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Building stock dynamics and its impacts on materials and energy demand in China

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HIGHLIGHTS

- Growths of China's building floorspace were projected from 2010 to 2050.
- A building stock turnover model was built to reflect annual building stock dynamics.
- Building related materials and energy demand were projected.

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ABSTRACT

China hosts a large amount of building stocks, which is nearly 50 billion square meters. Moreover, annual new construction is growing fast, representing half of the world's total. The trend is expected to continue through the year 2050. Impressive demand for new residential and commercial construction, relative shorter average building lifetime, and higher material intensities have driven massive domestic production of energy intensive building materials such as cement and steel. This paper developed a bottom-up building stock turnover model to project the growths, retrofits and retirements of China's residential and commercial building floor space from 2010 to 2050. It also applied typical material intensities and energy intensities to estimate building materials demand and energy consumed to produce these building materials. By conducting scenario analyses of building lifetime, it identified significant potentials of building materials and energy demand conservation. This study underscored the importance of addressing building material efficiency, improving building lifetime and quality, and promoting compact urban development to reduce energy and environment consequences in China.

1. Introduction

To limit global warming to 2 °C, China faces enormous pressures in global communities. Domestically, air pollution has become a major problem in China, and posed a threat to public health (Greenpeace, 2015). According to National Bureau of Statistics of China, total primary energy consumption was 4260 Mtce in 2014 (National Bureau of Statistics, 2014a). Coal roughly accounts for nearly 70% of China's total primary energy consumption and 80% of its electricity generation (National Bureau of Statistics, 2014b). Coal burning is the biggest contributor of air pollution and the nation could not afford to allow air pollution to continue taking such a heavy toll. In November 2014, China and the U.S. jointly announced new targets on CO_2 emission reductions. China has committed to peak CO_2 emissions around 2030, and to strive to peak earlier (U.S.–China Joint Statement on Climate Change, 2014). Furthermore, the nation issued its Energy Development Strategy Action Plan (2014–2020), which included a cap set on annual primary energy consumption at 4.8 billion tce and on total coal consumption at 4.2 billion tce until 2020 (State Council, 2014). More recently in June 2015, the government of China has submitted its intended nationally determined contribution (INDC) to the United Nations stating that it aims to cut its CO_2 emissions per unit of gross domestic product by 60–65% from the 2005 level and

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increase its installed capacities of wind power, solar power and natural gas (UNFCCC, 2015). China's endeavors to global CO_2 emission mitigation have been recognized by International Energy Agency. Its recent report revealed that global annual CO_2 emissions growth has remained stable for the first time in 40 years, and stated that an important factor could be that China's coal consumption fell in 2014, driven by efforts to fight pollution, use more energy efficiency technologies and deploy renewables (IEA, 2015).

Building energy consumption currently accounts for 20–25% of the nation's total primary energy consumption (Building Energy Research Center, 2013). It is expected to skyrocket due to growths in building floor space as well as improvements in indoor thermal comfort levels accompanied with rapid urbanization process. Between 1980 and 2013, urbanization rate has increased from 20% to 53.7%, and will continue grow to 75–80% by 2050, being equivalent to the current level of most developed countries (United Nation, 2012). In order to accommodate new migrants in urban areas, annual new building constructions in China is about 2 billion square meters (National Bureau of Statistics, 2014c), consuming 30–40% of the world's annual cement and steel production. Energy consumed to produce these building materials is about 9% of total national energy use, and 15% of total industrial energy use. At present, building energy intensity in China is much lower than that of developed countries, but end-use energy demand such as heating, cooling, ventilation, lighting, and appliances are soaring (Zhou et al., 2011). Moreover, Chinese buildings have relative shorter lifetimes than their international counterparts (Amecke et al., 2013). For example, average building lifetime is approximately 30–40 years for urban areas (Song, 2012) and 15 years or less for rural buildings (Huang, 2006) in China, comparing to 60 years in the United States (U.S. Department of Energy, 2011) and more than one century in United Kingdom (UK Department for Communities and Local Government, 2010). Reasons for this phenomenon happened in China might include: lack of building construction guidelines and skilled labor force, poor quality of building materials, short-sighted urban planning, and consideration of demolition and reconstruction as an effective way to increase GDP (Fawley and Wen, 2013). The outcome of fast building turnovers is the production of massive building wastes, approximately accounting for 30–40% of total waste production (Zhao et al., 2010). Therefore, the magnitude of building floor space has significant implications on materials and energy demand. Building sector is one of key areas to realize the social transition towards lower energy consumption, lower CO_2 emissions and less material consumption.

A lot of research focused on studying building energy consumption and building technologies, including projections of future building energy demand (Eom et al., 2012; Gouveia et al., 2012; Li et al., 2012), impacts of climate change on building energy demand (Xu et al., 2012; Zhou et al., 2014; Wan et al., 2011), building heating and cooling loads (Hepbasli, 2012; Wang and Chen, 2014), and application of renewable energy in buildings (Li et al., 2013; Liu et al., 2013; Zhang et al., 2015). Another bunch of research has explored characteristics of building materials, including thermal properties of certain material (Latha et al., 2015; Park et al., 2015), energy efficiency of building components (Ihara et al., 2015; Thiele et al., 2015), its impacts on environmental emissions such as VOC and GHG (Cheng et al., 2015; Marsono and Balasbaneh, 2015), sustainable and low emission building materials (Ng and Chau, 2015; Akadiri, 2015; Jelle et al., 2015). However, only a few studies have investigated the relationship between growth of building floor space and energy used for the production of building materials (Fernández, 2007). This paper aimed to identify major socioeconomic drivers of the growth in China's building floor space, and proposed a methodology for projecting residential and commercial floor space and related materials and energy demand. Also, a building stock turnover model was developed to quantify annual residential and commercial[1] new construction and retrofits from 2010 to 2050 in different regions. A series of sensitivity analyses have been conducted to verify the influence of key factors on driving the growths of building floor space and to quantify the effects of prolonging building lifetime on material and energy conservation. The results underscored the importance of addressing the efficiency of building materials, improving building lifetime and quality, and promoting compact urban development to reduce building energy consumption and CO_2 emissions in China.

2. Methodology

In order to project future building floor area, a building stock turnover model was developed to calculate annual existing, new, retrofit and retired residential and commercial buildings, according to the following equation:

$$N^B_{i,t}=S^B_{i,t}-S^B_{i,t-1}+D^B_{i,t} \tag{2.1}$$

where $S^B_{i,t}$ was the residential/commercial building stock in region i in year t, $N^B_{i,t}$ was the newly built residential/commercial building in region i in year t, and $D^B_{i,t}$ was the demolished residential/commercial building in region i in year t. A building stock retirement function was incorporated to reflect the probability of building stock being demolished after a certain number of years. It was assumed to follow the cumulative normal distribution.

$$D^B_{i,t}=\frac{1}{2}\left[1+erf\left(\frac{z^B_{i,t}-\mu}{\sigma\sqrt{2}}\right)\right] \tag{2.2}$$

where $z^B_{i,t}$ was the age of building stock in region i in year t, the mean of the distribution μ was assumed to equal to the average lifetime of building stock in region i, and the standard deviation σ was assumed to be one third of the average building lifetime. As noted above, the average lifetime of Chinese buildings in urban areas is 30–40 years (Song, 2012) and 15 years or less in rural areas (Huang, 2006). The following formula has been applied to calculate urban and rural residential building stock separately:

$$S^{RB}_{i,t-1}=P_{i,t-1}\times a_{i,t-1} \tag{2.3}$$

where $S^{RB}_{i,t-1}$ was the floor area of the residential building stock in region i in year $t-1$, $P_{i,t-1}$ was the population of area in region i in year $t-1$, and $a_{i,t-1}$ was the per capita floor area of residential building in region i in year $t-1$. Per capita residential floor space has been modeled as a logit function of gross domestic product (GDP) per capita in terms of purchasing power parity (I). In this formula, the parameter of α and β were determined to be −206.07 and 23.258.

$$a_{i,t-1}=\alpha\times\ln(I)+b \tag{2.4}$$

Commercial building floor space was modeled separately according to the percentage of employment in service sector and the floor space per service sector employee using the series of equations that follows:

$$S^{CB}_{i,t-1}=P^S_{i,t-1}\times a^S_{i,t-1} \tag{2.5}$$

where $S^{CB}_{i,t-1}$ was the floor area of commercial building stock in

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[1] In this paper, commercial buildings referred to both governmental buildings and buildings used in service sector, which were not used as residences, nor part of industrial facilities. By building functions, commercial buildings mainly include office, retail, hospital, school and other building types.

region i in year $t-1$, $P^{S}_{i,t-1}$ was the population of service sector employees in region i in year $t-1$, $a^{S}_{i,t-1}$ was the floor space per employee in service sector in region i in year $t-1$.

$$P^{S}_{i,t-1}=P^{EA}_{i,t-1}\times(1-R^{U}_{i,t-1})\times S^{S}_{i,t-1} \tag{2.6}$$

where $P^{EA}_{i,t-1}$ was the economically active population[2] in region i in year $t-1$. Historical value was gained from National Bureau of Statistics and projected valued was obtained from the International Labor Organization to 2020 and extrapolated thereafter (International Labor Organization, 2007). $R^{U}_{i,t-1}$ was unemployment rate in region i in year $t-1$. A national unemployment rate of 4% was adopted for all three regions in this study. $S^{S}_{i,t-1}$ was the share of service sector employee in total employee in region i in year $t-1$, which has been modeled as a logit function of gross domestic product (GDP) per capita in terms of purchasing power parity (I). The parameter of α and β are determined to be 0.122 and -0.596 based on a wide range of countries and for different years (McNeil et al., 2012).

$$S^{S}_{i,t-1}=\alpha\times\ln(I)+b \tag{2.7}$$

Floor space per employee, assumed to be a logistic function of per capita income only, was calculated as follows:

$$a^{T}_{i,t-1}=\frac{\varepsilon}{1+\gamma\times\exp\ (\theta\times I)} \tag{2.8}$$

In this equation, the maximum value ε was set to 40 m^2 per employee. The variable I denoted GDP per capita and θ and γ were determined to be -1.1285×10^{-4} and 1.5 respectively (McNeil et al., 2012).

3. Building floor space projection

3.1. Residential building floor space

Population growth is an important factor in consideration of residential building floor space projection in China. The United Nation (2015) has projected that China's total population will peak at 1.42 billion by 2028 and then decline to 1.35 billion by 2050. Due to the “One Child Policy”, average urban household size decreased from 4.3 persons per household in 1980 to 2.9 persons per household in 2012, and average rural household size declined from 5.5 persons per household in 1980 to 3.9 persons per household in 2012. There were some concerns that strict population controls will undermine economic growth and contribute to a swiftly aging population. A recent research conducted by the Academy of Social Science (Yang, 2014) suggested that current total fertility rate is as low as 1.4, much lower than replacement rate of 2.1. If this trend continues, 30% of population will be 60 years old and above by 2050. To promote a balanced growth of population, China's one-child policy recently has been replaced by a two-child policy that took effect starting Jan. 1, 2016. Despite the abolition of the one-child policy, however, only half of Chinese couples are willing to have two children, according to National Health and Family Planning Commission (NHFPC) research. Families in China have expressed concerns over financial instability as prices for housing and education surge amid an economic slowdown. Zhai et al. (2014) projected demographic consequences of an immediate transition to a two-child policy and concluded that new policy will increase labor supply and slow down population aging in the future.

Ongoing urbanization and increasing per capita living area are also drivers of growth in residential building floor space. During the 12th Five Year Plan Period (2011–2015), the Chinese government emphasized turning urbanization into a powerful engine to drive economic growth and remake the economy in an environmentally friendly way. According to the Central Urbanization Work Conference, China will map out 32 city clusters by 2030 across the country's central, western and northeastern regions to settle more rural residents in smaller cities rather than megacities (Xinhua, 2013). From 1980 to 2012, urbanization rate has increased from 19% to 53%; it is expected to further increase to 69% by 2030 and 80% by 2050 (United Nation, 2012). Accompanied with rapid urbanization, per capita urban residential building floor space increased from 7.2 m^2 to 32.9 m^2, and per capita rural residential building floor space increased from 9.4 m^2 to 37.1 m^2 (National Bureau of Statistics, 2014b). In China, personal living space has increased because of dwindling numbers of people per household and an expanding middle class that can afford more living space. The slightly increased population together with dramatically rising average floor space has resulted in impressive growth of residential building floor space in recent decades. By the end of 2012, total residential building floor space was 47.7 billion m^2, more than five times what it had been in 1980. In addition, overheated real estate investment in recent years caused construction growth to be on pace to exceed demand from migration and the growth rate of average urban floor space will slow down in the future. Therefore, average urban and rural floor space were projected to reach approximately 46 m^2/capita by 2050, which was equivalent to the average level of dwelling floor space per capita in developed countries (nations with per capita GDP above $20,000) (United Nation, 1997). As shown in Fig. 1, total residential building floor space will reach 67.3 billion m^2.

3.2. Commercial building floor space

Globally, total commercial building floor space is driven by the percentage of service-sector employment and floor space per employee in this sector. As mentioned in the methodology section, average commercial floor space per employee was a logistic function of per capita income. The maximum floor space per employee in China was set at 40 m^2 per employee, being similar to the level of United Kingdom. China has the world's largest number of migrant workers due to its nationwide urbanization process.

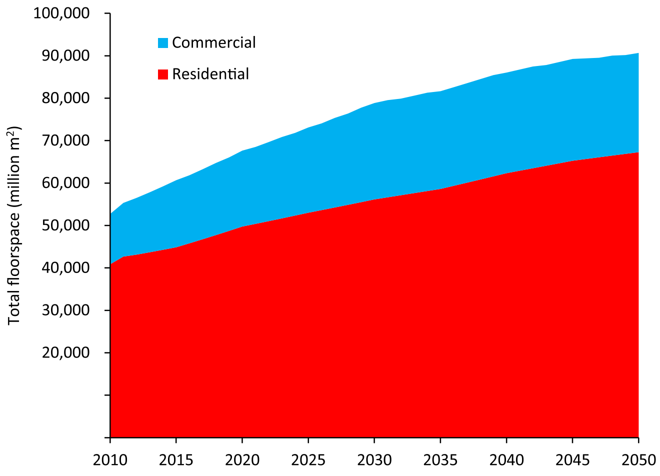

Fig. 1. China residential building floor area projection.

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[2] According to the Chinese National Bureau of Statistics, economically active population referred to all persons aged 16 years or above who furnish the supply of labor for the production of economic goods and services. It comprised both employed and unemployed population. In the paper, historical economically active population data from 1980 to 2012 was gained from annual Chinese Statistical Yearbooks.

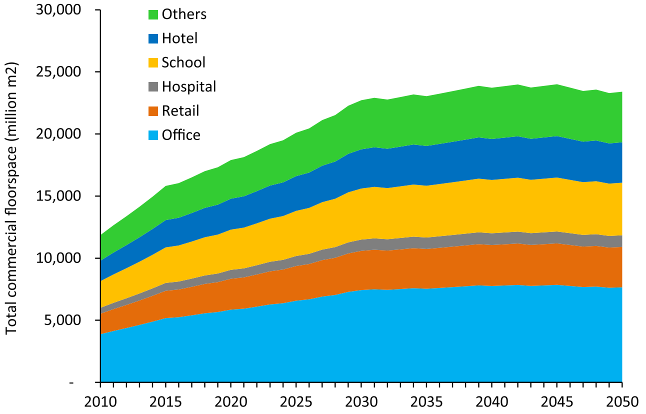

Fig. 2. China commercial building floor area projection.

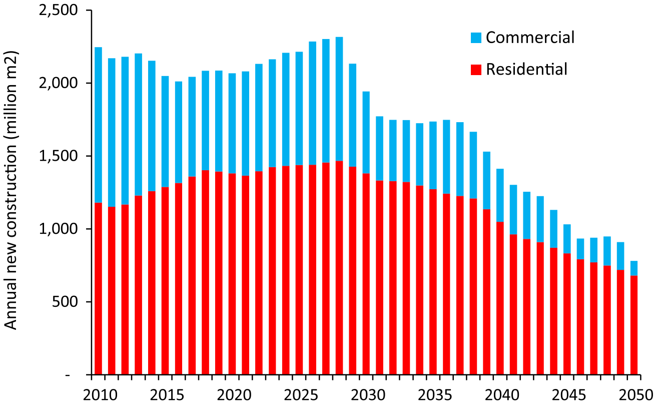

Fig. 3. Three year rolling average of new constructions (2010–2050).

From 2000 to 2013, the number of migrant workers has increased from 140 million to 260 million or approximately one-fifth of the nation's total population (Song, 2012). Most migrants move from rural areas to cities, and a majority of them work in manufacturing and service sector, approximately 70% and 22% respectively in 2010 (Song, 2012). However, official statistics on service-sector employment's share of the total economy omitted a large portion of employees because of the rigid Hukou[3] registration system, which resulted in a mismatch between the number of registrations and the actual numbers of rural migrants who live in cities. The adjusted tertiary employed share was 40% compared to the statistical figure of 35% in 2010. Fig. 2 showed historical and projected commercial floor space in China from 2000 to 2050. The total commercial floor space[4] has been projected to be 23.3 billion m^2 in 2050, more than one third of which will be office buildings.

4. Building stock dynamics

In this paper, average building lifetime is assumed to be 30 years for urban residential and commercial building built in 1980–1999, 40 years in 2000–2019 and 50 years in 2020–2050. Rural residential buildings normally have a shorter lifetime than urban residential and commercial buildings. The average lifetime of rural building was assumed to be 15 years for building built in 1980–1999, 20 years in 2000–2019 and 30 years in 2020–2050. Fig. 3 showed a 3-year rolling average of new constructions for residential and commercial buildings, because construction of a building usually requires more than one year of efforts. For residential buildings, new constructions will mainly come from urban areas accompanied by accelerated urbanization process. Rural new constructions are almost negligible between 2015 and 2040 because of continuously decreasing rural population and increases of rural building lifetime from 20 years to 30 years after year 2020. Residential new constructions follow the shape of a normal distribution. The number will grow from 1181 million m^2 in 2010, reach the peak of 1467 million m^2 in 2028, and then gradually decline to 680 million m^2 in 2050. The construction of new commercial buildings will be stable from 2010 to 2030 in the range of 700–1000 million m^2 and then sharply decrease to 100 million m^2 in 2050 due to prolonged building lifetime and thus reduced demand for new constructions.

A more interesting issue is residential and commercial building dynamics in different climate zones. Fig. 4 reflected the replacement of new constructions after 2010 to buildings built prior to 2010 in different climate zones from 2010 to 2050. In general, buildings built before 2010 will gradually be phased out by 2050 and replaced by new constructions. This dynamic process implied great energy and material saving potentials if adopting higher building codes and standards related to energy and material use, utilizing more advanced construction methods such as large-scale prefabrication and higher quality of building materials, and making more careful and rational urban planning in order to realize longer average building lifetime for the whole society. Also, Fig. 4 indicated annual building stock change of new constructions and energy retrofits in different climate zones from 2010 to 2050. Here, energy retrofits include building stocks built after the year 2010.

According to 12th Five Year Plan on Building Energy Conservation, cumulative retrofit area in northern Chinese[5] urban areas was 182 million m^2 in 2010; this figure was expected to increase to 582 million m^2 by 2015, while planned retrofit areas in transition urban areas will be 50 million m^2 by 2015. Overall, retrofit rates in northern and transition urban areas were 5% and 3%, respectively, of total residential building floor space in 2015. Current building energy efficiency policies have not set any retrofit target for rural residential buildings. In the reference scenario, the amount of retrofitted building in northern urban areas will be equivalent to all building stocks in 2010, approximately 40% of building stocks in 2050. And approximately 20% of building stocks in 2050 will be retrofitted in transition and southern urban areas. As shown in Fig. 4, annual retrofitted buildings will increase form 86 million m^2 in 2010–267 million m^2 in 2050 in northern urban areas. In terms of annual new constructions, the number will gradually peak at 628 million m^2 in 2029 and then decline to 280 million m^2 in 2050. As a result, retrofitted buildings and new

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[3] Hukou registration is a household registration system based on an individual's birthplace that was established in the 1950s. It is designed to control the movement of people between rural and urban areas. Individuals are categorized as a "rural" or "urban" workers; migrants whose Hukou is registered as "rural" workers usually can not enjoy public services such as health care and education in urban areas. In terms of statistics on urban and rural populations, there is significant mismatch between the Hukou registration figures and the actual numbers of residents in rural and urban areas because a large portion of rural migrants who live in cities have not registered as urban residents.

[4] It included commercial buildings in urban areas, counties, towns, and villages. Historical commercial building floor space was adjusted according to "Statistical Bulletin of City, County, Town and Village 2005–2007" published by the Ministry of Housing and Urban-Rural Development of the People's Republic of China.

[5] According to the Standard of Climate Regionalization for Architecture (GB50178-93) published by the Ministry of Construction in 1993, China is divided into five major building climate zones based on mean temperature in coldest and hottest months. These climate zone are: (1) severe cold, (2) cold, (3) hot summer and cold winter (HSCW), (4) temperate, and (5) hot summer and warm winter (HSWW). The model groups severe cold and cold regions as the northern region, HSCW and temperate regions as the transition region, and HSCW as the southern region. Urban and rural areas are further subdivided into northern/transition/southern regions.

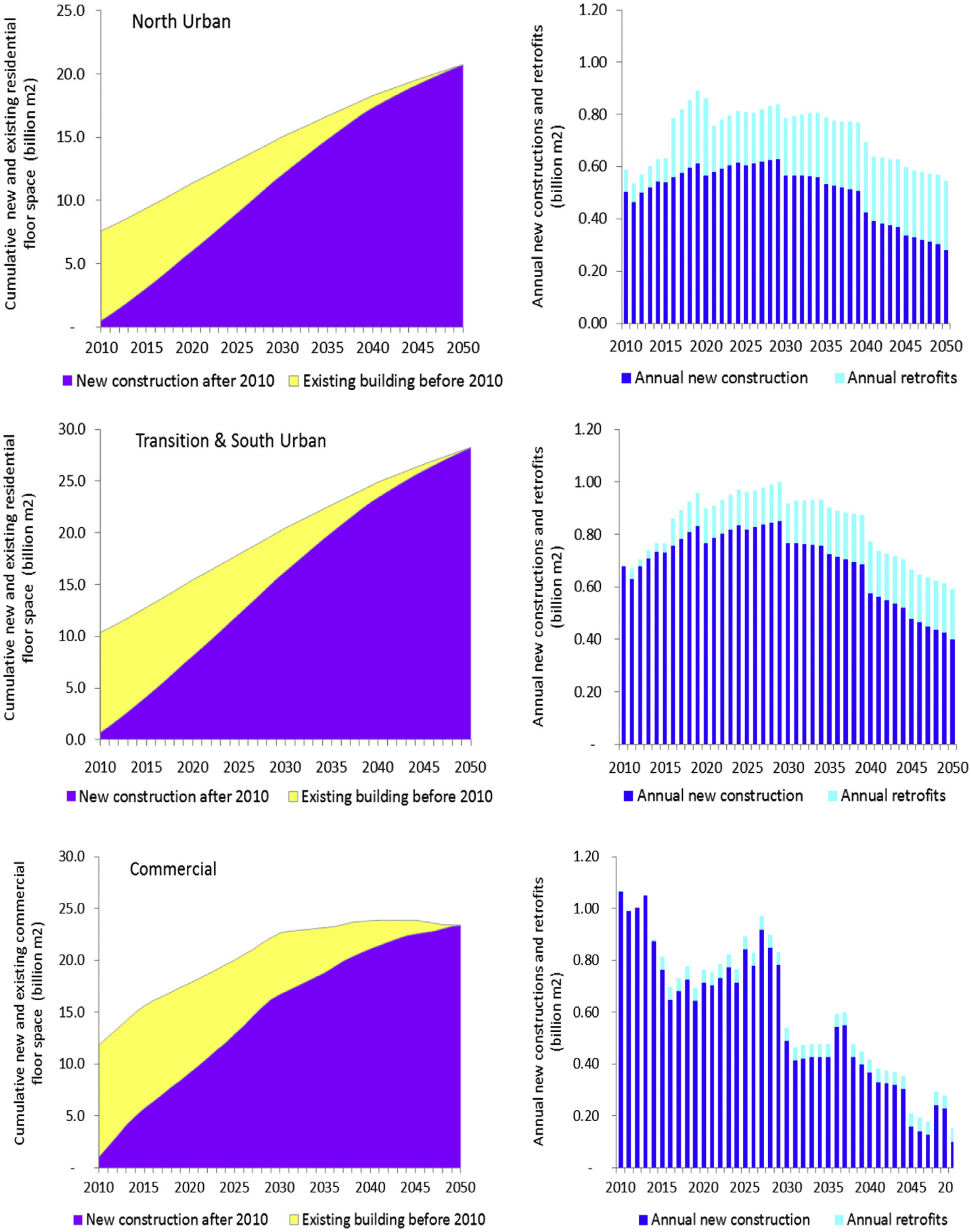

Fig. 4. Building dynamics by climate zones and building types (2010–2050).

constructions will account for half each in northern urban area in 2050. In southern and transition urban areas, annual new construction will peak at 850 million m^2 in 2029 and then reduce by 50% in 2050. At the same year, annual retrofitted buildings will be half of new constructions.

The energy retrofit target for commercial buildings is much less ambitious compared to the targets for residential buildings. The 12th Five Year Plan on Building Energy Conservation proposed to retrofit 60 million m^2 of commercial floor space by 2015 with a focus on large-scale commercial buildings and an aim of decreasing average commercial building energy intensity by 10% by the end of 2015. This retrofit target is equivalent to 0.41% of total commercial building stocks of that year. We assumed that 10% of total commercial building stocks will be retrofitted by 2050. The amount of newly constructed commercial floor space has continued to increase from 2000 to 2010, and will remain at a high level between 2010 and 2020, and then start to decrease after 2020 because of saturated average floor space per employee and increased average building lifetime. Regarding to annual retrofits, it will remain at a low level due to lack of targets and incentives.

5. Building materials and energy demand

Annual construction of large new buildings has created enormous demand for building materials such as concrete, steel (particularly for steel reinforcement of concrete), aluminum, glass, synthetic and natural polymers, and other materials in China. Three types of building structures are common, including brick-wood, brick-concrete, and reinforced concrete (Shi et al., 2012). Concrete and structural steel are used extensively as the primary materials in residential and commercial buildings. Because construction of a building usually requires more than one year of effort, a three-year rolling average of newly built constructions has been adopted to calculate related annual demand for building materials.

Building material intensity used here was defined as volume of construction material (ton) per unit of constructed area (m^2). These intensities were assumed to be the same across all regions of the nation. Commercial and urban residential buildings consume the greatest volume of resources among new buildings. The material intensity of urban residential and commercial buildings is greater than that of rural residential buildings. Because urban residential and commercial building occupants use more materials for interior partitions, ceilings, floors, wall finishes, water and electrical fixtures and distribution devices, lighting, heating, and air conditioning, and other space-defining and service-providing elements. By contrast, most rural residential buildings has fewer end-use demands for heating, cooling, and lighting and are constructed with relatively fewer materials. Cement intensity was assumed to be 0.15 t/m^2 for rural residential buildings (Liu, 2010), and 0.22 t/m^2 for commercial buildings (Liu, 2014). For urban residential buildings, cement intensity was expected to increase over time as China's buildings were projected to become taller on average and require more cement for structural support. Average cement intensity of urban residential buildings was expected to increase from 0.212 t/m^2 floor area in 2008 to 0.247 t/m^2 floor area in 2030 and remain constant thereafter (Hu et al., 2010). As with the cement projections, the share of 7-story or higher steel-concrete structures in urban residential buildings will rise from 60% in 2000 to 90% in 2020% and 100% in 2030 (Liu, 2010; McKinsey, 2009). The steel intensities for masonry-concrete and steel-concrete buildings will stay constant at current levels of 25 kg/m^2 and 59 kg/m^2, respectively (Hu et al., 2010). From 2010 to 2050, average steel intensity of urban residential buildings will therefore increase from 49 kg/m^2 in 2010 to 59 kg/m^2 in 2030 and thereafter. Rural residential buildings also consume small share of total structural steel, and its material intensity will also grow slowly from 5 kg/m^2 in 2000 to 7.7 kg/m^2 in 2050 (Hu et al., 2010). Commercial buildings were assumed to be all high-rise steel-concrete buildings with the same constant steel intensity of 59 kg/m^2 as steel-concrete residential buildings. Glass is another important building material used for windows. It has been recognized that the building construction sector is responsible for 80–87% of all flat glass consumption (Haley, 2009). Empirical studies suggested a glass intensity of 1.75 kg/m^2 for residential buildings and 7.5 kg/m^2 for commercial buildings in China (Fridley et al., 2011). Similarly, building construction is a driver of aluminum demand. Aluminum intensity of residential and commercial building construction was estimated to increase from 2.02 kg/m^2 and 4.9 kg/m^2 in 2010–2.20 kg/m^2 and 5.34 kg/m^2 in 2025 and remain constant thereafter (Aden et al., 2010). Fig. 5 showed projected annual demand of major building materials. By 2050, annual major building materials demand from industrial sector will be less than one third of those used today. Cement and structural steel will remain to be the most important building materials, and their materials demand will be 190 and 40 million tonnes by 2050.

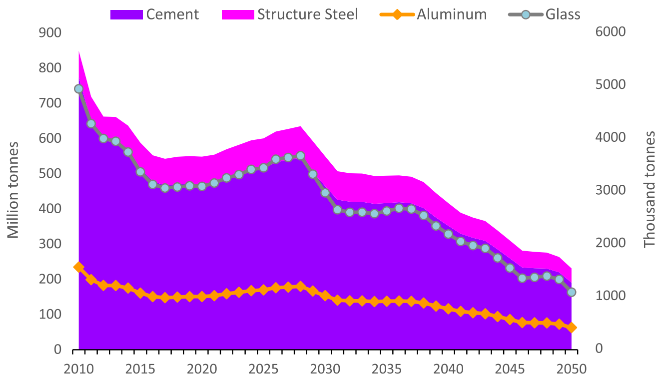

Fig. 5. Annual material demands of major building materials (2010–2050).

Energy demand of producing building materials could be calculated based on materials demand, technology share and energy intensity. Based on previous modeling on China's end use energy outlook to 2050 under continuous technology improvement (Zhou et al., 2011), cement energy intensity was assumed to meet 2005 current world best practice of 0.101 tce/t cement for Portland cement by 2025. All shaft kilns will be phased out and replaced by rotary kilns by 2020, while rotary kilns' final energy intensity will reach 0.09 tce/t cement by 2030 and 0.07 tce/t cement by 2050 (Zhou et al., 2011). Steel energy intensity will decline in both basic oxygen furnace (BOF) and electric arc furnace (EAF). Steel production from EAF will increase from 13% in 2010 to 25% in 2050. Regarding to aluminum production, it will reach current U.S. share of 65% primary and 35% secondary production by 2030 and further switch to share of 20% primary and 80% secondary production by 2050. Final energy consumption will decrease from 4.47 tce/t in 2010 to 2.41 tce/t in 2050 for primary production and from 2.51 tce/t in 2010 to 0.09 tce/t in 2050 (Zhou et al., 2011). Flat glass energy intensity will decrease from 0.34 tce/t in 2010 to 0.3 tce/t in 2030 and finally reach 0.26 tce/t in 2050 (Zhou et al., 2011). In general, annual total energy used to produce major building materials will reduced from 249 Mtce in 2010 to 35 Mtce in 2050, with cement, steel, aluminum and glass contributing 46.9%, 23.7%, 27.1% and 2.4% (Fig. 6). From 2010 to 2050, building materials demand will reduce by 73% and related energy demand will decrease by 77%.

6. Sensitivity analysis

Urbanization, population, and per capita living area were identified as key drivers for the growth of residential floor space. All these variables have a certain degree of uncertainty; therefore,

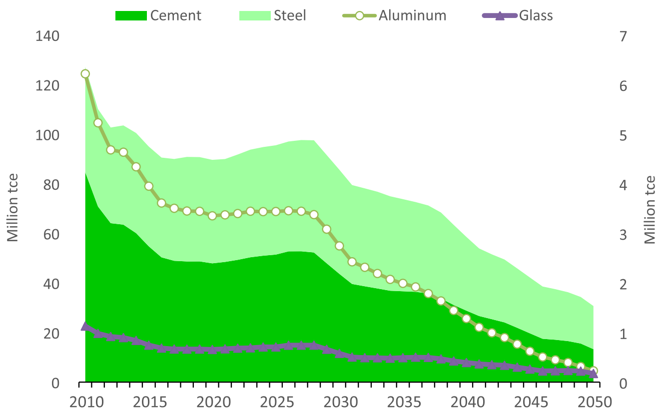

Fig. 6. Annual energy demand of major building materials (2010–2050).

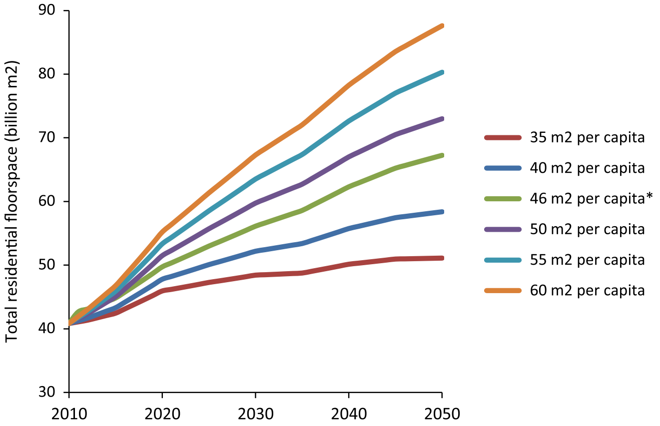

Fig. 7. Sensitivity analysis of per capita living area on residential floor space.

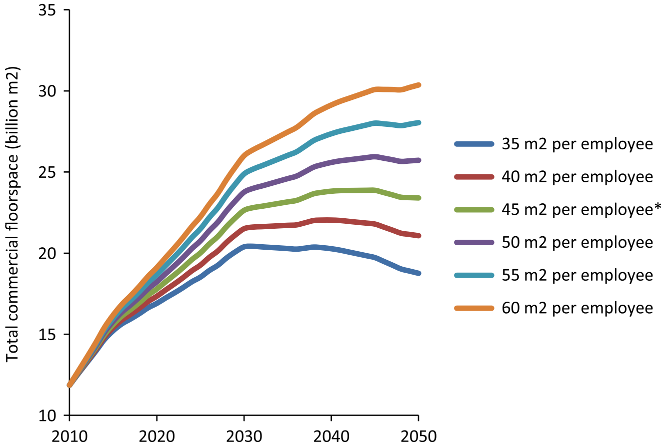

Fig. 8. Sensitivity analysis of per service employee area on commercial floor space.

it is important to verify the sensitivity of these factors on the calculated results. As gaps between per capita living area in rural and urban areas will gradually narrow down, it is actually total population rather than urbanization rate that have an influence on total residential floor space by 2050. Total population was obtained from the UN projection and population projection is not a focus of this paper, instead, we have compared various per capita living areas by 2050 on the total residential floor space in China as shown in Fig. 7. In scenario 1, average per capita living area remained at 35 m^2, which was the similar level of that in 2010. Despite of continuous growth of urbanization and economies, the nation has adopted measures to improve housing quality and compact urban development to curb urban expansion. In scenario 2, per capita living area reached 40 m^2, which was equivalent to the Netherland's average per capita living area in 2000. As described before, scenario 3 was the reference scenario, indicating that per capita living area in China by 2050 will reach the average level of OECD countries in 1997. In scenario 4, per capita living area arrived at 50 m^2, reaching the 2009 level of Denmark. In scenario 5, residents' housing requirements showed an apparent increase to 55 m^2, exceeding most developed European countries. In scenario 6, continuous economic growth has prompted a considerable increase in floor space demand. Residential building area rapidly increased from 2010 to 2050 until per capita living area got 60 m^2, still less than the U.S.'s current level,[6] almost doubles over the next 40 years.

Similarly, commercial floor space per service sector employee is the key drivers for the growth of total commercial floor space. From 2010 to 2050, commercial floor space grew more rapidly than residential floor space, with an annual average growth rate of 1.4%. Average commercial floor space per service sector employee in 2010 was 30.2 m^2, which was similar to South Korea's current level. Fig. 8 reflected the sensitivity of commercial floor space per service sector employee on the total commercial floor space. In scenario 1, this figure increased a little bit to 35 m^2 by 2050, reaching Japan's current average commercial floor space per service sector employee. In scenario 2, per capita commercial floor space reached 40 m^2, being equivalent to the UK's average per capita commercial area in 2010. Scenario 3 was the reference scenario, it was projected that average commercial floor space per service sector increase rapidly until 45 m^2 due to economic growth and higher demand for services such as office, retail, hotel and etc. This figure was equivalent to France's level. Scenario 4 and 5 represented more developed economies in Europe such as Sweden and Denmark, which associated with higher demand for average commercial floor space. In scenario 6, average commercial floor space per service sector employee arrived at 60 m^2, approaching the U.S.'s current level. This number was also the upper limit of this sensitivity analysis considering the large difference of population density between these two countries.

Also, impact of different building lifetime on annual building constructions from 2010 to 2050 was verified as reflected in Fig. 9. In the reference scenario, we assumed that average building lifetime was 30 years for urban residential and commercial building built in 1980–1999, 40 years in 2000–2019 and 50 years in 2020–2050. For rural buildings, the average lifetime was assumed to be 15 years for building built in 1980–1999, 20 years in 2000–2019 and 30 years in 2020–2050. This assumption was relative conservative. In China, designed building lifetime is 50 years and experts are discussing to extend it to 70 years to be the same as the ownership of residential buildings. In the longer building lifetime scenario, we assumed that average building lifetime was 30 years for urban residential and commercial building built in 1980–1999, 50 years in 2000–2019 and 70 years in 2020–2050. For rural buildings, average lifetime was assumed to be 15 years for building built in 1980–1999, 30 years in 2000–2019 and 50 years in 2020–2050. As shown in Fig. 8, annual new construction in longer building lifetime scenario peaked at 2069 million m^2 in 2026, earlier than that in the reference scenario. By 2050, annual new construction will be 569 million m^2, approximately 30% less than that of reference scenario. As the scope of this study is from 2010 to 2050, buildings built after 2010 would not reach their lifetime

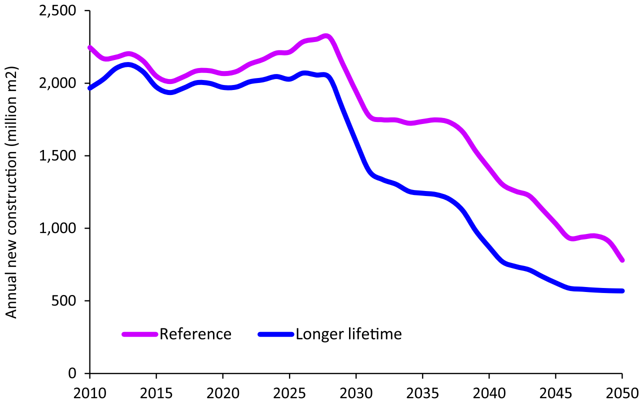

Fig. 9. Sensitivity analysis of building lifetime on annual new construction.

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[6] Per capita residential floor space in the U.S. is 70 m^2/capita (Moura et al., 2015). This article adopted 60 m^2/capita for the upper boundary of sensitivity analyses, under the circumstance of much higher population density and less livable land resources in China. Besides, per capita residential floor space in OECD countries could be found in the EU report (Dol and Haffner, 2010).

by the end of 2050. In other words, between these two scenarios, a 10-year extension of building lifetime contributes to 30% less new constructions and implied materials and energy demand.

7. Conclusion and policy implication

We have examined the long term trends of building floor space, building materials use and energy consumed to produce these materials, by simulating a variety of scenarios using a bottom-up building stock turnover model. The methodology could be applied to any other regions when data available. Also once we obtain more accurate data, model results could be refined easily. This paper unlocked hidden material and energy saving potentials in the building sector and provided the following policy implications.

Firstly, policies oriented to curb the fast growth of building floor space are needed. Future building floor space is mainly driven by several factors including population growth, urbanization rate, per capita area and etc. Based on the detailed bottom-up modeling work, China's total building floor space was estimated to increase from 47.7 billion m^2 in 2012 to 90.7 billion m^2 by 2050. Total residential building floor space will reach 67.3 billion m^2 by 2050, with 80% of population reside in urban areas. Total commercial building floor space will be 23.4 million m^2, with office buildings accounting for more than one third of it. Several other studies also made some assumptions and projections for China's building floor space. For example, Shi et al. (2016) estimated that total building floor space will be 87.7 billion m^2 by 2050, in which residential building accounts for 67.8%. Yu et al. (2014) concluded that per capita floor space will continues to increase in all sectors and total building floor space was projected to be approximately 80 million m^2 by 2050. In this paper, major assumptions used to project future building floor space were considered as using current development trend without any policy intervention. Admittedly, main drivers such as population growth and per capita area are influenced by policies and human behaviors, which will definitely lead to some uncertainties for projection results. Therefore, sensitivity analyses were used to verify the validity of projected results. It implied that total building floor space could be 7–15% lower than the predicted level if compact development policy is widely adopted to guide future urban development.

Secondly, it is necessary to reinforce current building energy retrofit targets and initiatives as well as promote more stringent energy performance standards for new constructions. Annual new building construction in China has been growing since 1990. It reached 2.3 billion m^2 in 2010, accounting for half of the world's total. This trend would not continue but will be more stable until 2029 due to continuous urbanization process and economic growth. Afterwards, annual new constructions will decline to 780 million m^2 by 2050 because of saturated per-capita building space and increased building lifetime. Currently, energy retrofit rate is low for both residential and commercial buildings in China, approximately 5% of northern residential stocks, 3% of transition residential stocks and 0.4% of commercial stocks (MOHURD, 2012). Besides, there is a lack of retrofit targets for the vast amount of rural buildings. Fig. 4 quantitatively elaborated impressive energy retrofit potentials in different climate zones of China over the next 40 years. The results implied regional discrepancy of building retrofit implementation, insufficiency of existing retrofit targets for all building types as well as massive energy and resource conservation potentials in the building sector. More importantly, as new constructions make up the majority of total building stocks by 2050, it is necessary to gradually improve building energy performance and construction standards and monitor the compliance and enforcement of these standards.

Thirdly, based on the projection of annual new constructions, we further predicted that annual materials and energy demand will significantly decline from 2010 to 2050. By 2050, annual materials and energy demand for major building materials in China will be 27% and 23% of today's demands respectively, reducing more than 80% indirect CO_2 emissions associated with building construction compared to the status quo. Cement and structural steel will remain the most important building materials. Nonetheless, demand for cement and structural steel will decline significantly, from 774 million tonnes in 2010 to 190 million tonnes in 2050 for cement, and from 74 million tonnes in 2010 to 40 million tonnes in 2050 for structural steel.

Finally, the analysis also highlighted the importance of prolong average building lifetime in order to conserve energy and resources. Based on the scenario analyses, a 10-year extension of building lifetime contributed to roughly 30% less new constructions and related materials and energy demand. It implied the necessity to produce and use higher-quality building materials, utilize advanced construction approaches such as prefabricated buildings, adopt stricter building codes, and promote long-term sustainable urban planning. All of above-mentioned changes will help reduce the demand for building materials and thus the energy used to produce them, as well as the environmental consequences related to energy consumption.

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