Modeling China's Building Floor-Area Growth and the Implications for Building Materials and Energy Demand

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ABSTRACT

China is the world's largest energy consumer and carbon emitter and is facing severe environmental consequences. Most of China's emissions source from an industrial sector dominated by heavy industries, many of which produce various building materials. Chinese buildings total nearly 50 billion square meters in area and new construction represents half of the world's total each year, with expansion expected to continue through 2050. Buildings in China currently have a lifetime of only roughly 30 years, with much higher material intensity than their international counterparts. This has significant impact on driving the production of building materials such as concrete and cement, glass, steel, and aluminum, and has important implications for the development of policies such as building codes and labels.

This paper presents a new methodology for projecting the growth in China's building floor area to 2050 and the implications of this growth for building materials and total energy demand. We identify key socioeconomic drivers of growth in residential and commercial building floor area and developed a building stock turnover model to predict annual new construction floor area. We then use typical material intensities and energy intensities to calculate demand for building materials and related energy demand to produce these building materials. The methodologies developed in this study provide a solid foundation for forecasting China's building stock growth in the absence of consistent historical data. Such forecasts will help assess future building energy demand. The results of our study underscore the importance of addressing building material efficiency, improving building lifetime and quality, and promoting compact urban living to reduce building energy consumption and associated emissions in China.

Introduction

As the world's largest energy consumer and carbon emitter, China faces severe environmental consequences. Most of China's emissions come from industrial sector dominated by heavy industrials, many of which produce building materials. In addition, direct energy use by building end uses accounts for 25% of the total energy use. This figure is expected to increase rapidly because of growth in the building stock as well as improvements in indoor comfort demands associated with urbanization[1]. Average building energy intensity in China is low, but demand by end uses such as heating, cooling, lighting, and appliances is growing quickly (Zhou et al. 2011).

[1] Between 1980 and 2012 the urbanization rate increased from 20% to 53%, while the urban population quadrupled. 663 cities are now home to more than half of the total Chinese population of 1.4 billion. According to existing studies, China's urbanization rate will continue to increase from 53% in 2012 to 75-80% by 2050, reaching the current level of most developed countries (United Nations 2012). Public and private funding have been directed to provide sufficient housing and commercial buildings for new city residents.

Chinese building floor space totals nearly 50 billion square meters and new construction represents in China accounts for half of the world's total each year, with growth expected to continue through 2050. Buildings in China currently have much shorter lifetimes and much higher materials intensity than their international counterparts. These two factors are significant drivers of the production of building materials such as concrete and cement, glass, steel, and aluminum. This has important implications for the development of policies such as building codes and labels; these policies could promote changes that would reduce the energy used to produce building materials and related carbon emissions.

Much research has focused on building energy use and technology efficiency, but few studies have looked at the relationship between building construction and building materials demand and the associated energy use. China's construction industry consumes nearly half of annual global cement and steel production, and the energy used by China's building materials industry accounts for approximately 9% of the country's total energy use and 15% of industrial energy use. In addition, Chinese buildings are poor quality, with an average lifetime of only approximately 30-40 years for urban buildings (Song 2005) and 15 years or less for rural buildings (Huang 2006), both much shorter than the average building lifetime of 60 years in the United States (U.S. Department of Energy 2011). Reasons include a lack of long-term urban planning and a preponderance of irrational short-term real estate interests in China (Song 2005).

This paper identifies the main socioeconomic drivers of the growth in China's building floor areas, and proposes a methodology for projecting residential and commercial floor areas to 2050. We developed a building stock turnover model that quantifies annual residential and commercial[2] new construction, which drives annual building materials and related energy demand. The results of our model underscore the importance of addressing the efficiency of building materials, improving building lifetime and quality, and promoting compact urban living to reduce building energy consumption and emissions in China.

Methodology

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

$$N_{i,t}^{B} = S_{i,t}^{B} - S_{i,t-1}^{B} + D_{i,t}^{B}$$

where $S_{i,t}^{B}$ is the residential/commercial building stock in region *i* in year *t*, $N_{i,t}^{B}$ is the newly built residential/commercial building in region *i* in year *t*, and $D_{i,t}^{B}$ is the demolished residential/commercial building in region *i* in year *t*. A building stock retirement function is incorporated to reflect the probability of building stock being demolished after a certain number of years. It is assumed to follow the cumulative normal distribution.

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

$$D_{i,t}^{B} = \frac{1}{2}\left[1 + \text{erf}(\frac{z_{i,t}^{B} - \mu}{\sigma\sqrt{2}})\right]$$

where $z_{i,t}^{B}$ is the age of building stock in region i in year t, the mean of the distribution μ is assumed to equal to the average lifetime of building stock in region i, and the standard deviation σ is assumed to be one third of the average building lifetime. As noted above, the average lifetime of Chinese buildings in urban areas is 30 to 40 years (Song 2005) and 15 years or less in rural areas (Huang 2006). The following formula is applied to calculate urban and rural residential building stock separately:

$$S_{i,t-1}^{RB} = P_{i,t-1} \times a_{i,t-1}$$

where $S_{i,t-1}^{RB}$ is the floor area of the residential building stock in region i in year t-1, $P_{i,t-1}$ is the population of area in region i in year t-1, and $a_{i,t-1}$ is the per capita floor area of residential building in region i in year t-1.

We model commercial building floor area 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:

$$S_{i,t-1}^{CB} = P_{i,t-1}^{S} \times a_{i,t-1}^{S}$$

where $S_{i,t-1}^{CB}$ is the floor area of commercial building stock in region i in year t-1, $P_{i,t-1}^{S}$ is the population of service sector employees in region i in year t-1, $a_{i,t-1}^{S}$ is the floor space per employee in service sector in region i in year t-1.

$$P_{i,t-1}^{S} = P_{i,t-1}^{EA} \times (1 - R_{i,t-1}^{U}) \times S_{i,t-1}^{S}$$

where $P_{i,t-1}^{EA}$is the economically active population[3] in region i in year t-1. Historical value is from National Bureau of Statistics and projected valued is from the International Labor Organization to 2020 and extrapolated thereafter (ILO, 2007). $R_{i,t-1}^{U}$ is unemployment rate in region i in year t-1. A national unemployment rate of 4% is adopted for all three regions in this study. $S_{i,t-1}^{S}$ is the share of service sector employee in total employee in region i in year t-1, which is modeled as a logistic 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).

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

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

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

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

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

Residential Building Floor Space Projection

Population growth is not a main driver of residential building floor space in China per se as population growth has slowed. Total population is projected to peak at 1.45 billion by 2030 and then decline to 1.39 billion (slightly above the 2012 level) by2050 (United Nations 2012). Because of the "One Child Policy", average urban household size in China 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. Because of concern that the strict population controls were undermining economic growth and contributing to a rapidly aging population, a new population policy issued in November 2013 allows couples to have two children if one of the parents is an only child. This population policy change was designed to relieve the pressure of an aging society to some degree. Yet there is no sign of broadly relaxing birth controls and dramatically increasing population growth in the future.

Ongoing urbanization and increasing per capita living area are two main drivers of growth in residential building floor space. During the 12th Five Year Plan Period (2011 - 2015), the Chinese government emphasizes turning urbanization into a powerful engine to drive economic growth and remake the economy in an environmentally friendly way. According to the plan, 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. From 1980 to 2012, the urbanization rate has increased from 19% to 53%; it is expected to further increase to 69% by 2030 and 80% by 2050 (United Nations 2012). At the same time, 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. 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 area in recent decades. By the end of 2012, total residential building floor area 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. We assume that average urban and rural floor space is projected to reach approximately 46 m^2/capita by 2050, which is the average level of dwelling floor space per capita in developed countries (nations with per capita GDP above $20,000) (United Nations 1997). As shown in Figure 1, total residential building floor space will reach 62.9 billion m^2.

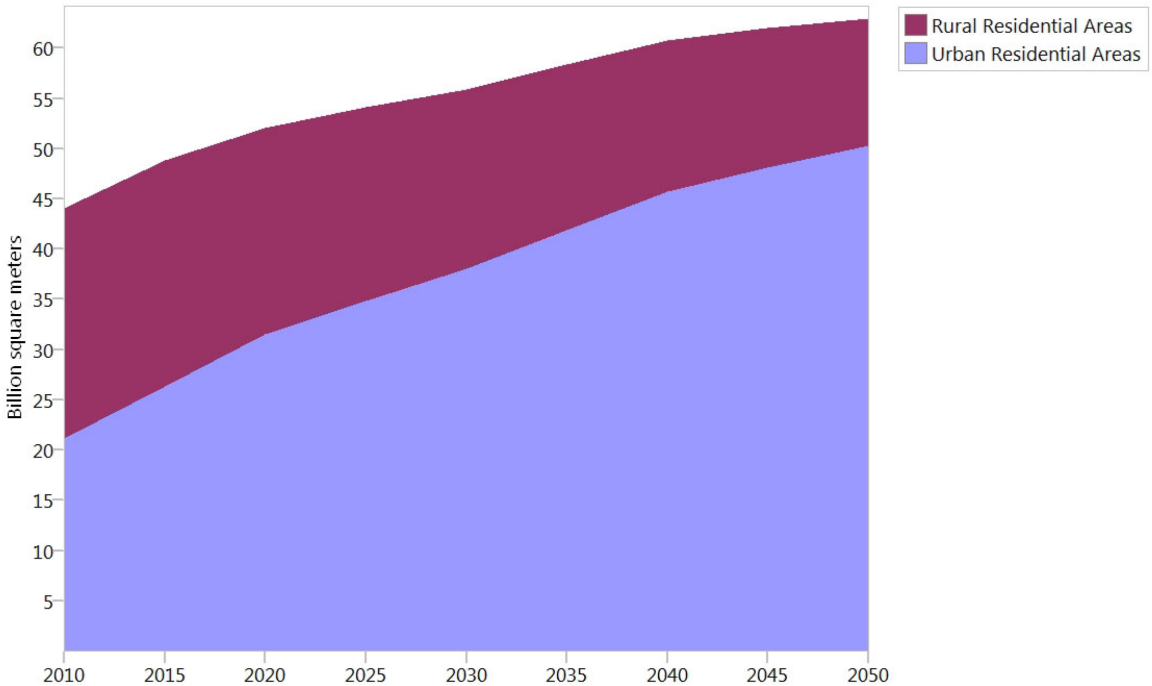

Figure 1. China residential building floor area projection.

Based on the average lifetime of Chinese buildings quoted above, we assume in our building stock turnover model that average lifetime are 30, 40, and 50 years for urban residential and commercial buildings built in 1980-1999, 2000-2019, and 2020-2050, respectively. The increases in average lifetime correspond to introduction of stricter building codes and higher quality of building materials over time. For rural residential buildings constructed during the same three time periods, the average lifetimes are 15, 20, and 30 years.

According to the 12th Five Year Plan on Building Energy Conservation, the cumulative retrofit area in northern Chinese[4] urban areas was 182 million m^2 in 2010; this figure is expected to increase to 582 million m^2 by 2015, and the planned retrofit areas in transition urban areas will be 50 million m^2 by 2015. Overall, retrofit rates in northern and transition urban areas are 5% and 3%, respectively, of total residential building stock, but there is no retrofit target for rural residential buildings. Annual energy retrofit of residential buildings increased significantly from 2010 to 2015, but it still represents a very small proportion of the total residential building stock if we assume that existing building energy conservation policies continue and that no additional, more ambitious building energy retrofit policies and plans are implemented by 2050.

[4] 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.

Commercial Building Floor Space Projection

Globally, the total commercial building floor space is driven by the percentage of service-sector employment and the floor space per employee in this sector. As noted in the Methodology section, average commercial floor space per employee is a logistic function of per capita income. The maximum floor space per employee in China is set at 40 m^2 per employee, which is equivalent to the UK level. China has the world's largest number of migrant workers because of its national wide urbanization process. From 2000 to 2013, the number of migrant workers increased from 140 million to 260 million or approximately one-fifth of the nation's total population, including 150 million who moved from one province to another and 110 million who moved from the place where they were registered to another place within the same province. 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 2010). However, the official statistics on service-sector employment's share of the total economy omits a large portion of employees because of the rigid Hukou[5] registration system, which result 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.

Figure 2 shows historical and projected commercial floor space in China from 2000 to 2050. The total commercial floor space[6] is projected to be 18.9 billion m^2 in 2050, more than one third of which are office buildings. The energy retrofit target for commercial buildings is much less ambitious than the targets for residential buildings particularly for residential buildings in northern heating areas. The 12th Five Year Plan on Building Energy Conservation proposes 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. The amount of newly constructed commercial floor space continues to increase from 2000 to 2010, remains at a high level between 2010 and 2020, and begins to decrease after 2020 because of saturated average floor space per employee and increased average building lifetime.

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[5] Hukou registration is a household registration system based on an individual's birthplace that was established in the 1950s. It was 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't 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 haven't registered as urban residents.

[6] This includes commercial buildings in urban areas, counties, towns, and villages. Historical commercial building floor space is 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.

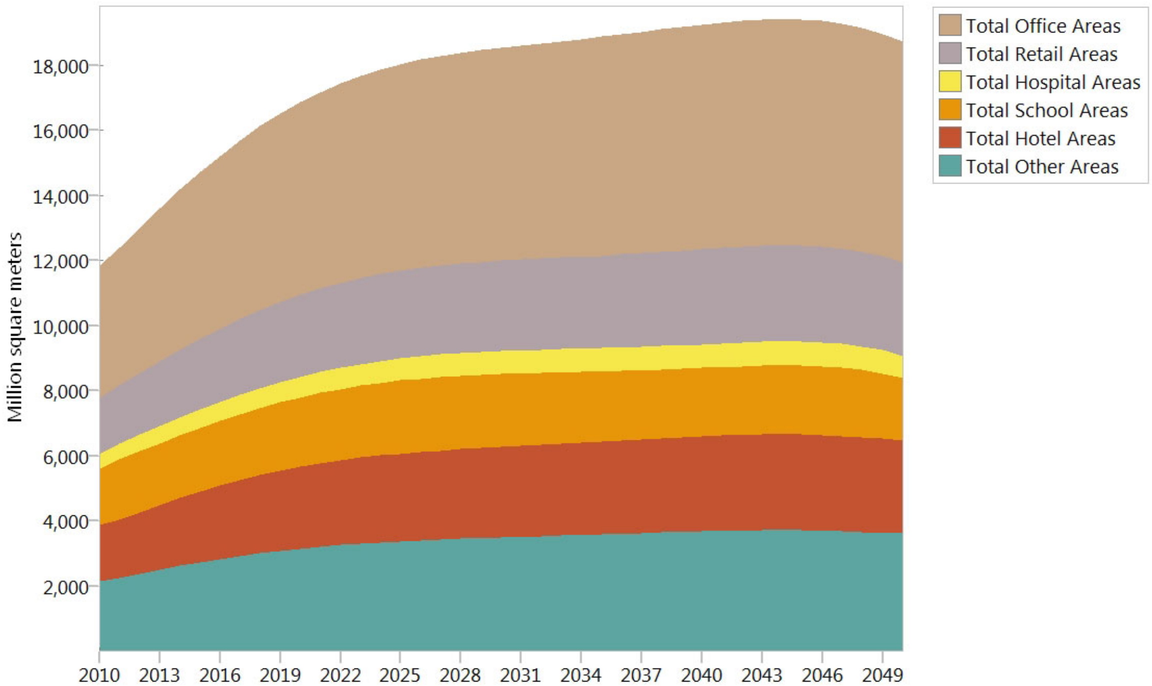

Figure 2. China commercial building floor area projection.

Building Materials and Energy Demand

Annual construction of large new buildings in China creates enormous demands 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 in China, 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, we use a three-year rolling average of newly built constructions is used to calculate related annual demand for building materials (Figure 3). The results suggest that new building construction peaks around 2010 and will gradually decline because of increased average building lifetime and saturated per capita floor space. In particular, new construction in rural areas almost ceases between 2020 and 2030 because of continuously decreasing rural population and increases of rural building lifetime from 20 years to 30 years after year 2020.

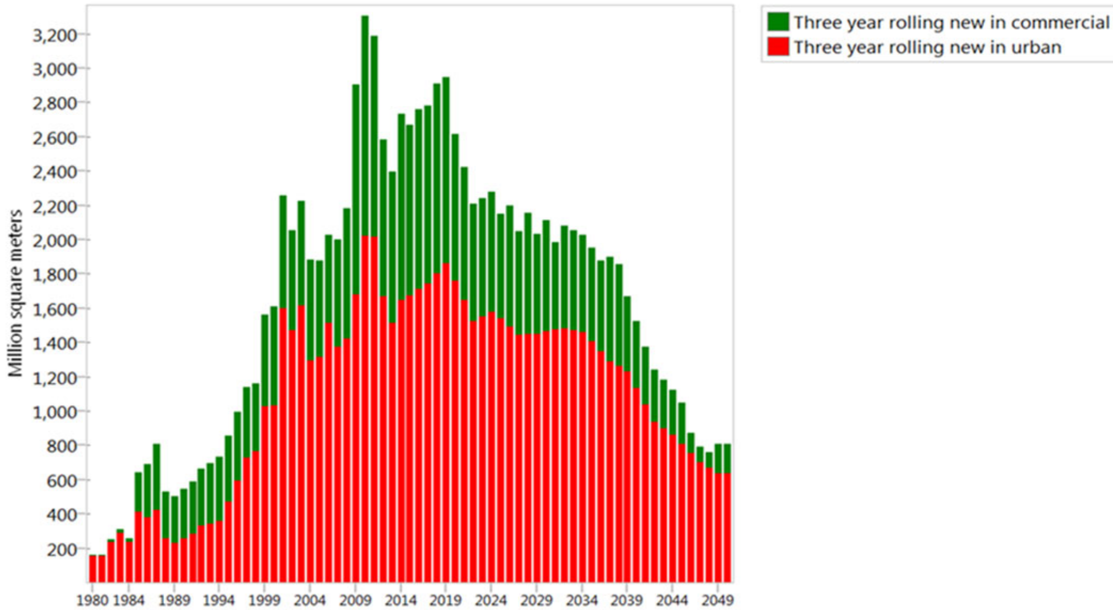

Figure 3. Three year rolling average of new constructions (1990-2050).

We define building material intensity used here is volume of construction material (ton) per unit of constructed area (m^2). These intensities are 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. This is because the demands of urban residential and commercial building occupants result in use of 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. In contrast, most rural residential buildings have fewer end-use demands for heating, cooling, and lighting and are constructed with relatively fewer materials. Cement intensity is assumed to be 0.15 ton/m^2 for rural residential buildings (Liu 2014), and 0.22 ton/ m^2 for commercial residential buildings (Liu 2014). For urban residential buildings, the cement intensity is expected to increase over time as China's buildings are projected to become taller on average and require more cement for structural support. The average cement intensity of urban residential buildings is expected to increase from 0.212 ton/m^2 floor area in 2008 to 0.247 ton/m^2 floor area in 2030 and remain constant thereafter (Hu et al. 2010). As with the cement projections, we assume 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 (McKinsey 2009; Hu et al. 2010). The steel intensities for masonry-concrete and steel-concrete buildings are assumed to stay constant at current levels of 25 kg/m^2 and 59 kg/m^2, respectively (Hu et al. 2010). From 2010 to 2050, the 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 is assumed to also grow slowly from 5 kg/m^2 in 2000 to 7.7 kg/m^2 in 2050 (Hu et al. 2010). Commercial buildings are 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 is indicated that the building construction sector is responsible for 80-87% of all flat glass consumption (Haley, 2009). Empirical studies suggest a glass intensity of 1.75 kg/m^2 for residential buildings and 7.5 kg/m^2 for commercial buildings in China (Zhou et al. 2011). Similarly, building construction is a driver of aluminum demands. The aluminum intensity of residential and commercial building construction is expected to increase from 2.02 kg/m^2 and 4.9 kg/m^2 in 2010 to 2.20 kg/m^2 and 5.34 kg/m^2 in 2025 and remain constant thereafter (Aden et al. 2010). Figure 4 shows the projected annual demands of major building materials. By 2050, annual major building material demands from industrial sector will be less than one third of those used in today. Cement and structural steel remain the most important building materials, and their material demands are 222 and 40 million tonnes by 2050, around 2-10 times of glass and aluminum.

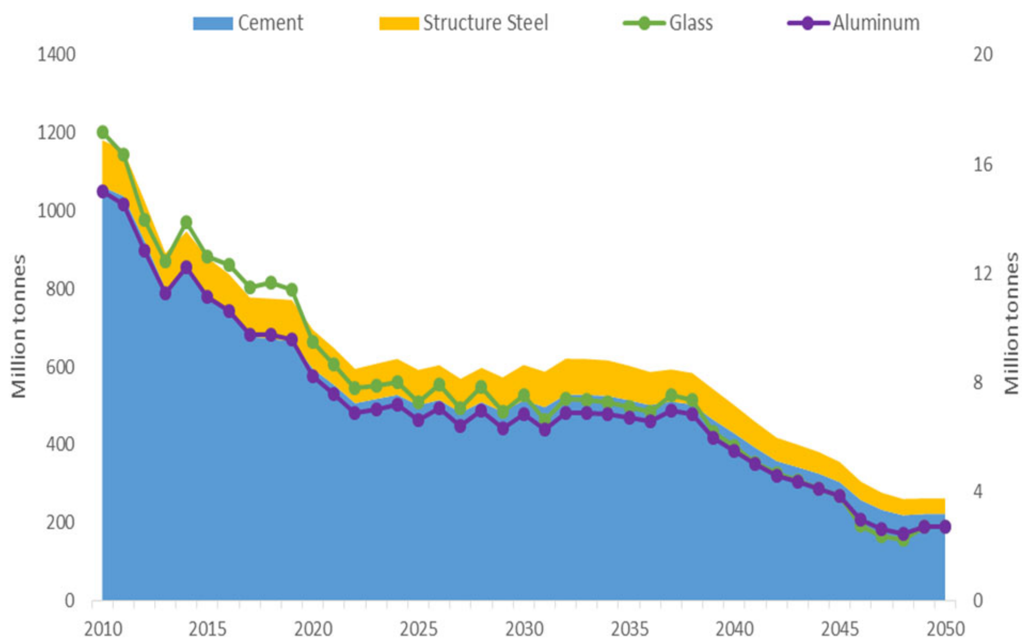

Figure 4. Annual material demands of major building materials (2010-2050).

Energy demands of producing building materials could be calculated based on material demands, 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 is 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 reaches 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% (Figure 5).From 2010 to 2050, building material demands reduce by 77.9% and related energy demands decrease by 86%.

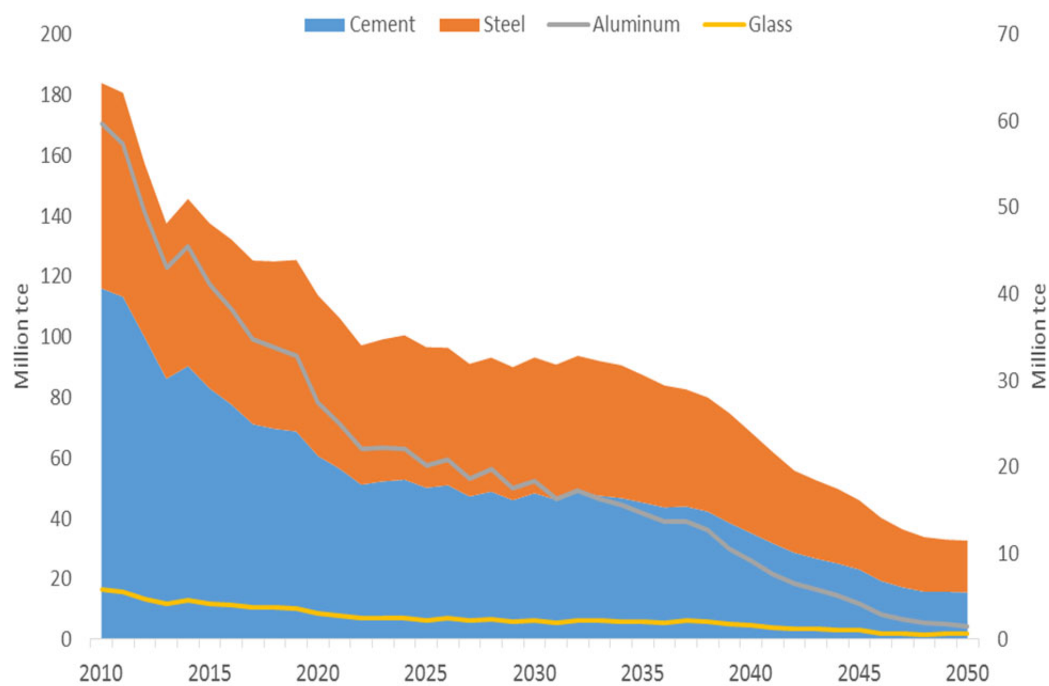

Figure 5. Annual energy demands of major building materials (2010-2050).

Conclusion

There are few statistics on residential and commercial floor space in China. This article provides a new methodology to project future building floor space which could help more accurately evaluate future trends in building industry and building energy use. It also unlocks the hidden material and energy demands and potential material and energy saving opportunities in building sector.

Based on our building stock turnover model, China's total building stock will increase from 47.7 billion in 2012 to 81.9 billion by 2050. By 2050, total residential building floor space will reach 62.9 billion m^2, with 80% of population reside in urban areas. Total commercial building floor space will be 18.9 million m^2, with office buildings accounting for more than one third of it. China's current new construction each year accounts for about half of the world's total, but this will decline from nearly 3 billion m^2/year currently to 2.5 billion m^2/year in 2020 and 0.8 billion m^2/year in 2050 because of saturated per-capita building space and increased building lifetime. The energy retrofit rate is low for both residential and commercial buildings in China. Policies and other actions to improve this rate, particularly in rural areas, will help reduce building energy use in China and its associated environmental consequences.

By 2050, annual material and associated energy demand for major building materials in China will be 22% and 14% of today's demand respectively, reducing the indirect energy emissions associated with building construction. Cement and structural steel will remain the most important building materials. Nonetheless, demand for cement and structural steel will decline significantly, from 1,062 million tonnes in 2010 to 222 million tonnes in 2050 for cement, and from 119 million tonnes in 2010 to 40 million tonnes in 2050 for structural steel.

The results of this study highlight the need to produce and use higher-quality building materials, the need for advanced construction approaches such as prefabricated buildings, the need for stricter building codes to promote energy efficiency and prolong average building lifetime, and the need for policies and other actions to promote compact urban living and thus reduce urban floor area and energy consumption. All of these changes will reduce the demand for building materials and thus the energy used to produce them as well as the environmental consequences related to energy consumption.

Acknowledgments

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References

Aden, N., Y. Qing, and D. Fridley. 2010. *Lifecycle Assessment of Beijing-Area Building Energy Use and Emissions: Summary Findings and Policy Applications.* Berkeley, CA: Lawrence Berkeley National Laboratory.

Fernández, J.E. 2007. "Resource Consumption of New Urban Construction in China." *Journal of Industrial Ecology* 11(2): 99-115.

Haley, U. 2009. *Through China's looking glass subsidies to the Chinese glass industry from 2004-08.* Economic Policy Institute Briefing Paper. Washington, DC: Economic Policy Institute.

Huang, W. 2006. *Speech given at the meeting of "Building New Countryside of the Socialist Society."* Beijing, China, 21 March, 2006, Ministry of Construction of China.

ILO (International Labour Organization). 2007. *Key Indicators of the Labor Market*, Fifth Edition, CD rom version.

McNeil, M.A., V.E. Letschert, S. De la Ru du Can, and J. Ke. 2012. *Bottom-up energy analysis system – methodology and results.* Berkeley, CA: Lawrence Berkeley National Laboratory.

Shi, F., T. Huang, H. Tanikawa, J. Han, S. Hashimoto, and Y. Moriguchi. 2012. "Toward a Low Carbon-Dematerialization Society." *Journal of Industrial Ecology* 16(4): 493-505.

Song, J. 2010. "Migrant employment in urban China: characteristics and determinants – a comparative study with rural left-behind people." *Population Research* 34(6): 32-42.

United Nations. 1997. *List of BSSA (Basic Social Services for All) indicators*. http://www.un.org/esa/population/pubsarchive/bss/tbssslac.htm.

United Nations. 2012. *UN World Urbanization Prospects*, the 2011 Revision. http://esa.un.org/unup/.

U.S. Department of Energy. 2011. *2010 buildings energy data book*. Silver Spring, MD: D&R International, Ltd.

Zhou, N., D. Fridley, M. McNeil, N. Khanna, J. Ke, and M. Levine. 2011. *China's energy and carbon emissions outlook to 2050.* Berkeley, CA: Lawrence Berkeley National Laboratory.