YSSP Report

Young Scientists Summer Program

Sustainable pathways of China's building construction sector

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Approved by

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Sustainable pathways of China’s building construction sector

Abstract: The energy use and emissions related with building construction consists an important part of that of the whole society. The choice of building stock development path, the construction mode, and synergy between building construction sector and industry sector will have a great influence on future’s energy use and emissions in China. Therefore, it is of great significance to carry out relevant research to explore the sustainable development path of the China’s building construction sector. This study developed the China Building Construction Model (CBCM) and related scenario, three parts of researches has been carried out: First, reviewed the development path of building stock in developed countries, and put forward the possible development scenarios of China's building stock in the future. Second, established the scenarios to analyze the impact of building retrofit on building material demand and related energy use and emissions. Third, further considered the synergy between the building construction sector and the industrial sector, and analyze the environmental impact of building construction in the future.

1. Introduction

1.1 Background

Urbanization in China has advanced rapidly during the past decades. From 2000 to 2018, China's urbanization rate increased from 36% to 60%[1]. With this trend, large amount of building materials has been consumed during building construction, which is an important driving factor of the rapid increase of energy consumption and carbon emissions in China[2].

At present, China is still in the process of rapid urbanization, and building stock will continue to increase. In fact, there are different development mode for the building stock in various developed countries. For China, it is of great significance choosing the appropriate development mode to reduce energy consumption and emissions related with building construction, and ultimately achieve sustainable development.

In addition, the treatment of old buildings in China is mainly to demolish and rebuilt new buildings, at current stage. This extensive construction mode has caused a lot of waste of building materials, and ultimately led to an increase in related energy use and emissions. Building retrofit can effectively extend the building lifetime reduce the demolished and newly built building stock over years. It has been widely applied in developed countries and also will be one of the important means for China to reduce energy use and emissions related of building sector in the future.

With the decreasing growth rate of total building stock, and increasing proportion of building material recovering, the synergy between the construction sector and the industrial sector will become more obvious. The increase of building materials recycling will promote the adjustment of industrial structure and the development of circular economy, which is also important for reducing the energy consumption and emissions from building material production.

Generally speaking, the energy use and emissions related with building construction consists an important part of that of the whole society. The choice of building stock development path, the construction mode, and synergy between building construction sector and industry sector will have a great influence on future's energy use and emissions in China. Therefore, it is of great significance to carry out relevant research to explore the sustainable development path of the China's building construction sector.

1.2 Existing research

At present, scholars have conducted a large amount of researches on the future development trend its impact of building construction sector[3-14], but there are still some shortcomings.
First, most of the existing studies mainly focus on the development trend of building stock,

and using and recovering of building materials[3-11,14]. But less attention is paid to building retrofit, and also few studies directly linking the material demand/recycling with the industrial production efficiency to reveal the synergy between the building construction sector and the industrial sector.

In addition, most researchers predict the development trend of China's building stock based on its historical trend and outlook of China's socio-economic factors such as population, GDP. However, China is currently in a critical period of transformation of its social development mode, it is difficult to make good judgments for the future only based on the historical trends. In this context, different development modes of developed countries are important references for China's future paths. However, few studies have proposed the possible development modes of China's building stock, based on the analysis on developed countries.

1.3 Content of this research

Based on the background and current research above, this study developed the China Building Construction Model and related scenario, three part of researches has been carried out:

First, this study reviewed the development path of building stock in developed countries, and put forward the possible development scenarios of China's building stock in the future.

Second, this study established the scenarios to analyze the impact of building retrofit on building material demand and related energy use and emissions.

Third, this study further considered the synergy between the building construction sector and the industrial sector, and analyze the environmental impact of building construction in the future.

2. Methods

2.1 Definition and framework

2.1.1 Physical process and research boundary

To analyze the building stock, material demand and embodied energy and carbon, this research establishes the China Building Construction Model (CBCM) with bottom-up approach.

The physical process described by the model can be divided into three levels: building stock flow, material stock flow, energy/carbon flow, which is shown in Figure 1. In the figure, the rectangle represents stocks, the oval represents flows, the parallelogram illustrates other determinants or drivers, the solid arrow depicts physical stock and flow relations, and the dashed arrow depicts the computation relations between the variables.

First, the model estimates the building stock overtime based on the per capita building stock and population. Then, according to the building life time, the building stock can be divided into inflow and outflow (which are newly built building stock and building stock at the end of life time). Furthermore, considering the retrofit rate, the outflow of the building stock can be decomposed into the retrofitted building stock and demolished building stock over years. Within the discussion of building stock flow, this research mainly considers three different building types, that is urban residential, rural residential and service buildings.

Then the inflow and outflow of the building stock can be converted to the flow of building materials. Consider the material use intensity of building construction and building retrofit, the material inflow and outflow over time can be obtained. With recovery rate, the material outflow can be divided into wasted materials and recovered materials. In the discussion of material flow, this study mainly considers four kinds of building materials, steel, cement, aluminum and glass, which are the most common used materials in buildings of China[15].

In addition, the material use intensity is largely influenced by the building structure types, so during the discussion of material flow, five different building structure types are also considered, which are: brick-wood structure, brick-concrete structure, frame-shear structure, shear-wall structure and steel structure. Among these structures, Brick wood and brick concrete structures were mainly used in rural residential buildings, while brick concrete, frame-shear, shear-wall, and steel structure were used in urban residential and service buildings which accounted for over 90% of the construction volume[16].

Finally, the material demand can be converted to the embodied energy and carbon based on the energy/carbon intensity during the material production.

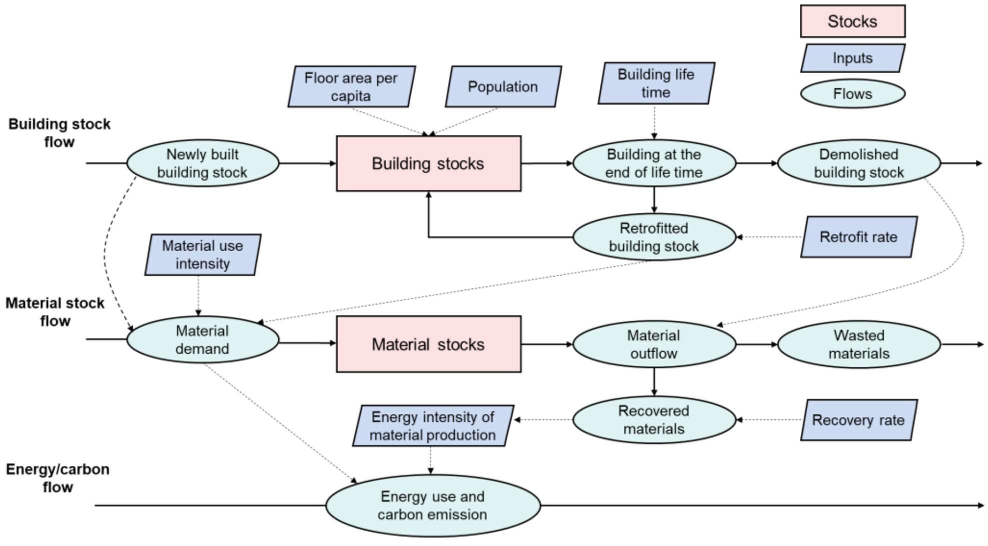


Figure 1 research scope ad physical process

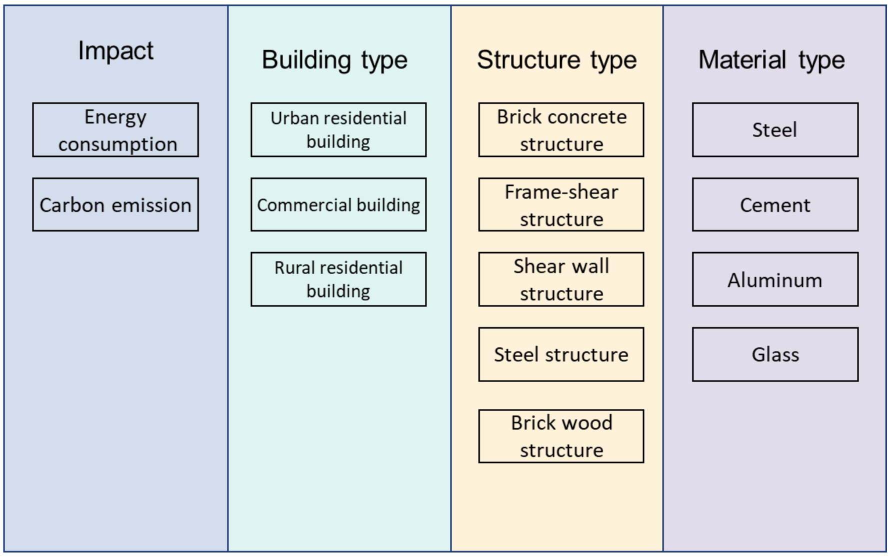


Figure 2 classification structure of the model

2.2 Methodology of Modelling

2.2.1 Modelling framework

Based on the consideration above， the model is mainly consists of four modules, the stock prediction module, stock turnover module, material demand module and environmental impact module, which is shown in Figure 3.

With the stock prediction module, the historical development trend of building stock in various developed countries will be considered to estimate the total building stock of China until 2050 under different scenarios. Then, with the stock turnover module, the total building stock will be decomposed into newly built, demolished and retrofitted building stock over years with the consideration of building lifetime and retrofitted rate. Next, with the material demand module, the material use intensity of different building types, and material recovery rate will be considered, the inflow and outflow of the building stock can be converted into the material demand and recovery over time. Finally, the synergy between building construction and industry efficiency will be taken into consideration, and the embodied energy and carbon can be obtained.

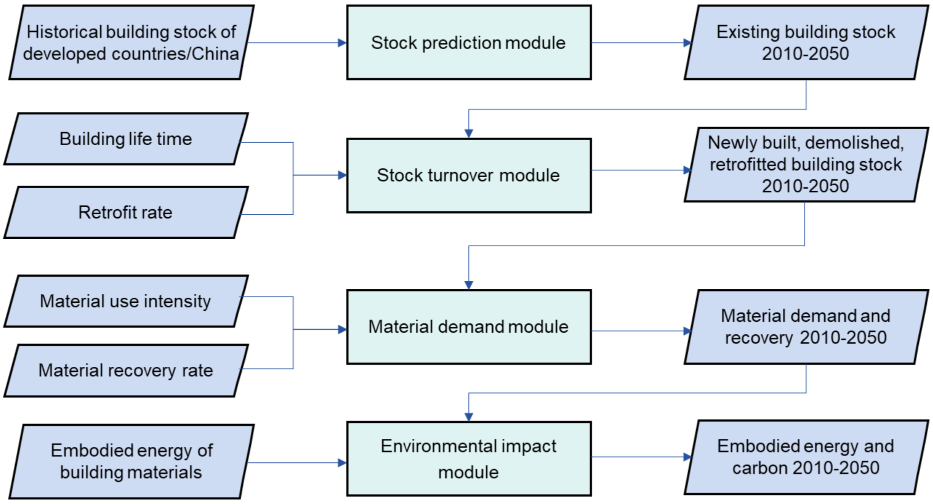


Figure 3 model composition and calculation process

In the following sections, the detailed methodology of four modules will be described.

2.2.2 Stock prediction module

In the existing research, there are two major prediction methods for future building stock. One is to extrapolate or regress based on the historical trend. The other is to consider the relationship between building stock and social economic drivers, which is also the most common used method in literature.

To predict the building stock based on the social economic factors, researchers usually decompose the building stock into the product of the per capita building stock and the total population, and then fit the growth trend of the per capita building stock in the future based on the driving factors such as per capita GDP and per capita disposable income.

In related research, the S-shaped curve was usually adopted to model the growth of per capita building stock. The common S-shaped curve includes Logit function, Logistic function, Gompertz function and Generalized logistic function.

Based on the discussion above, this study decomposes the building stock into per capita building stock and population, selects GDP per capita as the driving factor, and fits the growth trend of per capita building stock based on the Generalized logistic function. The specific functions are as follows:

$$A(t) = P(t) \times A(t)_{percapita}$$

$$A(t)_{percapita} = a \times (1 + b \times c \times \exp(-k \times GDP(t)_{percapita}))^{-1/b}$$

Where A(t) is the total building stock in year t, P(t) is the total population in year t, $A(t)_{percapita}$ is the building stock per capita in year t, $GDP(t)_{percapita}$ is the GDP per capita in year t.

2.2.3 Building stock turnover module

With the total building stock estimated by the building stock prediction module, the inflow and outflow (i.e. newly built building stock and building stock at end of the life time) can be calculated based on the building stock turnover function.

$$A_{in}(t) = A(t)\text{-}A(t-1)+A_{out}(t)$$

Where $A_{in}(t)$ is the newly built building stock in year t, $A_{out}(t)$ is the building stock at the end of lifetime.

For the building stock at the end of lifetime, it is usually estimated by the lifetime distribution equations in current research. Most of researchers use Normal or Weibull distribution to fit the building life distribution.

In this research, we choose the normal distribution to estimate the building stock outflow every year, which is shown as the following equations:

$$\frac{\mathrm{d}A_{out}(t)}{\mathrm{d}t} = \int_{t0}^{t} L(t,t)\cdot\frac{\mathrm{d}A_{in}(t')}{\mathrm{d}t}\mathrm{d}t'$$

$$L(t,t') = \frac{1}{\sigma\sqrt{2\pi}}\cdot\exp(\text{-}\frac{(t-t'-\tau)^2}{2\sigma^2})$$

Where L(t, t’) is the normal probability distribution, t is the model year and t’ is the initial year of the construction flow, τ is the mean value of building lifetime, and σ is the standard deviation the building lifetime, which is assumed to be 1/5 of the average building lifetimes τ in this research.

2.2.4 Building material demand module

Material consumption intensity differs a lot with respect to the building type and structure type. So this research decomposes the average material use intensity as the following equation:

$$M_{\text{int}}(t) = \sum M_{\text{int}}(i) \times P(t,i)$$

Where $M_{int}(t)$ is the average material use intensity in year t, $M_{int}(i)$ is the material use intensity of structure type i, P(t,i) is the share of structure type i in newly built buildings in year t.

Due to a lack of official data in China for structure type distribution and material use intensity, the historical data of used in this research is mainly from related research[16,17]. For the future, this study assumes that the distribution of building structure will remain unchanged. Take urban residential building as an example, the material use intensity and distribution are shown in Table 1 and Figure 4

Table 1 material use intensity of different structure type for urban residential buildings

Structure	Brick concrete	Frame shear	Shear wall	Steel
Unit	t/100m2	t/100m2	t/100m2	t/100m2
Cement	14.26	24.71	28.84	15.9
Steel	2.6	6.15	7.3	6.9
Aluminum	0.1	0.27	0.18	0.11
Glass	0.22	0.35	0.28	0.33

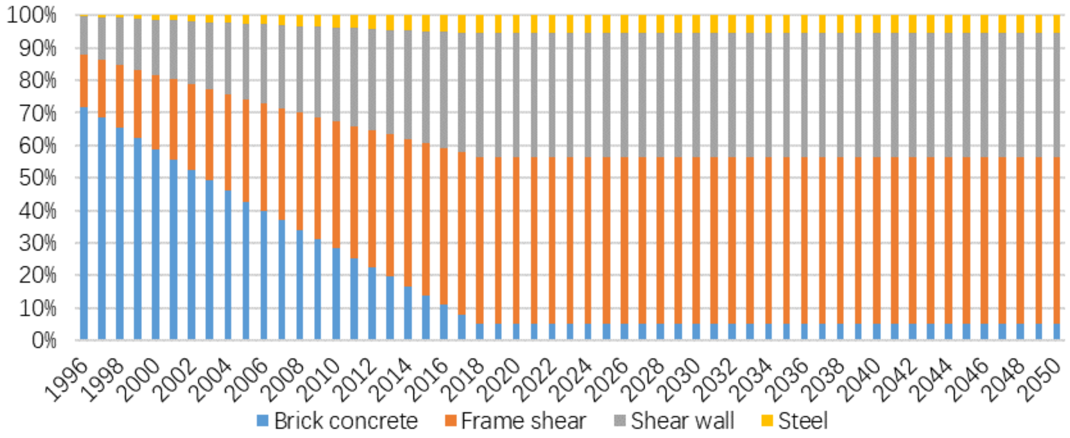


Figure 4 share of structure type in newly built urban residential buildings over years

For the material use of retrofitted buildings, related research find that the weight of the main structure is about 75% of the total weight of the building. Therefore, this study assume that material use intensity of building retrofit is about the 25% of newly built.

For the material recovery, this research mainly considers the steel recovery, and the recovery rate is assumed to be 70%.

2.2.5 Environmental impact module

In building construction sector, the consumption of steel and cement is much higher than aluminum and glass, this study mainly considers the environmental impact caused by the production of steel and cement. This process is conducted based on MESSAGEix-SCM (Steel & Cement Model) which is a technology-based model and providing a complete description of the process and the related retrofitting measures for steel and cement sectors. The detailed methodology can be found in previous research[18].

2.3 Scenario settings

2.3.1 Overall settings

Three levels of scenario setting are mainly considered in this research, the building stock development path, construction mode and industry efficiency, the overall scenario settings are shown as Figure 5.

For the building stock development path, it is consisting of High, Medium and Cap scenarios, which is referring different development mode of developed countries. For construction mode, two different scenarios are considered in this research, under demolition scenario, most of the old building which is at the end of lifetime will be demolished, but under retrofit scenario, more old buildings will be retrofitted to extend their lifetime. For industry efficiency, this study considers BAU scenario and Efficiency scenario. Under BAU scenario, the development trend of building material production technology will be estimated based on the current policy, under efficiency scenario more material recovery and electricity-based process will be considered.

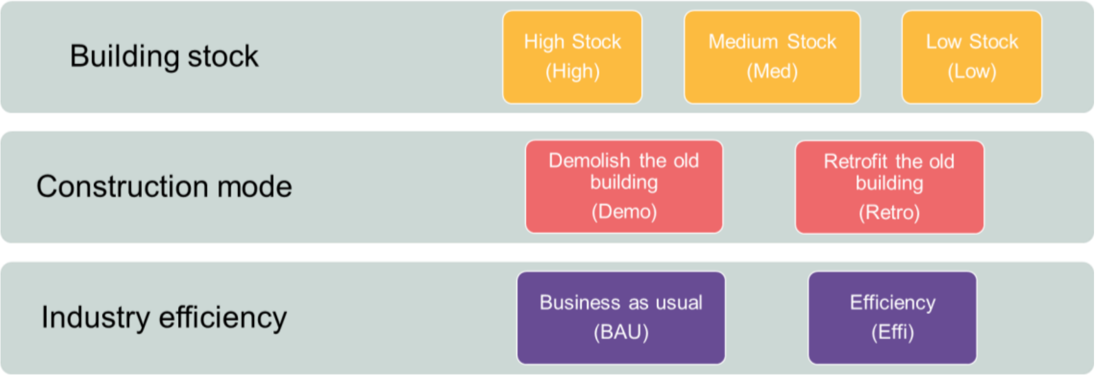


Figure 5 scenario settings of this study

2.3.1 Building stock scenario

To identify the building stock per capita of China in 2050, this study mainly refers the historical development trend building stock per capita and GDP per capita of various developed countries, and fits them based on the generalized logistic function, as is shown in Figure 6 and Figure 7. It can be find that the development law of different development countries differs a lot. Take residential building as example, the developed countries can be divided into three categories: the first category is represented by the United States, Canada and Australia, with a saturated per capita building stock of more than 55 m^2; the second category is represented developed countries from Europe such as France, Germany, with a saturated per capita building stock of about 40-50 m^2; the third category is represented by developed countries from Asia, such as South Korea, with a saturated per capita building area of about 30-40 m^2.

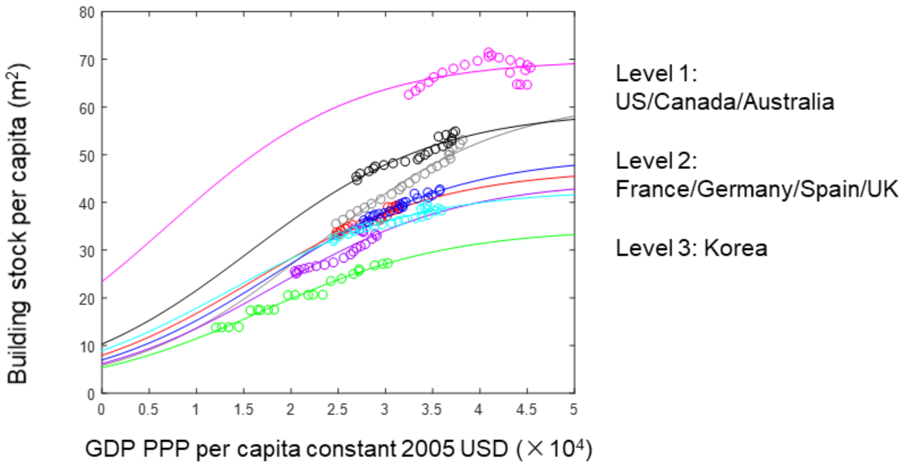


Figure 6 Residential building stock development mode of developed countries

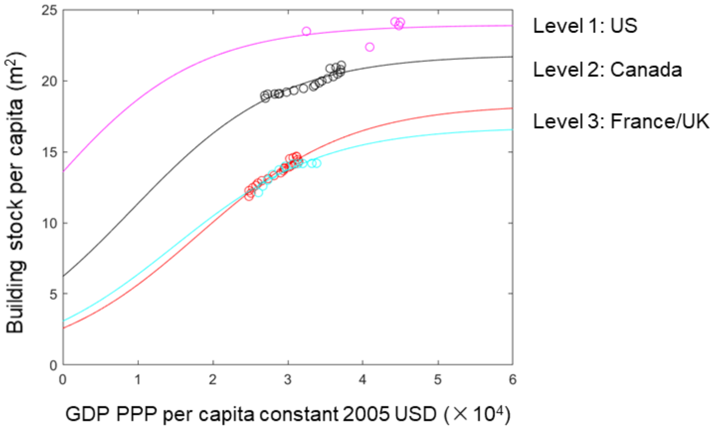


Figure 7 Service building stock development mode of developed countries

For the future development trend of GDP per capita of China, this study mainly refers to the data from IIASA SSP database. Under SSP2 scenario, the GDP per capita of China in 2050 will reach about 40000 USD (Figure 8). Therefore, referring to the per capita building stock with 40000 USD of above developed countries, the setting of China's per capita building stock under the High Medium and Low scenarios by 2050 can be proposed, as shown in Table 2.

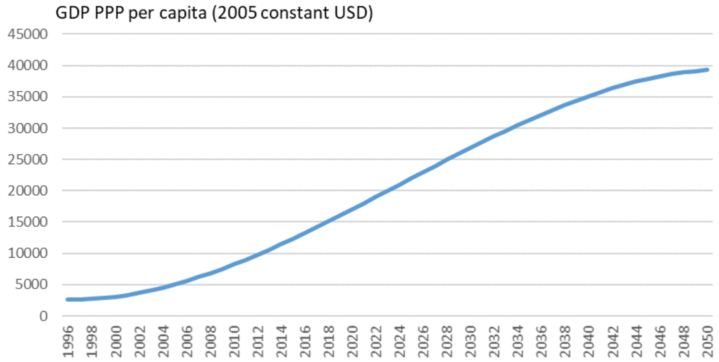


Figure 8 GDP per capita projection of China

Table 2 scenario settings of per capita building stock of China in 2050

Scenario	Per capita building stock of residential buildings in 2050	Per capita building stock of service buildings in 2050
High	55	25
Med	45	20
Low	35	15

2.3.2 Construction mode scenario

For construction mode, this research mainly considers two different scenarios, the retrofit scenario and demolition scenario. Under these two scenarios, there are different retrofit rate settings. The retrofit rate was defined as the following function.

$$Retrorate(t) = \frac{A_{retro}(t)}{A_{end}(t)}$$

Where Retrorate(t) is the retrofit rate in year t, $A_{retro}(t)$ is the building stock retrofitted in year t, $A_{end}(t)$ is the building stock at the end of the lifetime in year t. Under two scenarios, the development trend was assumed as in Figure 9.

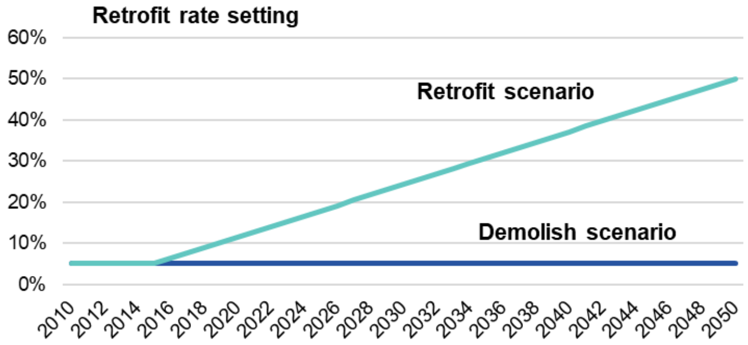


Figure 9 retrofit rate setting under retrofit scenario and demolish scenario

Building lifetime is the key factor in estimating the building stock outflow every year, which is closely related with the building type, technical level and government management. Due to extensive expansion and unreasonable demolition and construction, it is widely acknowledged that the service lifespan of China's building is relatively short. The estimation of China's building lifetime in related researches is reviewed as shown in Table 3.

Table 3 China's building lifetime in related literatures[6,9,19-22]

	Urban residential	Rural residential	Service building	Source
1	30~50	15~30	30~50	Building stock dynamics and its impacts on materials and energy demand in China Migrant employment in urban China: characteristics and determinants–a comparative study with rural left-behind people
2	15~30	-	15~30	Whole life and high grade quality stick to the implement housing performance certification. Modeling the evolution of the Chinese building stock in a sustainable perspective Speech on the meeting of "She Hui Zhu Yi Xin NongCun Jian She" ["Building new countryside of the socialist society"],
3	25~50		-	Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing
4	30	20	30	Changing patterns and determinants of infrastructures' material stocks in Chinese cities

So the settings of building lifetime in this research are shown in Table 4. Due to the lack of data for newly built building stock every year before 1996, this research divides the existing building stock into two categories. The first category is the buildings built before 1996, assuming their average construction time is 1980 and the average building lifetime is 35 years; the second category is the buildings built after 1996, and the building lifetime is assumed to be 40 years

Table 4 building lifetime settings

	Average Built time	Building life time		
		Urban residential	Rural residential	Service
Before 1996	1980	35	35	35
After 1996	-	40	40	40

2.3.2 Industry efficiency scenario

The scenario settings of industry efficiency is shown in Table 5. In efficiency scenario, more material recovery and electricity based process will be considered， besides this more energy efficiency measures in steel and cement industry will also be introduced.

Table 5 scenario settings of industry efficiency

Scenarios	**Scenario Description**	
	Common features	Different features
Business as usual (BAU)	The future power generation structure refers to the data from IIASA MESSAGE Model. The future thermal power generation efficiency is assumed to be unchanged.	The BOF share of total steel production will decrease by 2% The clinker to cement rate is assumed unchanged
Efficiency (Effi)		More material recovery and electricity based process will be considered. Besides this, 54 energy efficiency measures in steel industry and 36 energy efficiency measures in cement industry will be introduced

3. Results and discussion

3.1 Development path of China’s building stock

Based on the historical trend and scenario setting in 2050, the development path of China’s building stock per capita was fitted as generalized logistical curve (Figure 10). And finally, with the projection of future population in China, the building stock from 2010-2050 was identified, which is shown in Figure 11, Figure 12 and Figure 13.

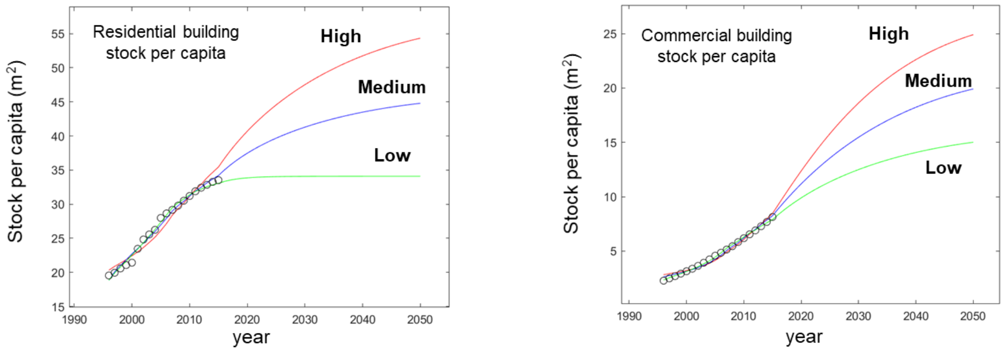


Figure 10 development path of building stock per capita to 2050

Notes: the black circle represents the historical trend, the red, blue and green line represents the estimated path under High, Medium and Low scenarios.

Under High scenario, the China's building stock will develop quickly, and reach a relatively high per capita floor area. In 2050, the total building stock will exceed 110 billion m^2, with about 77 billion m^2 residential building and 35 billion m^2 service building.

Under Medium scenario, the China's building stock will develop as the mode of European developed countries. In 2050, the total building stock will exceed 90 billion m^2, with about 63 billion m^2 residential building and 28 billion m^2 service building.

Under Low scenario, the China's building stock will develop as the mode of Asian developed countries, and will saturate at around 2035. In 2050, the total building stock will reach 70 billion m^2, with about 500 billion m^2 residential building and 200 billion m^2 service building.

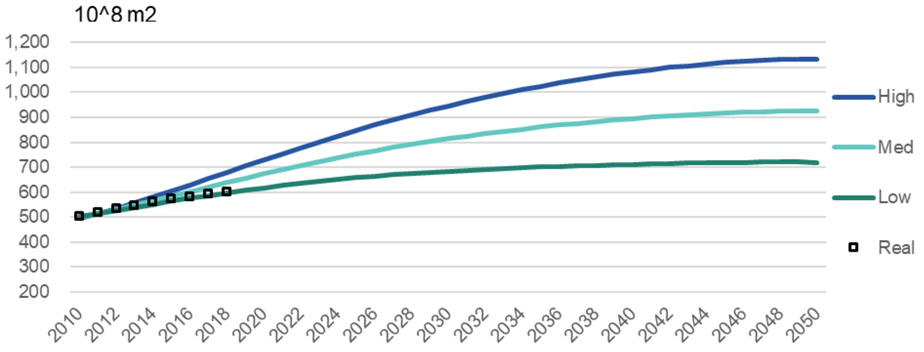


Figure 11 Total building stock estimation from 2010 to 2050

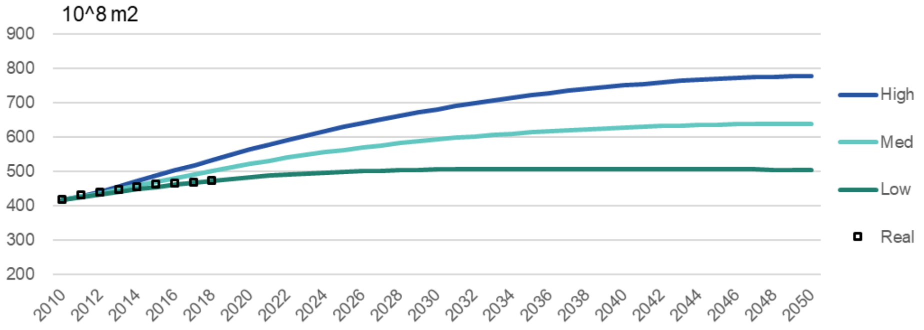


Figure 12 Residential building stock estimation from 2010 to 2050

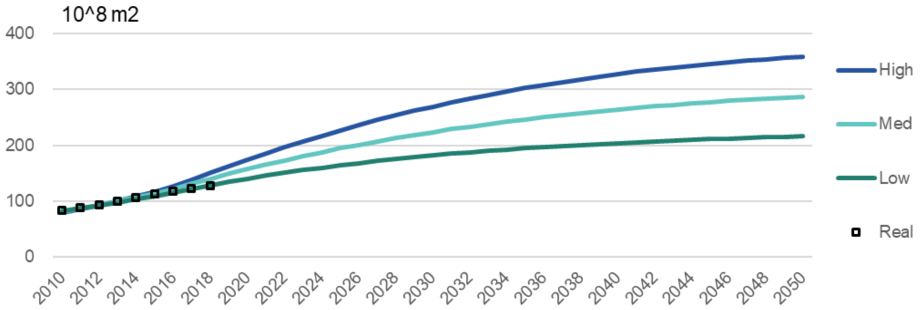


Figure 13 Service building stock estimation from 2010 to 2050

3.2 Building stock dynamics under different construction mode

The newly built, demolished and retrofitted building stock from 2010 to 2050 is shown in Figure 14, Figure 15 and Figure 16.

Under the demolition scenario, the newly built building stock after 2020 will decrease first and then increase. By 2050, the newly built building stock will still be about 2~3 billion m^2 per year. Under retrofit scenario, the newly built building stock after 2020 will maintain a downward trend, and newly built stock will be about 1-1.5 billion m^2 per year in 2050.

In addition, due to the large amount of buildings built from 1990s to 2010s, the demolished building stock under different scenario has an obvious upward trend after 2030. In the retrofit scenario, more buildings are repaired to extend their lifetime. Therefore, the stock of retrofitted buildings after 2030 is much higher than that of demolition scenarios, and the scale of demolished buildings is also significantly lower than that of demolition scenarios.

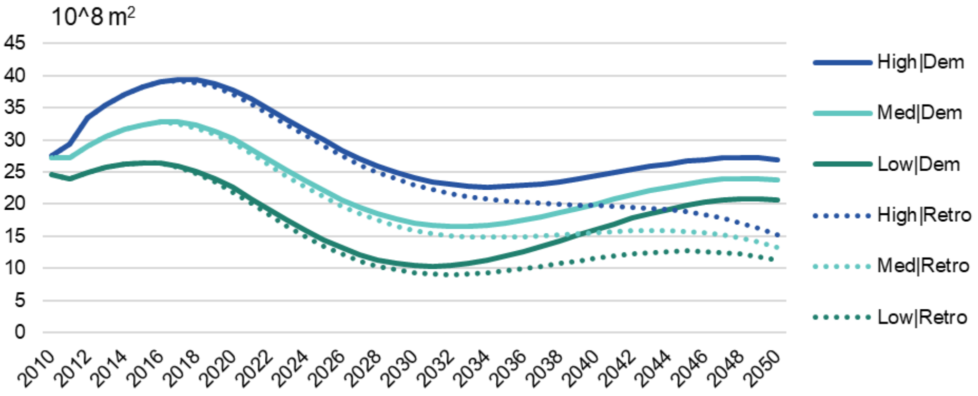


Figure 14 total newly built building stock from 2010 to 2050

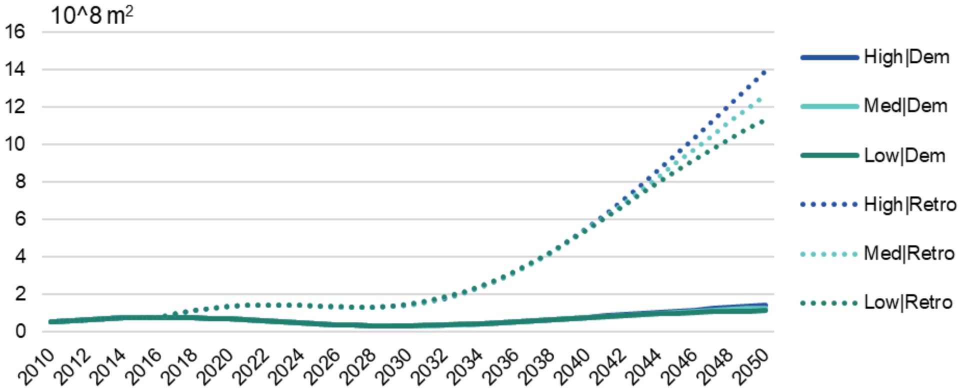


Figure 15 total demolished building stock from 2010 to 2050

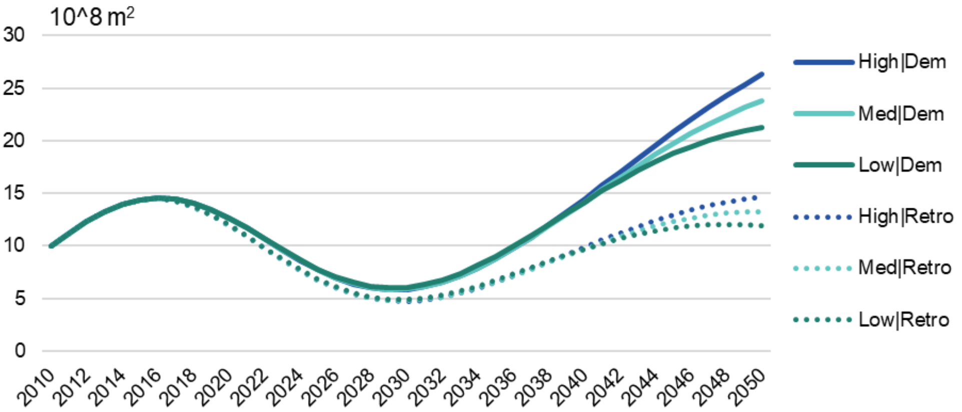
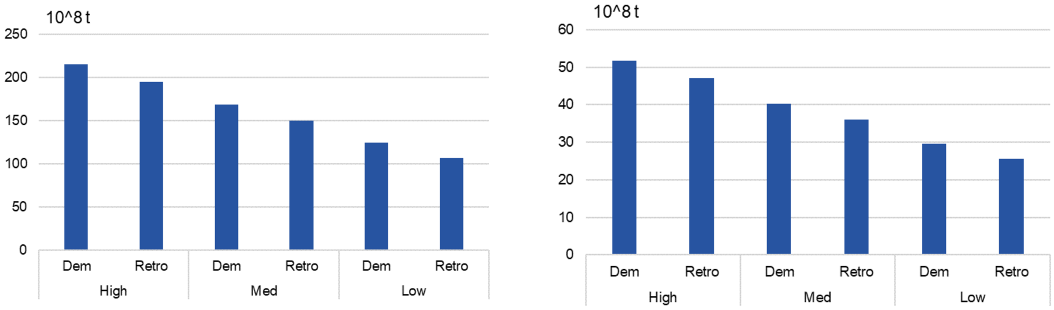


Figure 16 total retrofitted building stock from 2010 to 2050

3.3 Material demand and recovery

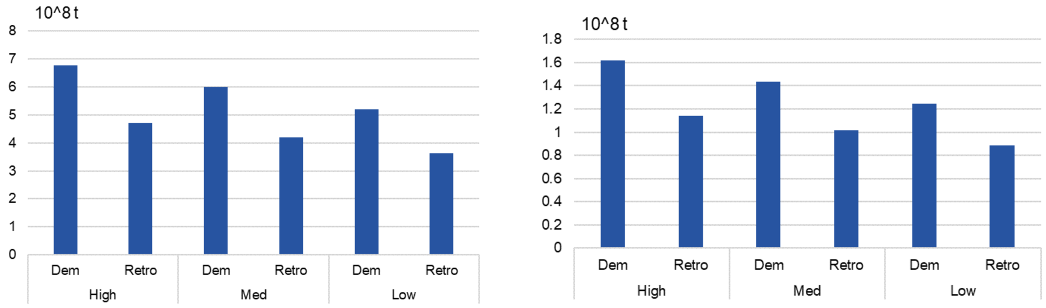
Take cement and steel as examples, the accumulated building material demand and the material demand in 2050 are shown in Figure 17 and Figure 18. It can be found that, the accumulated material demand decreased significantly under Low scenario compared with Medium and High scenario. Also, the material demand of retrofit scenario is lower than that of demolition scenario.

The building material demand in 2050 also shows a similar pattern, but the material saving is more obvious in retrofit scenario compared with demolition scenario. That is because the retrofit rate will be higher at that time. That means once the building retrofit has been promoted, it will have a more obvious material saving effect after 2050.



a) Cement b) Steel

Figure 17 accumulated material demand from 2020 to 2050



a) Cement b) Steel

Figure 18 material demand in 2050

The steel recovery is shown in Figure 19 and Figure 20. During 2020-2050, the steel demand and steel recovery are gradually approaching. Under the demolition scenario, the steel recovery will reach about 75~100 million tons per year at 2050, and under retrofit scenario, it will be around 50 million tons per year.

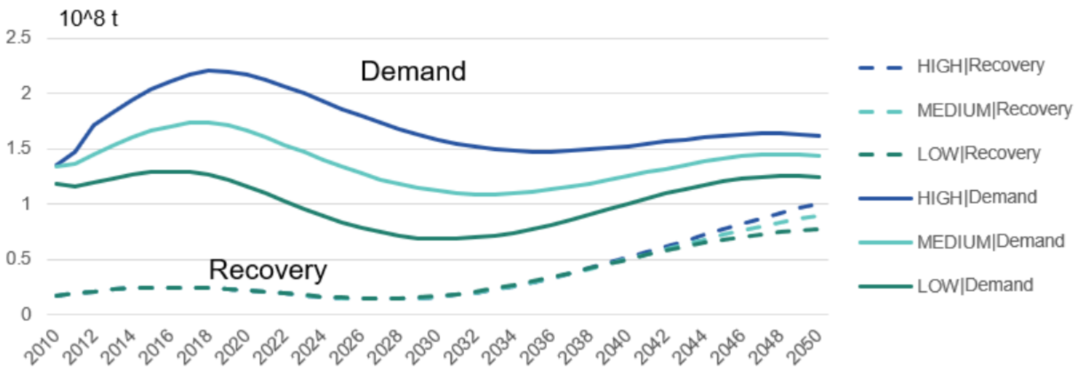


Figure 19 the steel recovery of demolition scenario

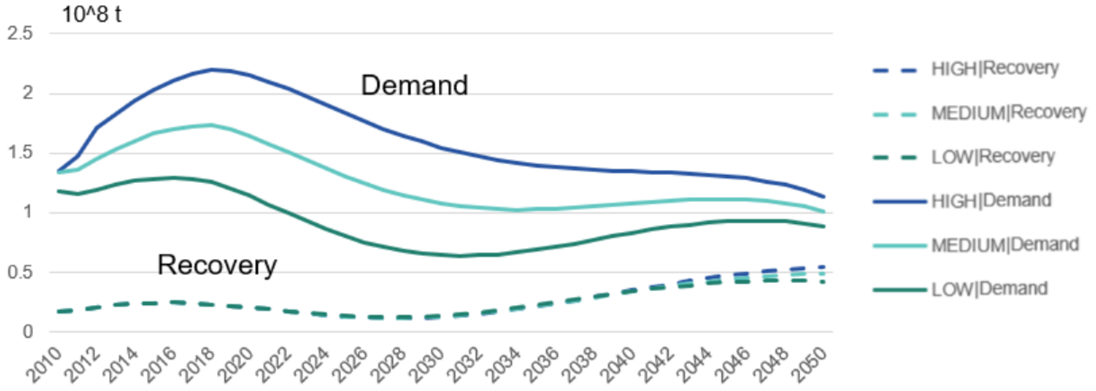


Figure 20 the steel recovery of retrofit scenario

3.4 Environmental impact from building construction

The relative environmental impact from building construction sector is shown in Figure 21. For High, Med, Cap scenario, the accumulated carbon emission from 2010-2050 are 52.7, 42.3, 31.9 Billion ton separately, the carbon emissions under High scenario are nearly 70% higher than that of Cap scenario, which means different stock development paths have a great influence on the carbon emissions of China's construction sector in the future.

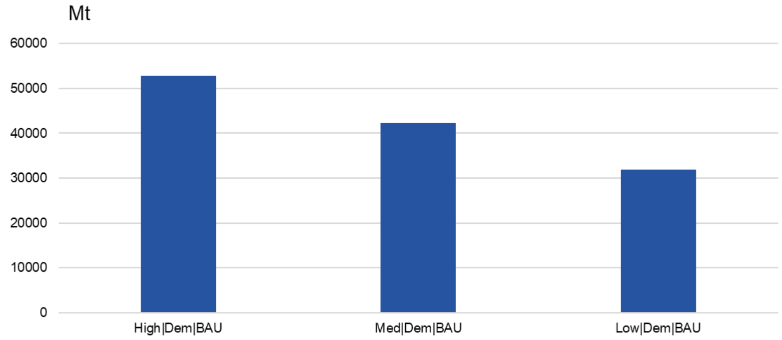


Figure 21 accumulated carbon emissions related with building construction from 2020-2050

Take Medium-demolition scenario as the baseline, building stock control and building retrofit can reduce the carbon emissions caused by construction sector effectively as is shown in Figure 22 and Figure 23. For accumulated carbon emissions from 2020-2050, stock control can reduce the emissions by 24%, and building retrofit for 7%. For carbon emissions in 2050, stock control and building retrofit can reduce the emissions by 13% and 26% separately. Which means the stock control can reduce the cumulative carbon emissions in the incremental stage effectively, and building retrofit is also very important for emission control after the total building stock is saturated.

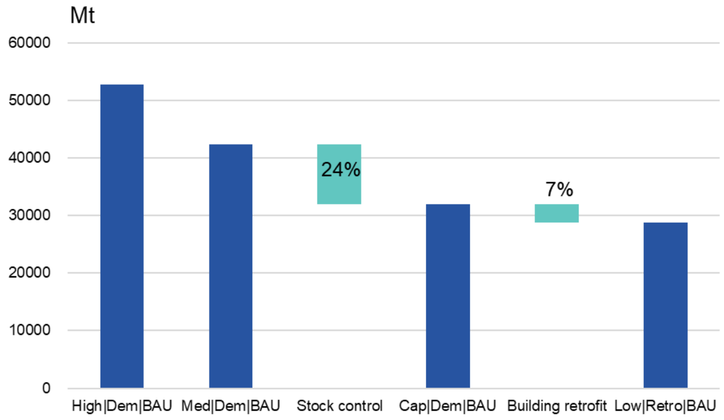


Figure 22 reduction potential of different measures on accumulated carbon emissions from 2020-2050

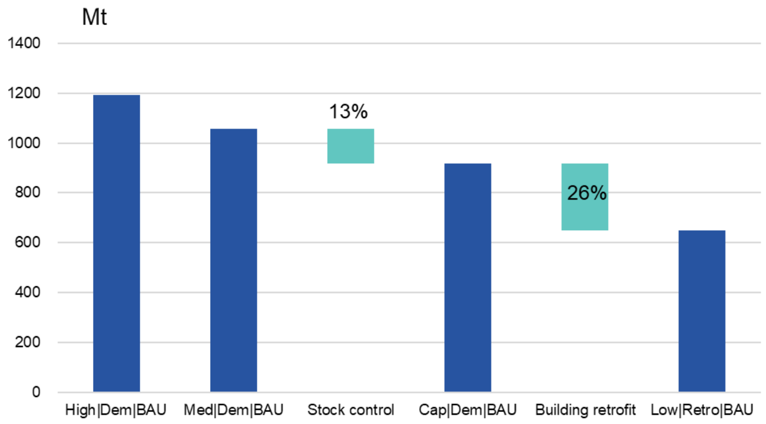


Figure 23 reduction potential of different measures on carbon emission in 2050

4. Future research

The above are the preliminary results of this study, and the following three aspects are planned to be studied:

(1) Complete the scenario on industry efficiency level, link the material demand and recovery with industrial production efficiency.

(2) Carry out the sensitive analysis on building life time to explore it's influence on the result.

(3) Explore the influence of building structure selection, material use intensity, develop the scenarios on building construction technology.

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