating the carbon emissions in the entire national industries (including building, transportation, agriculture, forestry, etc.), and there are very few models intended for a particular sector, especially for buildings in China. In 2015, Peng et al. [21] inventively defined a calculation model called the China Building Energy Model (CBEM) and quantified a reasonable limit for energy-use in China's building; however, they only focused

on energy consumption and did not move further to consider carbon emission factors.

In summary, a gap still exists in the current research on building carbon emissions in China. It results from two reasons: One is that these studies rarely focus on the building sector, especially in China, where actually there have been several researches concentrating on other sectors, like transport sector [22], mining sector [23], cement sector [24], power sector [25], manufacturing sector [26], etc.; Another reason is that when some research come to study on the building sector, they mostly focus on energy consumption only, scarcely including carbon emissions. To fill this gap, in this paper, we firstly estimate the controlled ceiling of building carbon emission, splitting from the overall reduction goal in China. It determines the corresponding amount of responsibility and goal for building sector. Then, we establish a bottom-up framework, the China Building Carbon Emission Model (CBCEM), to provide a comprehensive perspective of carbon emissions from different end users of different types of buildings in different areas. Several scenarios of different building floor space and carbon emission intensity are developed, based on different mitigation strategies. This scenario analysis allows us to predict the possible challenges and chances in the future, which offer a good reference for practical policy formulating. Finally, combining the control ceiling of carbon emission and the possible carbon scenarios, we discuss the feasibility of achieving the control target and present some viable mitigation policy suggestions.

2. Control target of China's building carbon emission

To ensure the synchronized responsibility achieved, we should firstly estimate the control target, namely the ceiling of building carbon emission, splitting from the overall reduction goal in China. This ceiling represents the corresponding responsibility and goal for emission reduction in the building sector. It is the basis for the subsequent analysis of practical mitigation policies.

The Chinese government releases authoritative statistic reports every year that include a large amount of data regarding population, energy, buildings, etc. Based on the official statistic data and recent research of Bi [27], we analyzed the control targets for energy consumption and carbon emissions of the building sector in China.

2.1. Building energy consumption

Table 1 illustrates the projections of Chinese national primary energy consumption (Million tons of standard coal equivalent (M tce) and CO₂ emissions (Million tons)) from 2020 to 2050, as cited from the research of Bi [27]. The projections are developed by two major policies. One is the *National Programme of Action to Climate Change 2014–2020* [28] which specifies the goals of energy structure adjustment. The other is *U.S.-China Joint Announcement on Climate Change* [11], in which Chinese government promises the CO₂ emissions in China peaking around 2030. An accelerated process of urbanization and improved standards of living will definitely cause a consistent growth of energy consumption. However, in order to meet the goal of emission reduction, more non-fossil

Table 1
Projection of national primary energy consumption and CO₂ emissions in China.

Year	2020	2030	2040	2050
Primary energy consumption (M tce) [27]	4260	5038	5849	6265
Annual growth rate (%) [27]	1.8	1.7	1.5	0.6
CO ₂ emissions (M t) [27]	8370	9350	9280	9150
Upper limit of building energy consumption (M tce)	1065	1260	1462	1566

energy will be used and the consumption of coal will be controlled. Therefore the carbon emission factor (CEF) will experience a drop in future. As a result, CO₂ emissions will experience rapid growth initially and then slowly decrease after peaking at 2030, even though the primary energy consumption will keep increasing. Specifically, from the detailed data (presented in Table 1), the primary energy consumption in China gradually increases from 3.91 billion tce in 2015 to 6.265 billion tce in 2050; the rate of annual energy consumption growth slows down, decreasing from 1.8% to 0.6%. The CO₂ emissions are 8.01 billion t in 2015, peak at 9.35 billion t in 2030, and then fall to 9.15 billion t in 2050.

Generally, the building share of the national energy consumption in China has remained steady at 20%–25% historically [29], while the share of the industry growth, the main impetus behind the GDP, keeps more than 65% with an annual increasing rate rather steady around 5%. Upon that, considering the 10% share of the transportation sector and its growing trend, to ensure the prosperous and sustainable development of the economy, the share of building energy consumption out of the total energy consumption must be controlled under 25% [30]. Therefore, we specify 25% as the ceiling for the building sector out of the total energy consumption from 2020 to 2050, as shown in Table 1.

2.2. Building carbon emission factor

In addition to the energy consumption, the carbon emission factor, closely tied to energy structure, is essential to estimating carbon emissions. The energy structure in the building sector is different than in the overall national industries. So it is necessary to separate out the future trend of the carbon emission factor in the building sector. Eq. (1) and Eq. (2) are used to the energy structure of building sector and the synthesized CEF.

$$Cb_i = C_i B_i / \sum_i C_i B_i \quad (1)$$

where i refers to the type of primary resources: coal, natural gas, oil, and non-fossil fuels; Cb_i is the share of primary resource i in the total energy consumption of the building sector, reflecting the energy structure in the building sector; C_i is the share of primary resource i in the national energy consumption; B_i is the share of

resource i consumed by buildings compared to that consumed by all sectors.

$$CEF = \sum_i f_i Cb_i \quad (2)$$

where f_i is the carbon emission factor of each kind of primary resource converted to coal equivalents. Note that these values can't be constant due to the innovation in energy utilization.

In Table 2, the various energy shares of buildings in all sectors are calculated as the change trend from 2006 to 2012 [29] with the fitting method, while the share of each energy type in total national energy consumption is determined by scenario analysis. When setting these scenarios, the goal of peaking carbon dioxide emissions around 2030 [31] should be taken into consideration, as well as the policies and regulations like improving coal-fired facilities to cleaner approaches to curb the haze pollution [32]. In addition, as renewable energy is getting more reliable, it is projected to hold a bigger share in the future due to the success in marketization. Meanwhile, China is reducing the reliance on the coal and shifting its economy towards a service-based orientation. Considering all factors above, a base scenario I is set up, where B_i (the share of individual energy consumed by buildings compared to that consumed by all sectors) follows the historic trend and C_i (The share of an individual energy type out of the total energy consumption of all sectors) is cited from B_i 's research [27] to comply with the policy (refers to Table 3). Two more scenarios are established in Table 4 to simulate more stringent policy. Calculated from these assumptions, the results are presented in Table 5. These three scenarios present a progressive relation.

2.3. The control target of building carbon emissions

Using the carbon emission factors, we can convert the energy consumption of the building sector into carbon emissions. As shown in Fig. 1, building carbon emissions will continue to increase under scenario I, whereas it will reach a maximum in 2040 and 2030 under scenario II and scenario III, respectively. It can be seen that under only scenario III will the building carbon emissions change in coordination with the overall industry. Therefore, we select this scenario as the upper limit of carbon emissions in the building sector. Thus, the control targets of the building carbon

Table 2
Energy structure in China during the period of 2006–2012 [29].

	Year	2006	2007	2008	2009	2010	2011	2012
B_i								
The share of individual energy consumed by buildings compared to that consumed by all sectors	coal	54.8%	55.1%	52.9%	53.2%	52.4%	53.4%	53.0%
	natural gas	27.7%	33.2%	33.4%	37.5%	41.5%	40.1%	38.4%
	oil	5.1%	4.5%	4.2%	4.1%	4.0%	4.2%	4.3%
	non-fossil fuel	29.7%	28.9%	30.4%	30.8%	29.8%	29.9%	30.0%
C_i								
The share of an individual energy type out of the total energy consumption of all sectors (National energy structure)	coal	71.1%	71.1%	70.3%	70.4%	68.0%	68.4%	66.6%
	natural gas	2.9%	3.3%	3.7%	3.9%	4.4%	5.0%	5.2%
	oil	19.3%	18.8%	18.3%	17.9%	19.0%	18.6%	18.8%
	non-fossil fuel	6.7%	6.8%	7.7%	7.8%	8.6%	8.0%	9.4%

Table 3
The prediction of energy structure in China [27].

	Year	2015	2020	2025	2030	2035	2040	2045	2050
C_i	Coal	64%	61.8%	60.0%	60.0%	55.0%	50.0%	47.0%	45.0%
	Oil	17.0%	12.2%	11.0%	9.0%	8.0%	8.0%	8.0%	8.0%
	Gas	7.0%	11.0%	11.0%	11.0%	11.0%	11.0%	11.0%	11.0%
	Non-fossil fuel	12.0%	15.0%	18.0%	20.0%	26.0%	31.0%	34.0%	36.0%

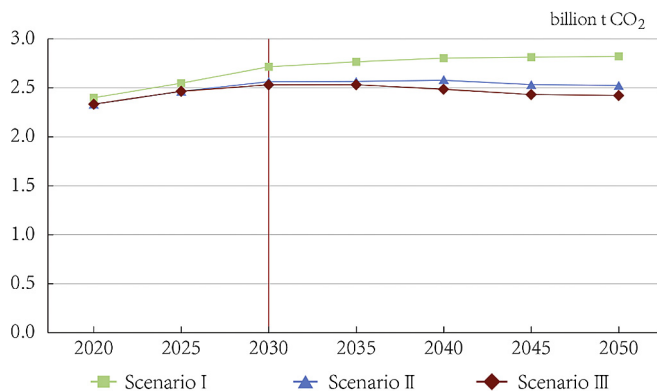
Table 4

Energy structure scenarios in the building sector.

Scenario	Description
Scenario I	The share of an individual energy type out of the total energy consumption of all sectors (C_i) follows the prediction in Table 3. The share of an individual energy type out of the total energy consumption of all sectors (B_i) follows the original trend.
Scenario II	Based on scenario I, the share of oil and natural gas change follows the trends of previous years. The share of the non-fossil fuels consumed by buildings is raised to 35%, and the share of coal gradually declines to 50%, 45%, 45%, and 43%.
Scenario III	Based on scenario I, the share of oil and natural gas change follows the trends of previous years. The share of non-fossil fuels gradually increases to 35%, 38%, 40%, and 40%, and the share of coal gradually declines to 50%, 45%, 45%, and 43%.

Table 5Carbon emission factors in the building sector under different scenarios (kgCO₂/kgce).

Years	2020	2030	2040	2050
Scenario I	2.26	2.16	1.92	1.80
Scenario II	2.19	2.04	1.77	1.62
Scenario III	2.19	2.01	1.70	1.55

**Fig. 1.** Building carbon emissions under the three energy structure scenarios from 2020 to 2050.

emissions are 2.34 billion t in 2020, 2.53 billion t in 2030, 2.49 billion t in 2040, and 2.42 billion t in 2050, as showed in Fig. 1.

3. China Building Carbon Emission Model

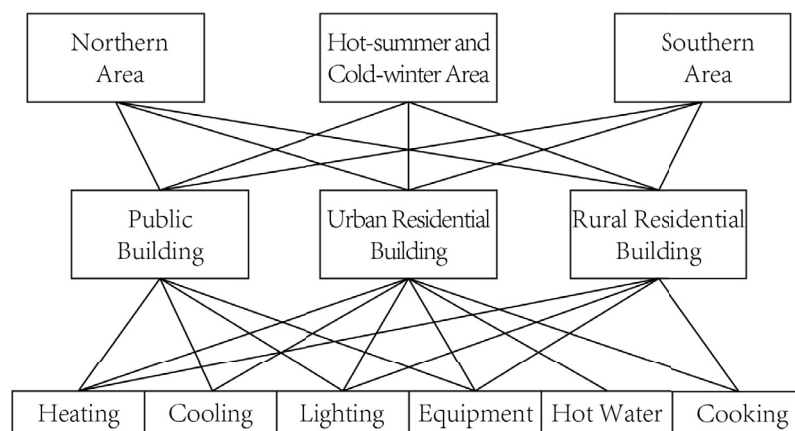
To explore the practical path to achieve the given target, we

establish a model to analyze different influencing factors and assess the carbon emission in buildings under various scenarios. This model is the China Building Carbon Emission Model (CBCEM), a bottom-up framework. It provides a comprehensive perspective of carbon emissions from different end users of different types of buildings in different areas.

Fig. 2 illustrates the construction of the China Building Carbon Emission Model. Building carbon emissions are influenced by many factors, including local climate, building type, urban-rural configuration, and energy end users. Considering these factors, we collected macroscopic statistics data using bottom-up methods, mainly from the *China Statistics Yearbook* [29] and the *Annual Report on China Building Energy Efficiency* [33], and subdivided the model framework into each energy end user for each building type in each thermal zone. This could provide abundant facilities to value the targeted type of CO₂ emissions and its influencing factors.

These factors are sorted through three levels from top to down:

The top level is the climate area level. The climate is important since it determines the heating and cooling load and therefore the overall energy consumption pattern. For example, climates mold different habits in energy consumption, like more heated earthen beds exist in northern cottages while air-conditioners are often used in the south during winter. As shown in Fig. 3, the climate zones could be divided into five parts. That is Sever Cold Zone (SC), Cold (C) Zone, Hot-summer and Cold-winter (HSCW) Zone, Hot-summer and Warm-winter (HSWW) Zone, as well as Temperate (T) Zone. This division has been specified in the *Thermal design code for civil building (GBT50176)* [34] for many years to guide the construction of buildings, thus buildings in these zones have similar thermal properties. In this paper, we aggregate the five regions to generate three main climate areas (Northern, HSCW, and Southern). The reasons are as follows: the temperate region holds only 6% of china's population and rather small area, so we merge it with

**Fig. 2.** Framework of the China Building Carbon Emission Model.

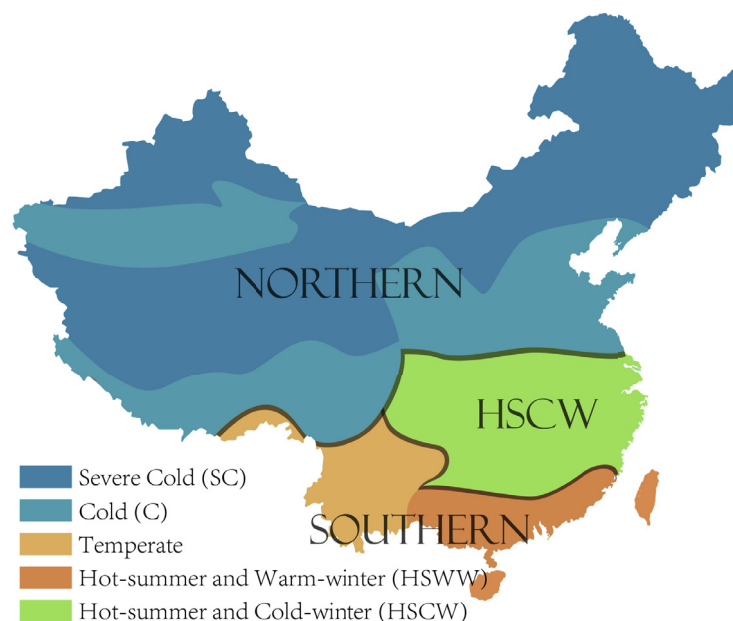


Fig. 3. Climate zones in China.

HSWW region, forming southern area; considering that SC and C regions have the similar climate and both of them apply district heating systems only, we forge them into the northern area. This simplification, widely adopted in general research and discussion in China [32], will largely facilitate the following scenario analysis without prejudice to the results.

The middle level is the building type level. According to the situation in China, buildings are categorized into three types: public buildings (where people participate in various public events, including offices, retail stores, hotels, schools, and hospitals), urban residences and rural residences. This classification is in line with the stipulation in the *Regulations on Energy Conservation in Civil Buildings (2008)* [35]. As the statistical data of energy-use is generally a general average rather than collected separately according to a certain detailed type of public building, we analyze the carbon emission of public buildings as a whole. Further detailed policies of the special segments could be discussed with the specific

conditions or more subdivided data in the future on the basis of the whole analysis we have conducted.

The bottom level is the end-user level. The carbon emissions due to various energy end users such as heating, cooling, lighting, appliances, hot water and cooking are calculated for each building type.

Overall, we develop 42 carbon-calculating paths to assess the carbon emission of buildings in China. All of the three levels are categorized according to the categorization in the general research and data in China, and is adequate to cover all the basic situations from different climate levels, different building types, and different end-uses. A more specific division will generate a more complicated calculation, and bring few improvements on the reliability of the model.

Based on the IPCC model, a prototype of the calculation model combining activity level data and emission factors to estimate carbon emissions [14] can be described as “carbon emission

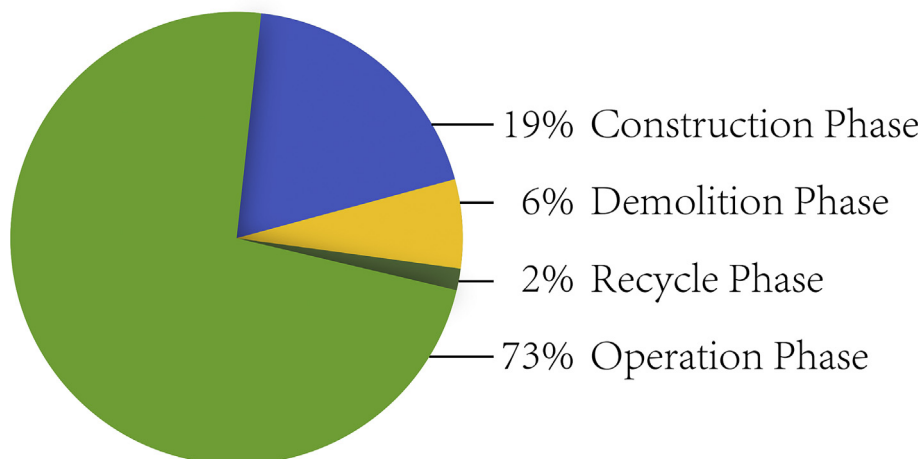


Fig. 4. Energy consumption of China's building sector in 2012 [29].

(CE) = building floor space (BFS) \times carbon emission intensity (CEI)". Considering the major role of buildings' operation phase in the mitigation path (presented in Fig. 4) and the fact that other phases of the building life cycle, including construction, demolition, and recycling, mainly depend on the construction industry, but have nothing to do with the energy conservation of buildings, this study focuses on the CO₂ emissions in the operation phase of buildings, different from the usual concept of the whole building life cycle's carbon emissions.

Eq. (3) presents the calculation model. CEI can be described as the product of the final energy use intensity (EUI) and carbon emission factor (CEF). The consumption of all types of primary resources is multiplied by the corresponding CEF to generate CEI.

$$CE_y = \sum_t \sum_r \sum_k BFS_{y,t} \cdot TS_{y,t,r} \cdot CEI_{y,t,r,k} \quad (3-1)$$

$$CEI_{y,t,r,k} = EUI_{y,t,r,k} \cdot CEF_y \quad (3-2)$$

where CE_y is the amount of carbon emission in year y (t CO₂); $BFS_{y,t}$ is the total building floor space of building type t in year y (m²); $TS_{y,t,r}$ is the share of the building floor space of building type t in climate area r in year y (%); $EUI_{y,t,r,k}$ is the energy end use k of building type t in climate area r per m² in year y (tce/m²), which is presented after transformed into the standard coal equivalent; and CEF_y is the carbon emission factor in year y (t CO₂/tce).

The calculation was conducted from the bottom (end-user level) to up (climate area level), and the parameters in Eq. (3) are predicted by scenario analysis to estimate the carbon emissions of various types of buildings in China and to eventually propose some policy suggestions.

4. Scenario analysis of building carbon emissions in China

Building carbon emissions are determined by the floor space and the carbon emissions intensity. For the future in China, various influential factors exist: on one hand, China is experiencing an accelerated urbanization process and improved standards of living, which will result in more energy activities and thus more carbon emissions; on the other hand, the Chinese government has released several industry regulations and technical specifications, trying to

improve building energy efficiency through policy and technology and to slow down the growth rate of carbon emissions.

After specifying the total control target of building carbon emissions in China, in this section we analyze the feasibility of its realization by conducting scenario analysis of the two main influencing factors: building floor space (BFS) and carbon emissions intensity (CEI, defined as the carbon emissions per building floor area). The future trends are both elaborated following the introduction of historical data. It is noted that the year 2020 is the landmark node for the carbon mitigation action of the united countries of the world and is also the watershed of China's modernization construction, which drives different policies in China. After the accomplishment of a moderately prosperous society in 2020, policies can be more stringent focusing on energy and construction, so projections on this time point call for precision. Therefore, the focused period of this study is accordingly divided into two stages, namely, before 2020 and after 2020.

4.1. Building floor space

4.1.1. Historical data

Fig. 5 illustrates the building floor space in China from 2000 to 2012 [29]. From the historical data, China's floor space has witnessed a general growth trend during this time, with some slight fluctuations in the increasing rate. Urban residential buildings increased the fastest, with floor space growing from 4.41 billion m² in 2000 to 15.38 billion m² in 2012, which largely results from the accelerated urbanization in recent years. The floor space of urban residences in the three different areas (the northern area, the hot summer and cold winter area, and the southern area) all experienced synchronous growth. The growth rate of rural residential buildings, which was 18.18% from 2000 to 2012, is the smallest among the three building categories. Rural residential buildings account for the most area out of the building types, but this portion decreased from 72.37% in 2000 to 49.19% in 2012. The floor space of buildings in the hot summer and cold winter area remained the highest, which to some extent is related to the total area and population in this region.

4.1.2. Future trend

We use different methods to forecast the future trend of the

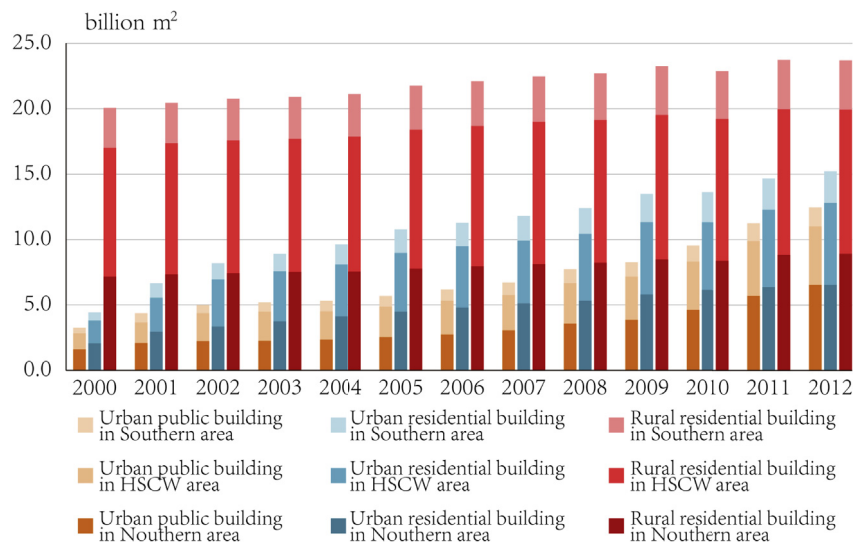


Fig. 5. Building floor space in China [29].

building floor space in China in the two stages: in the first stage (before 2020), the historical data are sufficient for us to use the GM(1, 1) gray model [36] and the trend fitting method for the prediction; in the second stage (after 2020), we change to scenario analysis because the gray model of GM(1, 1) is unable to obtain reliable results.

The GM(1, 1) grey model [36] is a time series forecasting model and one of the important models in the grey model group. Liu S. et al. have brought GM(1,1) into the residential BFS per capita prediction of Shanghai and justified its accuracy in model theory [37]. In his research, the projecting value 18.6 surpasses the government's goal of 14 and is closer to the statistical data 22.86. Similar results can be found in the work of Liu W. et al. [38] and both indicates that the short time prediction might be more reliable.

With the feature of requiring minimum data (usually only four continuous observations) and offering convenience in computational applications with MATLAB, this model has been widely applied in various areas, such as society, economy, agriculture, and industry [39–42]. The GM(1, 1) model has the features of both differential and difference equations. Its whitened differential Eq. (4) and the restored values of raw data Eq. (5) are presented below.

$$\hat{x}^{(1)}(k+1) = (x^{(0)}(1) - b/a)e^{-ak} + b/a \quad (4)$$

$$\hat{x}^{(0)}(k+1) = x^{(1)}(k+1) - x^{(1)}(k) = (1 - e^a)(x^{(0)}(1) - b/a)e^{-ak} \quad (5)$$

$$\hat{a} = [a, b]^T = (B^T B)^{-1} B^T Y \quad (6)$$

$$B = \begin{bmatrix} -\frac{1}{2}(x^{(1)}(2) + x^{(1)}(1)) & \cdots & -\frac{1}{2}(x^{(1)}(n) + x^{(1)}(n-1)) \\ 1 & \cdots & 1 \end{bmatrix}^T \quad (7)$$

$$Y = [x^{(0)}(2) \quad x^{(0)}(3) \quad \dots \quad x^{(0)}(n)]^T \quad (8)$$

where a and b are the unknown parameters forming parameter vector \hat{a} which can be solved by a least square estimation method with Eqs. (6)–(8). $k = 1, 2, \dots, n$. refers to time series.

Taking the whole urban residential BFS per capita for example, we apply the GM(1,1) to process the data from 2002 to 2012 (listed in Table 6). It turns out the prediction of BFS per capita in 2020 is 33.2, which is close to the goal of 35.0 suggested by the 13th Five-Year Plan [43]. Likewise, we can get the per capita BFS value of each type of building in each climate area, altogether 9 paths, then multiply them by population prediction of the corresponding climate area to generate BFS predictions (showed in Fig. 6).

The final prediction results in 2020 are illustrated in Fig. 6. The total public BFS is 16.1 billion m^2 and the rural BFS is 22.9 billion m^2 , which complies with the goal 40 m^2 per capita [43] after divided by the predicting rural population [44,45].

In the second stage, this scenario analysis for building floor

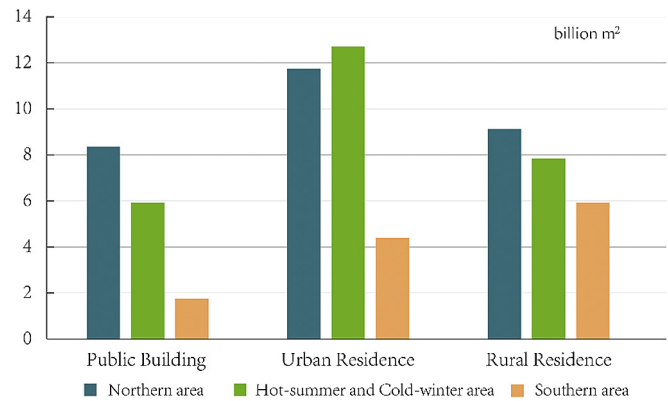


Fig. 6. Prediction of building floor space in 2020.

Table 7
Population and urbanization in the period of 2030–2050 [27].

	2030	2040	2050
Population (Billions)	1.47	1.46	1.44
Urbanization rate (%)	72.2	74.9	75.4
Urban population (Billions)	1.06	1.10	1.09
Rural population (Billions)	0.41	0.37	0.35

space is developed based on the relationship with population and BFS per capita during the corresponding periods in China.

According to the research of Bi [27], China's population will peak at 1.47 billion in 2030 and then decrease to 1.44 billion in 2050. The urbanization will also expand, increasing from 61.2% to 75.4%, but the rate will be slowing down (see Table 7). Based on the population and urbanization trends, especially in the watershed year 2020, we selected three typical scenarios for predicting the BFS, as presented in Table 8. The gray model could give much more aggressive predictions in the years after 2020, so we compile these uncontrolled values in the base scenario A. Rural population will continue to decrease due to urbanization, and the rural BFS per capita will definitely increase, so total rural BFS should be controlled under 24 billion [33]. Alternatives B and C are based on scenario A with stricter controls on the BFS.

The building floor areas of various building categories under various scenarios were predicted and are illustrated in Fig. 7. The building floor space under scenario B is 86.31 billion m^2 in 2030 and 101.88 billion in 2050, less than that under scenario A. The building floor space under scenario C is 89.29 billion m^2 in 2050, which somewhat exceeds the ceiling value of 80.00 billion m^2 proposed by Jiang et al. [30] but is below the ceiling value of 94.11 billion m^2 from the United Nations Environment Programme [46]. The average residential building floor space per capita is 45.07 m^2 , which matches the value of 45 m^2 proposed by the UNEP control model. In addition, by the end of 2012, China's average urban residential building floor space per capita was 32.9 m^2 [29], while this value will gradually increase to 33.19 m^2 in 2020, 34.52 m^2 in 2030 and 36.26 m^2 in 2050 based on our prediction in this paper. As the standard of living continues to increase, there will be a higher demand for larger residential spaces. Meanwhile, considering healthy

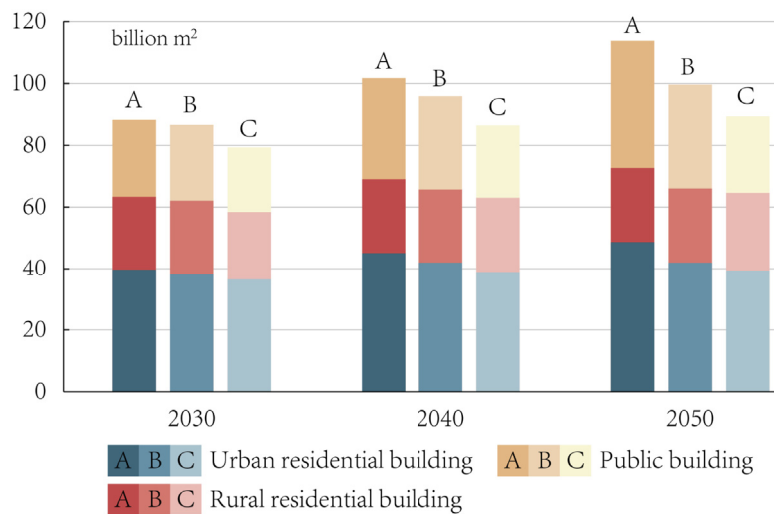
Table 6
BFS per capita from 2002 to 2012 [29].

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
$x^{(0)}(i)$	24.5	25.3	26.4	27.8	28.5	30.1	30.6	31.3	31.6	32.7	32.9
$x^{(1)}(i)$	24.5	49.8	76.2	104.0	132.5	162.6	193.2	224.5	256.1	288.8	321.7

Table 8

Scenario analysis of building floor space in the period of 2030–2050.

Scenario	Scenario description
Scenario A: uncontrolled building floor space	<ol style="list-style-type: none"> 1. The average urban residential building floor space per capita changes following the trend from 2008 to 2012. 2. The average public building floor space per capita changes at the lowest rate from 2008 to 2012. 3. The average rural residential building floor space increases from 22.9 billion m² in 2020 to 24 billion m² and holds still in the future.
Scenario B: mild control on building floor space	<ol style="list-style-type: none"> 1. The average urban residential building floor space per capita increases by 8%, 6%, and 5% each decade. 2. The average public building floor space per capita increases by 25%, 20%, and 15% each decade. 3. The average rural residential building floor space increases from 22.9 billion m² in 2020 to 24 billion m² and holds still in the future.
Scenario C: strict control on building floor space	<ol style="list-style-type: none"> 1. The average urban residential building floor space per capita increases by 4%, 3%, and 2% each decade. 2. The average public building floor space per capita increases by 8%, 8%, and 6% each decade. 3. The average rural residential building floor space increases by 35%, 20%, and 10% each decade.

**Fig. 7.** Prediction of building floor space under scenarios A, B and C.

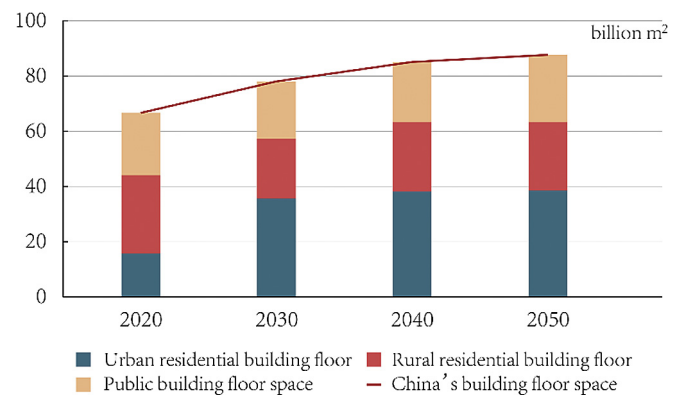
economic development and stabilized societal improvement, the Chinese government is bound to release several relative policies and regulations to conduct positive control; therefore, the building floor area will not increase sharply without a limit. Concerning all of the factors above, we predict that the urban residential building floor area per capita shows a strong operational possibility. Another interesting point is that the building floor space in rural areas will not significantly increase in the future because many rural dwellers will become urban residents and migrate to cities due to the burgeoning urbanization in China. Therefore, the prediction under scenario C is the most reasonable for the current situation. Further details are presented in Fig. 8.

4.2. Carbon emissions intensity

4.2.1. Historical data

Carbon emissions stem from the consumption of energy in various operational end-use activities. This energy consumption can be divided into different end users, as illustrated in Fig. 2. Taking the situation in 2011 as an example, Fig. 9 displays the detailed characteristics of carbon emissions intensity of different types of buildings in various areas.

For public buildings, the end users of carbon emissions consist of heating, air conditioning, lighting, and equipment. Among these, the carbon emissions intensity of urban heating in the northern area is the highest and is much higher than that of the other end users, such as cooling, lighting, and equipment as well as heating in

**Fig. 8.** Prediction of building floor space under Scenario C.

the hot summer and cold winter area. This large value is attributed to the district heating system supplied by the municipal network in northern China. However, with the preliminary application of various energy conservation measures (ECMs), such as enhancing the thermal insulation of exterior walls, increasing the proportion of high-efficient heating sources, and improving the efficiency of the supply system, the carbon emissions intensity of urban heating in the northern area has been decreasing in recent years. Fig. 10 shows this downward trend.

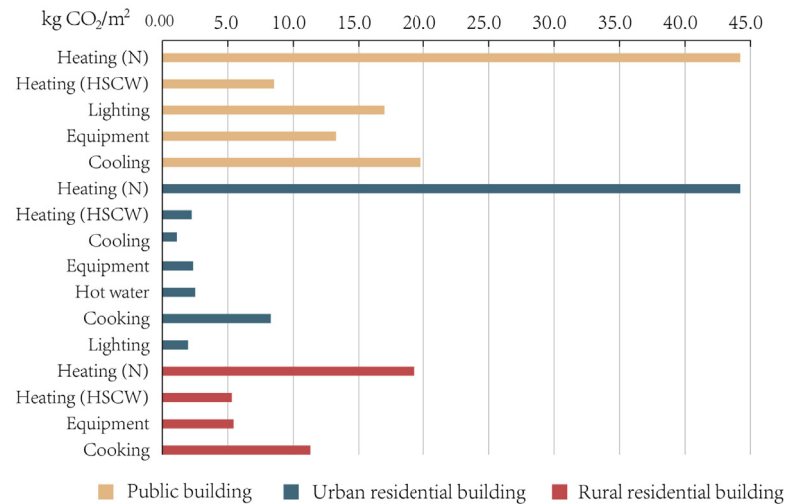


Fig. 9. Carbon emissions intensity of different types of buildings in various areas in 2011 [29,33] (N stands for the northern area; HSCW stands for hot summer and cold winter area).

Similar to that of public buildings, the carbon emissions intensity of heating in the urban residences in the northern area were the largest factor in 2012. However, the emissions from other end users are significantly lower than that in public buildings. In 2012, the carbon emissions of lighting from public buildings were 16.96 kg/m², while those from urban residence were 1.96 kg/m², which is 88.44% smaller than the former. This difference exists due to the diversities of the environmental standards and user habits in different building spaces. For example, Chinese people staying in their own residence tend to control the indoor environment in partial spaces during discontinuous time periods, while environmental control in public buildings usually covers entire working places during the continuous working time.

The carbon emissions intensity of heating from rural residences is lower than that of urban areas. One reason for this is that the biomass energy consumed in rural areas is not included in the official statistics. In the future, the proportion of biomass energy will decrease because more people prefer to use commercial energy resources. Similarly, carbon emissions in rural areas come from various energy end users, such as heating, cooking, and equipment (including lighting). Their carbon emissions are continuously increasing, as illustrated in Fig. 11. On one hand, as more and more household appliances are used in rural residences, energy consumption will inevitably increase. On the other hand, the application of energy efficiency techniques, such as developing biogas

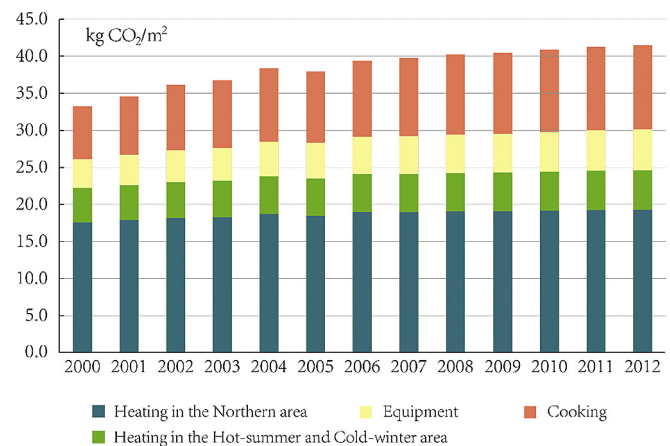


Fig. 11. Carbon emissions intensity from rural residences [29,33].

plants or improving building envelopes, will limit the increasing carbon emissions. In addition, the population of rural residents is decreasing as the urbanization rate is expected to increase [47], which also decreases the energy consumption and therefore the carbon emissions.

Fig. 12 presents the trend of the total building carbon emissions, which is compiled based on the energy consumption data from Tsinghua University Building Energy Research Center (THUBERC) [33,47,48] and the building floor areas and carbon emission factor in National Bureau of Statistics of China (NBSC) [29]. It is obvious that the total amount of carbon emissions continuously increased from 2000 to 2012.

4.2.2. Future trend

The design standards for energy efficiency of various types of buildings have been implemented in succession in China since 1986. The first standard, the *Design standard for energy efficiency of residential buildings* (JGJ 26–1986) [49], was applied to space heating in the northern area. The Chinese government formulated stricter codes and standards for energy efficiency in steps, taking the building energy consumption in 1980s as the baseline. The first stage is a 30% improvement based on the energy efficiency in 1980s,

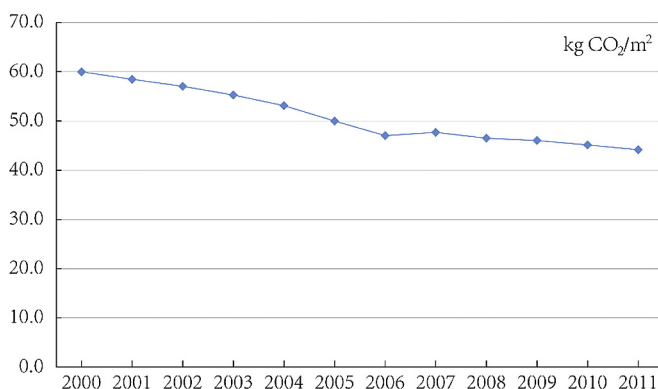


Fig. 10. Carbon emissions from urban heating in northern China [29,33].

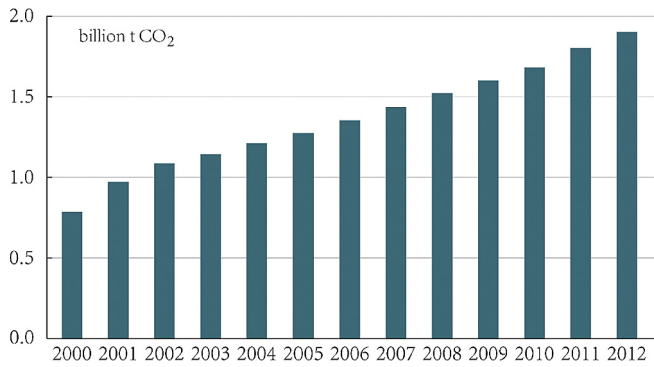


Fig. 12. Trend of total carbon emissions from buildings in China [29,33].

known as the 30% Energy Efficiency Policy, and the second stage is another 30% improvement from the first stage, namely, $30\% + 70\% \times 30\% = 51\%$, known as the 50% Energy Efficiency Policy. Following this, the third stage is the 65% Energy Efficiency Policy, which is the current stage. Moreover, according to the statistics of the *Special planning on building energy conservation during twelfth five-year-plan period*, the average coverage ratio of energy conservation building in 2010 is 20.28%. For some well-developed regions, such as Shanghai and Tianjin, this data could reach around 30%. Therefore, considering the comparison of different levels of policy controls, from strict to mild, three scenarios before 2020 and four scenarios after 2020 (during the period of 2030–2050) were developed based on these policies, and are listed in Table 9.

At the current development stage, no clear evidence that a Kuznets curve between income level and energy consumption and conservation activities will appear [50]. Citizens are mostly willing to improve their living standard regardless of energy consumption. Under the base scenario of Scenario 1 before 2020, the standard of living of people in China is continuously improved, while no new energy efficiency policies are implemented by the Chinese government. Therefore, carbon emission from various energy end-users will probably change following the previous growth trend from 2000 to 2012. Moreover, we propose two other scenarios: in Scenario 2, the government will implement new mild energy policies and in Scenario 3, the government will implement strict energy policies to further control the growth of carbon emissions. The main driving forces are the level of focus that the Chinese government gives to energy efficiency and environmental protection and the improvement of building technologies in China. Therefore, as stated above, the energy efficiency in 2020 is assumed to be

Table 9-1

Energy efficiency trends for different scenarios (before 2020).

	Scenario 1	Scenario 2	Scenario 3
Energy efficiency growth rate (compared with 2010) (%)	The same as the trend from 2000 to 2012	30%	30%
Coverage ratio (%)*		30%	35%

Table 9-2

Energy efficiency trends for different scenarios (after 2020).

		Scenario I	Scenario II	Scenario III	Scenario IV
Energy efficiency growth rate (%) (compared with the previous decade)	2030	The same as the trend from 2012 to 2020	30%	30%	30%
	2040		30%	30%	30%
	2050		30%	30%	30%
Coverage ratio (%)	2030		25%	30%	30%
	2040		25%	30%	25%
	2050		25%	30%	20%

improved by 30% based on that in 2010, covering 30% (Scenario 2) and 35% (Scenario 3) of all the buildings.

In the years after 2020, considering the increased uncertainties resulting from the long-span period, four scenarios are defined. Scenario I is the base scenario, which is defined the same as that on the first stage, namely, the carbon emissions intensity follows the previous trend without implementing new energy efficiency policies. On this basis, we also develop another three scenarios for possible policies from the Chinese government, corresponding to strict, increasingly strict, and mild energy policies, respectively: the energy efficiency goes up by 30% at the end of every ten years, covering 25% (Scenario II), 30% (Scenario III) and (30%, 25%, 20%) (Scenario IV).

5. Results and discussion

Fig. 13 presents the building carbon emissions in 2020 under different scenarios. This prediction follows the comprehensive consideration of increased space heating in the southern area of China, changing residential living habits, and energy structure adjustments. The people dwelling in the southern area of China will improve the heating condition at home, which will result in higher energy consumption. Moreover, China's urban residents will dramatically increase to 72.2% by 2030 according to the prediction of Bi [27]. However, during the urbanization process, there is always a certain inertia in the living habits of residents migrating from rural to urban areas, which means that their lifestyles will not change as quickly. Therefore, the short-term partial maintenance of rural energy-use habits will account for a weight in the carbon emissions intensity of urban residences.

Under scenario 1, the carbon emissions in the building sector will not be able to reach the goal of the limit control proposed in section 3, so this scenario is not considered. Moreover, considering the stable and successful implementation of the energy efficiency policy, we select the mild scenario 2 in 2020 as the prediction basis for assessing the situation after 2020; the building carbon emissions from 2005 to 2050 are illustrated in Fig. 14.

As proposed in section 4, the scenarios after 2020 consist of 12 types with a combination of three types of building floor space and four types of carbon emissions intensity. Under scenarios A1, B1, and C1, which are characterized by the same CEI scenario and different BFS scenarios, the carbon emissions will increase sharply and continuously. Although it will synchronously achieve the mitigation promise of the Chinese government in 2020, which is a 40–45% reduction of CO₂ intensity based on GDP compared to 2005, they will not be able to guarantee an emissions peak at 2030. Under the B2–B4 and C2–C4 scenarios, the carbon emissions will all peak at approximately 2030, and most scenarios will not surpass the upper limit.

After presenting the scenario analysis of carbon emissions, we combine it with the results of the building floor space. Fig. 15 presents the control target of building carbon emissions and floor space in China.

The control target through 2050 is realized by controlling

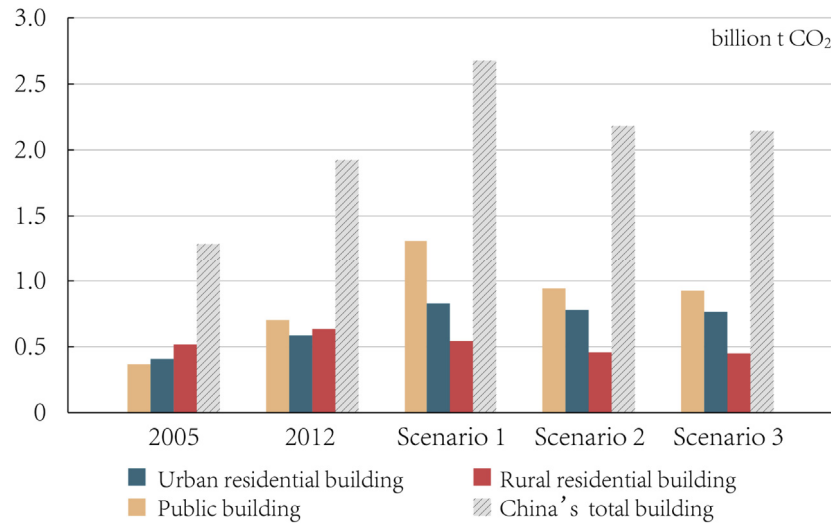


Fig. 13. Building carbon emissions in 2020.

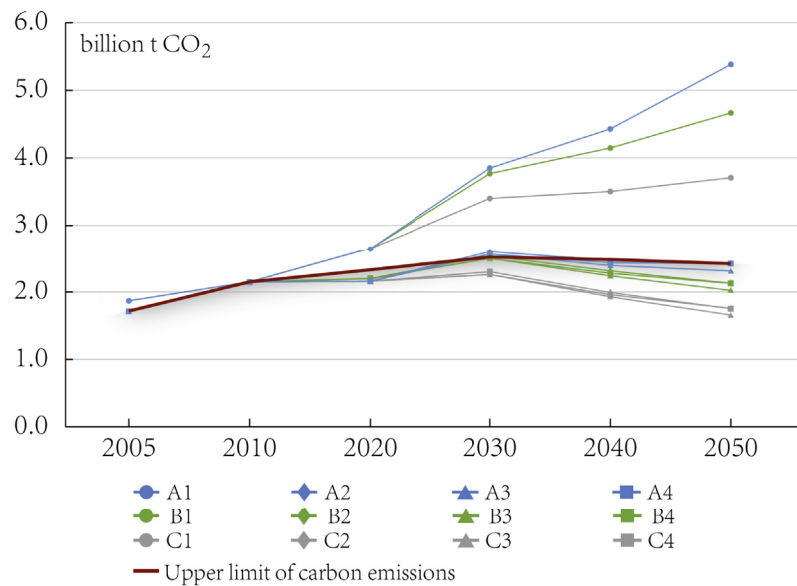


Fig. 14. Building carbon emissions from 2005 to 2050. (Capital letters correspond to scenarios A, B, and C of building floor space, distinguished by different colors. Numbers represent scenarios I, II, III, and IV of carbon emissions intensity, differentiated by geometric shapes. The thick red line indicates the upper limit of the total building carbon emissions control.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

building energy consumption, floor space and energy structure. According to the previous scenario analysis of building floor space and carbon emissions intensity, the relatively mild scenario of C4 is the most reasonable and one of the referable mitigation paths. A more detailed discussion is presented later.

For building floor space, the urban residential building floor space increases by 4%, 3%, and 2% every ten years during the period of 2020–2050, public building floor space increases by 8%, 8%, and 6%, and rural residential building floor space increases by 35%, 20%, and 10%. For building energy consumption, the energy efficiency increases by 30% with a reference year of 2010 every 10 years, covering 35%, 30%, 25%, and 20%. For the building energy structure, the gas-coal ratio increases, and the share of non-fossil fuels increases each year, as shown in Fig. 16.

5.1. General discussions

Some meaningful information can be obtained from the scenario analysis and carbon emissions prediction in the above paper:

1. The Chinese government plays a pivotal role in the mitigation action of building carbon emissions. Several reasonably matched policies and regulations, such as design standards of building energy efficiency (BEE), should be further discussed and promptly formulated. During the scenarios in 2020, comparing the data of scenario 1 (no new energy efficiency policy is implemented) to that of scenario 3 (more effective measures to reduce emissions are implemented), we find that regardless of how strict the implemented energy policy is, the building carbon emissions will steadily increase; the building

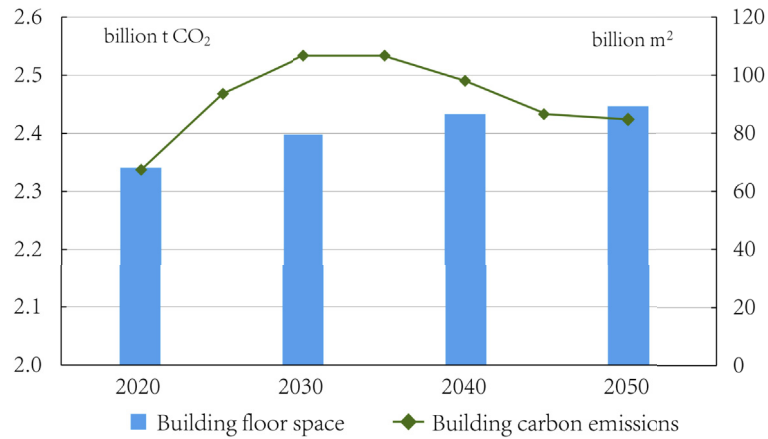


Fig. 15. Control target of building carbon emissions during the period of 2020–2050.

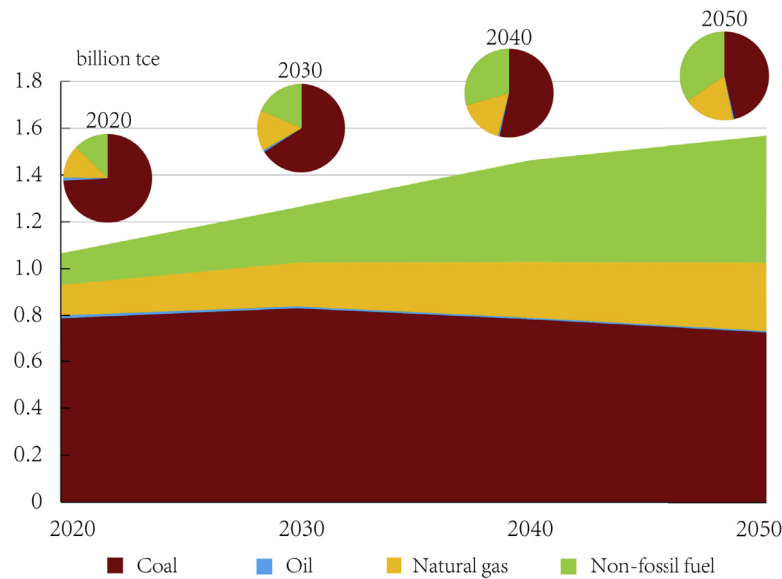


Fig. 16. Improvement of the building energy structure.

carbon emissions in 2020 under scenario 1 are 2.08 times the amount of those in 2005 and 1.39 times in 2012. Under scenario 3, these values are 1.66 and 1.12, respectively. Nevertheless, the difference between scenario 1 and scenario 3 implies that it is essential and effective for the government to propose stricter energy policies that result in 19.88% more energy savings and the potential to reduce carbon emissions in the building sector.

- Differences exist in the carbon emissions from various building types. In all scenarios, the carbon emissions of the rural residential buildings are the lowest and those of public buildings are the highest. Moreover, the carbon emissions reduction varies among different building types. Compared to that in scenario 1, the reduction rate of carbon emissions is 29.32% for public buildings in scenario 3, 7.40% for urban residential buildings, and 16.03% for rural residential buildings.
- Energy-saving measures should be further developed and promoted. Learning from the different energy efficiency predictions presented in Table 9-2, with the increasing demand for energy, the research and application of building energy efficiency

technologies must be given priority, which would lead to more efficient energy use and less carbon emissions from buildings. The adoption of a detailed energy-saving measure should consider the difference among various areas, buildings and phases. For example, in the design phase of new buildings, the government should implement legislative control of building envelope and shape, adapting to the corresponding climate area. In addition, the government should emphasize the need to refurbish buildings and encourage ECMs. In fact, Chinese government has conducted the *Green Building Action Plan* [9] to retrofit 570 million m² of existing buildings by 2015, and provide approximately \$7.0/m²–\$8.6/m² for facilitating implementation of this plan [8]. The success of this plan justifies further development and promotion of this plan.

- The energy consumption and floor space of buildings need to be controlled synergistically. In the second analysis stage of 2030–2050, under scenario I for carbon emission intensity, the building floor space in all scenarios will result in the sharp growth of carbon emissions, and the situation under scenario A

- for building floor space is similar. Therefore, it is not realistic for us to solely rely on a single controlling factor of either building floor space or carbon emissions intensity. The Chinese government must issue policies on both sides to achieve the target for reducing carbon emissions in the building sector.
- The rise of the building stock related to population increase and the evolution of the energy conservation measures jointly and inversely determine the trend of building energy consumption and carbon emission. The increasing demand for living standard definitely results in the rise of building floor area per cap, which will contribute to the evolution of the new building stock. However, there is a widespread relief that the development and promotion of building energy efficiency measures will decelerate this rising trend. For example, a residential building in the HSCW climate area, built according to the 1980s code, was retrofitted under the current code. It would save 25% heating and 10% cooling energy consumption. For commercial buildings in the HSCW climate area, adding the insulation layer and increasing the efficiency of boiler and chiller will reduce 20% heating and 10% cooling energy consumption compared to 1980s building specifications. In addition, the adjustment of energy structure will successfully reverse the trend, and finally realize the goal of emission deduction.
 - The improvement of the energy structure will be conducive to controlling carbon emissions from buildings and guaranteeing a carbon emissions peak at approximately 2030. Table 10 presents the predictions of building carbon emissions in 2020 with and without considering energy structure adjustment. Therefore, the improvement of the energy structure, e.g., enhancing the share of natural gas, will contribute to reducing carbon emission. If the energy structure is developed in correspondence with that reported in the *Energy Development Strategy Action Plan (2014–2020)* [51], the effect of carbon reduction in the building sector will increase by 15.77% compared with the situation without it. Furthermore, renewable energy sources should be given sufficient importance. China is endowed with plentiful and under-exploited renewable energy reserves, including hydropower, wind power, solar energy, biomass, ocean energy, geothermal energy, etc., which provide sufficient potential to adjust its energy structure. With the development of economy in China, energy demands and pollution risks create two big problems. These problems could be addressed by further integrating renewable energy into a future energy structure.
 - The improvement on living standard, which is coherent with GDP growth, affects carbon emissions dramatically from the end-use sides. 1% improvement in the economy contributes to 0.35% of total residential CO₂ emissions [52]. Under the national-wide affluence, residents' demands for a comfortable indoor environment increases, along with cooling, heating, cooking and water heating needs [50], thus causing carbon emissions surging. According to the research of Fan et al. [53], the basic need for heating and cooling, cooking and water heating accounts for 40% and 30% respectively, which needs to be controlled. Since the central heating covers the most northern area and is under supervision of the government, measures

like district heat metering should be promoted to restrain the consumption.

5.2. Feasibility analysis to meet the control target

Combined with the scenario analysis for building carbon emissions from 2020 to 2050, we performed a feasibility analysis of China's total building carbon emission control targets. In the first analysis phase (before 2020), building carbon emissions in 2020 are presented in Fig. 13. The amount of building carbon emissions under scenario 2 and scenario 3 are 18.53% and 19.88% lower than scenario 1, respectively. The carbon emissions in the building sector will not be able to reach the goal of limit control under scenario 1 but succeed under scenario 2 and scenario 3.

The Chinese government committed itself to a nationwide reduction of CO₂ intensity of GDP by 40%–45% in 2020 compared to 2005. Table 11 shows that the CO₂ emissions in the building sector under three scenarios will all achieve this goal, synchronizing the building sector to all industries.

The predictions of building carbon emissions in 2030, 2040, and 2050 are presented in Fig. 14. In view of the feasibility of energy conservation, we consider scenario C4 as the most suitable carbon reduction path to realize the control target and set it as the basis for developing the future course of action.

In summary, by enhancing the energy efficiency standards for new buildings, retrofitting existing buildings, controlling building floor space and improving the energy structure in the building sector, it is feasible to fulfill the control target proposed in this paper. In the process of realizing this fixed prospect, the role of governmental policy in China is essential. Therefore, in the next section, we discuss the corresponding policy advice.

6. Policy advice

Based on the control target of China's building carbon emissions and scenario analysis, referring to existing studies and standards of building energy efficiency, and considering the focus on China's energy conservation, in this section, we suggest carbon reduction strategies to achieve the target of carbon emissions control in the building sector.

- Synergistically control building energy consumption and floor space. Considering different climates, economies, energy and resources, building energy consumption should be controlled regionally. In the central and western regions, where the energy resources are rich but economic development is relatively backward, it is necessary to introduce advanced energy efficiency technology to control energy consumption beforehand. In the eastern region with a developed economy, dense population, and scarce resources, it is essential to strictly command a reasonable target for building energy consumption and carbon emissions. Controlling building floor space and energy consumption are the two most critical ways to realize this target.

Table 10

Carbon emissions in the building sector with and without considering a change in energy structure.

Billion t CO ₂	Without considering a change in energy structure	With considering a change in energy structure
Building carbon emissions in 2020	2.57	2.16

Table 11

Building carbon emissions intensity of GDP in 2020.

Scenario	Scenario 1	Scenario 2	Scenario 3
Carbon emissions intensity of GDP (kg/RMB)	0.0412	0.0356	0.0352
Reduction compared with 2005 (%)	56.91%	64.90%	65.48%

RMB, also called Yuan, is the monetary unit of China. 1 RMB = 0.1449 dollar (2017.03).

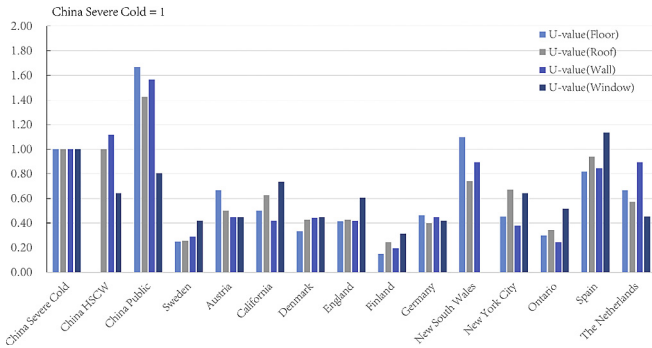


Fig. 17. Comparison of U-value of building envelope in different countries and regions [58].

2. Improve the energy structure. From our analysis, energy consumption in China's building sector will grow continually each year. However, if the energy structure is improved, especially by increasing the gas-coal ratio and the share of non-fossil fuels, carbon emissions in the building sector will be controlled effectively, reaching a peak at 2030 and then declining in later years. This suggestion meets the energy strategy in *Strategies and Action for Energy Development 2014–2020* [28]. If the energy structure in 2020 develops in correspondence with the results reported in this plan, the effect of carbon reduction will increase by 15.77% compared with the situation without it. Therefore, improving the energy structure in the building sector is a prerequisite to successfully check the growth rate of carbon emissions and guaranteeing its peak at approximately 2030.
3. Implement more stringent building energy efficiency design standards. As an important basis and minimum requirement for building energy efficiency, building energy efficiency design standards extensively promote the favorable implementation of carbon mitigation strategies. Currently, the design standards in China are insufficient compared with those of other developed countries. Take the U value, an indicator of building energy efficiency, as an example, it varies a lot from China to other regions, which is shown in Fig. 17. Table 12 exhibits some deficiency in the current China's design standards [54]. In the light of this, policy calls for an accelerating update of design

standards to meet the level set up by the ASHRAE. Zhou et al. [32] had performed an analysis of the relationship between building efficiency policy and energy saving in retrospect of China's 11th Five Year Plan, and have demonstrated that almost 69% Mtce saving in building sector should be attributed to an enforcement of more stringent building codes. Therefore, there is great potential for the Chinese government to improve relative codes to promote the development of building energy efficiency and thus to effectively reduce carbon emissions. In this process, considering the gap between developed countries and the local situation in China, it is imperative for relative regulations to guide building design towards energy efficiency and emissions reduction from the start of design.

4. Need more supporting regulations. The Ministry of Housing and Urban-Rural Development (MoHURD) leads annual national inspections in the enforcement of building energy efficiency policies and public results on its website, under provisions such as *Notice on the Strict Implementation of Energy Efficiency Design Standards for New Residential Buildings (2005)* [55], *Energy Conservation Law(2007)* [56] and *Regulations on Energy Conservation in Civil Buildings (2008)* [35]. In the future, other aspects will need to be spotlighted. One of the suggestions is about the district heating, which dominates the heating in northern area during the winter. The district heat metering and controlling could not only regulate better the indoor air temperature at a reasonable level, but also avoid personal modification of the system. Though difficulties like the high fault rate at 22% in practical applications exist [57], the significant energy savings potential deserves more attentions. Another is the energy efficiency label that may save almost 6% in heating and cooling relative to the baseline [32]. Some incentives should be made for the building constructor, with not merely the finance but also the policies, to cut the transaction costs by increasing the number of trained practitioners in labeling program.

7. Conclusions

China has become the number one country in energy consumption and carbon emissions worldwide with sufficient potential and ability to contribute to global carbon emissions mitigation.

Table 12
Comparison of China standard and ASHRAE 90.1–2013 in the same climate zone [54].

Item	GB 50189-2014/Cold Zone		ASHRAE 90.1–2013/Climate Zone 5	
Roofs	Shape coefficient<0.3	0.45	Insulation entirely above deck	0.184
Maximum U-factor (W/m²K)	0.3 < Shape coefficient<0.4	0.40	Metal building	0.218
			Attic and other	0.119
Walls (above grade)	Shape coefficient<0.3	0.5	Mass	0.513
Maximum U-factor (W/m²K)	0.3 < Shape coefficient<0.4	0.45	Metal building	0.286
			Steel framed	0.315
			Wood framed and other	0.291
Windows	WWR<0.2	—	0.4/0.4	
Maximum SHGC (E, S, W/N)	0.2 < WWR<0.3	0.52/—		
	0.3 < WWR<0.4	0.48/—		
	0.4 < WWR<0.5	0.43/—		
	0.5 < WWR<0.6	0.40/—		
	0.6 < WWR<0.7	0.35/0.60		
LPD (W/m²)	Office room	9.0	Office room	12.0
	Hotels-Guest room	7.0	Hotels-Guest room	9.8
	Schools-Class room	9.0	Schools-Class room	13.4
COP requirements for air cooled unitary air conditioners	Ductless	4.1 kW < CP < 14 kW	CP < 19 kW	3.81
		CP > 14 kW	19 kW < CP < 40 kW	3.22
	Ducted	4.1 kW < CP < 14 kW	40 kW < CP < 70 kW	3.16
		CP > 14 kW	70 kW < CP < 223 kW	2.87
			223 kW < CP	2.78

*SHGC: Solar heat gain coefficient. WWR: Window-to-wall ratio LPD: Lighting power density. COP: Coefficient of performance. CP: Cooling power.

With the development of social economy, the acceleration of urbanization and increases in standards of living, building-related energy consumption and carbon emissions have gradually increased as relevant scientific technology has continued to improve. The building sector is the largest source of carbon emissions and is responsible for 40% of energy consumption and one-third of GHG emissions worldwide. Therefore, energy efficiency strategies must be implemented without delay, and official organizations play an important role in this process. The Chinese government has released a series of documents, such as the *U.S.–China Joint Announcement on Climate Change* [11] and *Strategies and Action for Energy Development 2014–2020* [28]; however, specific building-level documents that have synchronized responsibility with the overall industries for GHG emissions mitigation have rarely been developed and published. In addition, the research about buildings in China mostly concerns energy consumption and rarely addresses carbon emissions, resulting in limited guidance and suggestions for the Chinese government to form corresponding policies.

This paper creatively provides a detailed view of carbon emissions in China's building sector. First we implement an inverse method, an up-bottom approach, to assess the control target of China's building carbon emissions based on governmental policies and official statistics in the future and then build the China Building Carbon Emission Model (CBCEM) using a bottom-up method. Two critical factors, building floor space and carbon emissions intensity (consisting of energy consumption and the carbon emission factor), are presented and discussed through scenario analysis. Finally, we propose several carbon mitigation policy suggestions.

The main research results are as follows:

1. A calculation framework called the China Building Carbon Emission Model is developed to provide comprehensive perspectives to evaluate carbon emissions from different end users of different types of buildings in different areas. In future work, based on this model, we will research the application of various universal and specialized techniques in each type of area in detail.
2. For carbon emissions from buildings, there are three main influencing factors: building floor space, energy intensity, and the carbon emission factor. Behind these factors, there exist several other complex factors, such as the GDP of China, the process of urbanization, and the changing heating strategy in the southern area, where the feasible mitigation path lies.
3. China's carbon emissions from the building sector continuously increase. Nevertheless, there is no doubt that China's building sector can achieve the carbon emissions goal of 40%–45% mitigation in 2020, but to reach the peak at approximately 2030, the Chinese government must adopt more policies to control building carbon emissions.
4. Considering the coordinating development of whole industries, using the up-bottom approach, China's building carbon emissions are suggested to be controlled under 2.37 billion t in 2020, 2.53 billion t in 2030, and 2.42 billion t in 2050.
5. As a prosperous developed country, China is characterized by an accelerated urbanization rate. This feature will result in some particular phenomena that affect the carbon emissions from the building sector and its scenario analysis. Lifestyle habits of the residents mitigating from the rural area to the urban area have a certain inertia, and the building floor space in rural areas will not significantly increase in the future but remain under approximately 25 billion m² through 2050.
6. Improving the energy structure, including the increasing introduction of non-fossil fuels, is an essential way to control the carbon emissions from buildings in China. The future trend of the energy structure in the building sector is presented in Fig. 16.
7. Building energy consumption and floor space should be controlled synergistically. It is not realistic to rely solely on a single controlling factor, and the Chinese government must introduce policies on both sides to achieve the target reduction in carbon emission in the building sector. China's building sector could successfully reach the goal of keeping pace with the emissions reduction commitment proposed by the Chinese government under the mild C4 scenario.
8. The Chinese government plays a critical role in the mitigation process of carbon emissions. There is a great potential for reducing carbon emissions in China's building sector if appropriate policies are effectively implemented to simultaneously improve the energy efficiency, adjust the energy structure of energy-using systems in buildings, and control the building floor space.

References

- [1] Egenhofer MJ, Mark DM. Geographic information science. Second international conference, GIScience 2002, Boulder, CO, USA, September 25–28, 2002. Proceedings. Conference Geographic information science.
- [2] Zuo J, Zhao Z-Y. Green building research—current status and future agenda: a review. *Renew Sustain Energy Rev* 2014;30:271–81.
- [3] Robert A, Kummert M. Designing net-zero energy buildings for the future climate, not for the past. *Build Environ* 2012;55:150–8.
- [4] Stojiljković MM, Ignjatović MG, Vučković GD. Greenhouse gases emission assessment in residential sector through buildings simulations and operation optimization. *Energy* 2015;92(Part 3):420–34.
- [5] Xing Y, Hewitt N, Griffiths P. Zero carbon buildings refurbishment—A Hierarchical pathway. *Renew Sustain Energy Rev* 2011;15(6):3229–36.
- [6] European Union. 2030 energy strategy. 2014. Available from: <http://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy>.
- [7] Zhang N, Wang B, Liu Z. Carbon emissions dynamics, efficiency gains, and technological innovation in China's industrial sectors. *Energy* 2016;99:10–9.
- [8] He J, Deng J, Su M. CO₂ emission from China's energy sector and strategy for its control. *Energy* 2010;35(11):4494–8.
- [9] Du K, Lin B. Understanding the rapid growth of China's energy consumption: a comprehensive decomposition framework. *Energy* 2015;90(Part 1):570–7.
- [10] Zhou N, Fridley D, Khanna NZ, Ke J, McNeil M, Levine M. China's energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model. *Energy Policy* 2013;53:51–62.
- [11] U.S. and China Governments. U.S.–China joint announcement on climate change. 2014. Available from: <https://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change>.
- [12] United Nations Framework Convention on Climate Change. In: 2015 United Nations climate change conference; 2015. Available from: http://unfccc.int/meetings/paris_nov_2015/meeting/8926.php.
- [13] Barker T, Bashmakov I, Alharthi A, Amann M, Cifuentes L, Drexhage J, et al. Mitigation from a cross-sectoral perspective. *Climate change*. 2007. p. 619–90.
- [14] Houghton J, Jenkins G, Ephraums J. *Climate change*. Cambridge, UK: the IPCC scientific assessment Cambridge University Press; 1990.
- [15] Coondoo D, Dinda S. Causality between income and emission: a country group-specific econometric analysis. *Ecol Econ* 2002;40(3):351–67.
- [16] Antanasijević D, Pocajt V, Ristić M, Perić-Grujić A. Modeling of energy consumption and related GHG (greenhouse gas) intensity and emissions in Europe using general regression neural networks. *Energy* 2015;84:816–24.
- [17] Yeo MJ, Kim YP. Changes of the carbon dioxide emissions and the overshoot ratio resulting from the implementation of the 2nd Energy Master Plan in the Republic of Korea. *Energy Policy* 2016;96:241–50.
- [18] York R, Rosa EA, Dietz T. STIRPAT, IPAT and ImpACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecol Econ* 2003;46(3):351–65.
- [19] Ahmad A, Zhao Y, Shahbaz M, Bano S, Zhang Z, Wang S, et al. Carbon emissions, energy consumption and economic growth: an aggregate and disaggregate analysis of the Indian economy. *Energy Policy* 2016;96:131–43.
- [20] Hao H, Geng Y, Li W, Guo B. Energy consumption and GHG emissions from China's freight transport sector: scenarios through 2050. *Energy Policy* 2015;85:94–101.
- [21] Peng C, Yan D, Guo S, Hu S, Jiang Y. Building energy use in China: ceiling and scenario. *Energy Build* 2015;102:307–16.
- [22] Xu B, Lin B. Carbon dioxide emissions reduction in China's transport sector: a dynamic VAR (vector autoregression) approach. *Energy* 2015;83:486–95.
- [23] Shao S, Liu J, Geng Y, Miao Z, Yang Y. Uncovering driving factors of carbon emissions from China's mining sector. *Appl Energy* 2016;166:220–38.
- [24] Li N, Ma D, Chen W. Quantifying the impacts of decarbonisation in China's cement sector: a perspective from an integrated assessment approach. *Appl Energy* 2017;185(Part 2):1840–8.
- [25] Weilong H, Xiang Y, Wenying C. Prospective scenarios of CCS implementation

- in China's power sector: an analysis with China TIMES. *Energy Procedia* 2014;61:937–40.
- [26] Lin B, Moubarak M, Ouyang X. Carbon dioxide emissions and growth of the manufacturing sector: evidence for China. *Energy* 2014;76:830–7.
- [27] Chao B. Scheme and policies for peaking energy carbon emission in China. *China Popul Resour Environ* 2015;25(5):20–7.
- [28] National Development and Reform Commission. National Programme of action to climate change 2014–2020. 2014. Available from: <http://www.sdpc.gov.cn/zcfb/zcfbtz/201411/t20141104642612.html>.
- [29] National Bureau of Statistics of China. China statistics yearbook. Beijing: China Statistics Press; 2001–2014.
- [30] Jiang Y, Peng C, Yan D. China's building energy efficiency technology roadmap. *Constr Sci Technol* 2012;17:12–9.
- [31] The Chinese Government. Enhanced actions on climate change: China's intended nationally determined contributions. 2015. Available from: <http://www.china.org.cn/environment/2015-06/30/content35950951.htm>.
- [32] McNeil MA, Feng W, du Can SdR, Khanna NZ, Ke J, Zhou N. Energy efficiency outlook in China's urban buildings sector through 2030. *Energy Policy* 2016;97:532–9.
- [33] Energy conservation research center of Tsinghua university (THUBERC). 2013 annual report on China building energy efficiency. Beijing: China Building Industry Press; 2013 [in Chinese].
- [34] Ministry of Housing and Urban-Rural Development of China (MOHURD). Thermal design code for civil building GB 50176–931993.
- [35] China SCotPsRo. Regulations on energy conservation in civil buildings. 2008.
- [36] Zhao H, Guo S. An optimized grey model for annual power load forecasting. *Energy* 2016;107:272–86.
- [37] Liu S, Jiang L. The application of GM(1,1) model in the prediction of resident building floor space per capita in Shanghai. *Hous Sci* 1999;3–6 (in Chinese).
- [38] Liu W, Chen F. The application of GM(1,1) grey model to predict the resident building floor space per capita in Nanjing. *Urban Probl* 1999;15–8.
- [39] Chang T-C, Chang H, You M-L. Inverse approach to find an optimum/spl alpha/ for grey prediction model. In: Conference Inverse approach to find an optimum/spl alpha/ for grey prediction model, vol. 3. IEEE; 1999. p. 309–13.
- [40] Mao M, Chirwa E. Application of grey model GM (1, 1) to vehicle fatality risk estimation. *Technol Forecast Soc Change* 2006;73(5):588–605.
- [41] Tseng F-M, Yu H-C, Tzeng G-H. Applied hybrid grey model to forecast seasonal time series. *Technol Forecast Soc Change* 2001;67(2):291–302.
- [42] Yu PS, Chen CJ, Chen SJ, Lin SC. Application of grey model toward runoff forecasting. *JAWRA J Am Water Resour Assoc* 2001;37(1):151–66.
- [43] Ministry of Housing and Urban-Rural Development of China (MOHURD). The goal of building a moderately prosperous society in all aspects. 2005.
- [44] The State Council of China. National population development plan. 2016.
- [45] Chinese Academy of Social Sciences (CASS). Annual report on development of small and medium-sized cities in China. 2013.
- [46] United Nations Environment Programme. Modelling China's green economy 2010–2050. 2014. Available from: http://www.unep.org/chinese/publications/pdf/greeneconomyChina2010_2050.pdf.
- [47] Energy conservation research center of Tsinghua university (THUBERC). 2012 annual report on China building energy efficiency. Beijing: China Building Industry Press; 2012 [in Chinese].
- [48] Energy conservation research center of Tsinghua university (THUBERC). 2014 annual report on China building energy efficiency. Beijing: China Building Industry Press; 2014 [in Chinese].
- [49] Ministry of Housing and Urban-Rural Construction of the People's Republic of China. Design standard for energy efficiency of residential buildings. 1986 [in Chinese].
- [50] Miao L. Examining the impact factors of urban residential energy consumption and CO₂ emissions in China – evidence from city-level data. *Ecol Indic* 2017;73:29–37.
- [51] General Office of the State Council. Energy development strategy action plan (2014–2020). 2014. Available from: <http://www.lse.ac.uk/GranthamInstitute/law/energy-development-strategy-action-plan-2014-2020>.
- [52] Donglan Z, Dequn Z, Peng Z. Driving forces of residential CO₂ emissions in urban and rural China: an index decomposition analysis. *Energy Policy* 2010;38(7):3377–83.
- [53] Fan J-L, Yu H, Wei Y-M. Residential energy-related carbon emissions in urban and rural China during 1996–2012: from the perspective of five end-use activities. *Energy Build* 2015;96:201–9.
- [54] Hong T, Li C, Yan D. Updates to the China design standard for energy efficiency in public buildings. *Energy Policy* 2015;87:187–98.
- [55] Ministry of Housing and Urban-Rural Development. Notice on the strict implementation of energy efficiency design standards for new residential buildings. 2005.
- [56] Standing Committee of the National People's Congress. Energy conservation Law of the People's Republic of China. 2007.
- [57] Yuan S, Xu W, Liu Y. Research of heat metering development situation and application effect evaluation model in China. *Energy Policy* 2016;88:329–42.
- [58] Li J, Shui B. A comprehensive analysis of building energy efficiency policies in China: status quo and development perspective. *J Clean Prod* 2015;90:326–44.