ABSTRACT

Title of Dissertation: TRANSITION PATHWAYS OF CHINA AND IMPLICATIONS FOR CLIMATE CHANGE MITIGATION: EVOLUTION OF THE BUILDINGS SECTOR

Sha Yu, Doctor of Philosophy, 2017

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China, as the world's largest energy consumer and greenhouse gas emitter, also has the largest construction market. Energy use in Chinese buildings (including traditional biomass) constitutes 28% of China's total final energy consumption and 16% of global building final energy consumption in 2012. Driven by economic growth, urbanization, and lifestyle changes, energy consumption in Chinese buildings is expected to continue to grow. Buildings will therefore be an important element of efforts by the Chinese government to plan infrastructure, constrain energy growth, or meet a range of related sustainability goals.

This dissertation examines the evolution of the Chinese buildings sector and focuses on three issues. First, in order to make robust projections, we investigate the historical growth of the buildings sector in China, Japan, and the United States. The growth paths of Japan and the United States provide useful historical analogs for China's future growth. We find that the change in energy use intensity was driven by short-term events, such as introduction of new policies, and showed greater variability compared to other drivers, whereas growth in per capita floorspace and household characteristics showed consistent long-term trends and was less responsive to short-term events.

Second, we examine the growth in floorspace by province and building type. We use Gompertz model to estimate future floorspace growth, as it captures dynamics between floorspace and income and the saturated demand. This study shows variation across provinces in floorspace growth and a wider range of floorspace at the aggregate level than literature. It also has strong policy implications, as housing policies, in addition to building energy policies, are critical to curbing the growth in China's building energy use.

Third, using the Global Change Assessment Model-China (GCAM-China), we assess China's future building energy demand under different transition pathways while accounting for provincial heterogeneity. We find that distinct development paths can lead to different levels of building energy consumption in China (25-42 EJ in 2050), and most growth would happen in the next two decades. Strong, provincial-specific near-term policy actions are needed in order to avoid locking in the inefficient infrastructure.

TRANSITION PATHWAYS OF CHINA AND IMPLICATIONS FOR CLIMATE CHANGE MITIGATION: EVOLUTION OF THE BUILDINGS SECTOR

By

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2017

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To my loving parents

Yumei Liu & Shihai Yu

Acknowledgements

This dissertation would not have been completed without help and support from many people over the years. First and foremost, I would like to express my deepest appreciation and gratitude to my advisor, Nathan Hultman, for the intellectual guidance, mentorship, support, and encouragement he provided throughout my entire doctoral education. Nate helped me shape the dissertation, think through policy implications, and learn how to communicate research results with broader audience. I am truly fortunate to have had the opportunity to work with him.

I owe a huge debt of gratitude to Leon Clarke, for his patient guidance and thought-provoking suggestions in the dissertation process. Leon taught me how to think about and develop research questions, how to frame and interpret research results, and how to be an effective communicator. These skills will benefit me for the rest of my life.

I would also like to acknowledge Anand Patwardhan for his great insights and suggestions on the scenario analysis, floorspace model, and policy analysis. His suggestions helped improve the dissertation to a great extent. In a similar vein, I want to thank Margaret Pearson. I benefited a lot from the discussion with Margaret on China's policies and political situations, especially how to think about the role of middle class in China's development. Finally, I thank Laixiang Sun for being a part of my committee and serving as the Dean's Representative.

I would like to thank the team developing and maintaining the Global Change Assessment Model (GCAM) and colleagues at the Joint Global Change Research

Institute (JGCRI), Pacific Northwest National Laboratory. The dissertation builds on the previous GCAM work and benefits from discussions with colleagues at JGCRI.

I would also like to recognize the Office of Fossil Energy and the Integrated Assessment Research Program in the Office of Science of the U.S. Department of Energy for their funding support. The Integrated Assessment Research Program supported the development of the floorspace model in Chapter 3. The Office of Fossil Energy supported the development of GCAM-China and its application in Chapter 4. The views and opinions expressed in this paper are my own.

Finally, I am indebted to my parents Yumei Liu and Shihai Yu and my husband Chongzhi Zang. They supported me to start this journey 5 years ago and had belief in me the entire time. I also would like to give special thanks to friends who stayed by my side during this process. The dissertation journey has ups and downs; the encouragement from my family and friends always helped me bounce back in those down moments and complete the doctoral education.

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Chapter 1. Introduction

Buildings are the largest end-use sector globally (Figure 1.1). They consume more than one-third of all final energy and half of electricity, and account for around one-third of global carbon emissions (IEA, 2014b). With expected economic development and population growth, especially in the developing world, energy demand and carbon emissions from the buildings sector will continue to increase, posing challenges to infrastructure planning, energy security, and climate change mitigation (IEA, 2013; Lucon et al., 2014).

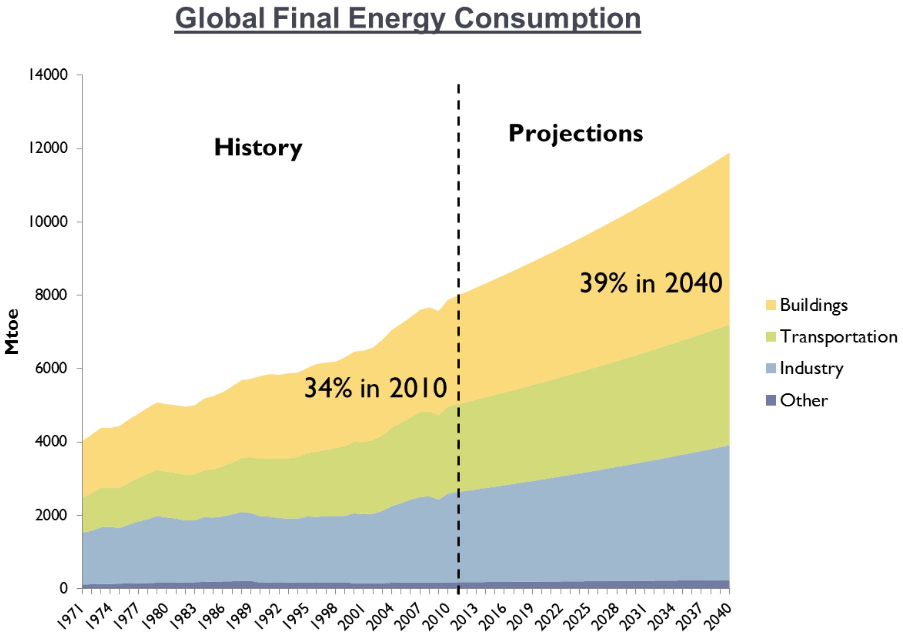

Figure 1.1 Global final energy consumption by sector (1971-2040)

Sources: (EIA, 2014b; IEA, 2014b).

Stabilizing global climate change would require substantial mitigation efforts from all sectors, with strong technological, institutional, and economic support. To limit global temperature rise to 2 Celsius would require over 70% reduction in total CO_2 emissions in the buildings sector by

2050, compared to the current level. In addition, buildings often last for decades, and therefore, reduction in energy use and carbon emissions in the buildings sector are critical to any long-term mitigation strategy (IEA, 2013).

China, as the world's largest energy consumer and greenhouse gas emitter, also has the world's largest construction market. China is a top building energy consumer and the amount of building energy use in China is similar to that of the United States and the European Union (IEA, 2014a). Buildings are also important to China's energy system. Energy use in buildings (including traditional biomass) constitutes 28% of total final energy consumption in China (IEA, 2014a; Jiang et al., 2014). Driven by economic growth, urbanization, lifestyle changes, and changes in the economic structure, energy consumption of the Chinese buildings sector is expected to continue to grow rapidly. Buildings will therefore be an important element of efforts by the Chinese government to plan infrastructure, constrain energy growth, or meet a range of related sustainability goals such as local air pollution and greenhouse gas emission reductions (Daioglou et al., 2012; Delmastro et al., 2015; IEA, 2014b, 2015c; Jiang et al., 2014; McKinsey & Company, 2009; Shi et al., 2014; Ürge-Vorsatz et al., 2012; WBCSD, 2009; Yu et al., 2014b; Zhou et al., 2013).

Previous studies on future building energy use in China showed a wide divergence in final energy consumption and mitigation opportunities, caused by differences in methodologies, scope, resolution of sectors and technologies, and assumptions of future growth (Figure 1.2). These studies examined how the changing composition of the energy system and building energy technologies would impact future building energy demand in China. For example, Jiang et al. (2014), Zhou et al. (2013), and the World Energy Model group at the International Energy Agency (IEA) (2014b) developed scenarios with different levels of low carbon technologies and policies and assessed building energy demand in these scenarios. Eom et al. (2012) and IEA's Energy Technology Perspective modeling group (2015c) assessed impacts of climate policies on the buildings sector and explored China's building energy use with different fuel and technology mix of the energy system.

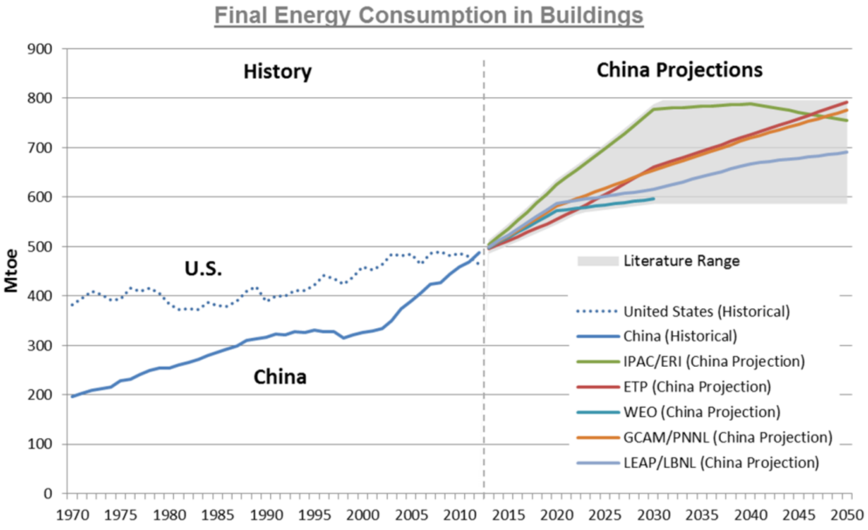

Figure 1.2 Final energy consumption in buildings across studies

Sources: (Eom et al., 2012; IEA, 2014b, 2015c; Jiang et al., 2014; Yu et al., 2014b; Zhou et al., 2013; Zhou et al., 2014).

In addition to technology and energy system profile, variations in development paths can affect building energy demand. Countries with similar income levels and technology advancement may still have different building energy outcomes. For example, per capita building energy use in Japan is much less than that of the United States, France, United Kingdom, and Germany (Dzioubinski and Chipman, 1999; Howarth et al., 1993; McDonald, 1990; Pérez-Lombard et al., 2008). The development path China might pursue would have strong implications on future building energy use and by extension emissions reduction.

China is a large, diverse country, and heterogeneity across provinces and regions may also influence building energy demand at both provincial and national levels. There is a wide disparity in energy consumption patterns of the buildings sector across provinces. Housing size, occupancy density, income level, climate, lifestyle and behavior, and use of appliances all vary widely by province. For example, in the northern provinces, a significant portion of building energy consumption is used for heating, while buildings in the central China with hot summers and cold winters only have modest heating loads. The regional heterogeneity also has a strong influence on technology and policy options for energy efficiency improvement and carbon emissions abatement and needs to be considered in the assessment of China's building energy demand.

To better understand the development of the Chinese buildings sector and mitigation strategies, this dissertation accounts for provincial heterogeneity and examines future building energy demand in China under different transition pathways. In particular, it answers three questions. First, how would historical growth in building energy use inform future projections? Second, given that floorspace is a key driver of building energy use in China, what do different development paths imply for floorspace estimates? Finally, how might variations across provinces and development pathways might influence building energy outcomes?

The first essay (Chapter 2) examines the historical trends of building energy consumption and explores how the key drivers of building energy use simultaneously shaped buildings sector outcomes. Understanding how the buildings sector evolved in the past and how different drivers affected the development process and building energy use can help inform the future development of the buildings sector in China. Building on the previous research, this essay contributes in three ways. First, it compares the key trends and drivers across countries, while existing studies focused on a single country or a group of advanced economies. Looking beyond China, it also assesses the growth in Japan and the United States, which are among the largest building energy consumers globally and represent two distinguished development paths. The historical analysis of Japan and the United States can shed light on alternative development paths China might pursue. Second, it uses a longer time series of historical data than existing analyses and captures transitions in policies, socioeconomic conditions, and lifestyles, as well as their impact on building energy consumption. Third, while the majority of previous studies only focused on residential buildings, this essay extends the study scope to both residential and commercial buildings to provide a full picture of the evolution of the buildings sector.

The second essay (Chapter 3) focuses on the future growth in building floorspace. Developing countries like China are expected to experience rapid floorspace growth in the next several decades, which has the potential to shape the energy system. Growth in floorspace affects future energy demand of the buildings sector; it also has strong linkages to the upstream and downstream industries and influences the energy demand of the industrial sector. Therefore, understanding future growth in building floorspace is critical to assessing future energy demand and greenhouse gas emissions in China. The second essay estimates future building floorspace of rural residential, urban residential, and commercial sectors for individual provinces in China, and contributes to the literature in the following ways. First, it draws on historical experience and derives the relationship between floorspace and income growth at the provincial level. Second, it considers how urban planning and development path would shape the evolution of the buildings sector and develops alternative floorspace projections that span a range of uncertainties in the saturation level. Third, it explores how floorspace and energy use intensity interact and shape future building energy demand in China. It is worth noting that the methodology developed in this paper is widely applicable and can be extended to study building floorspace growth in a different country and at the global scale.

The third essay (Chapter 4) aims to better understand and characterize the uncertainty in China's building energy demand. This study builds on this previous research in three main ways. First, rather than focusing on a single possible pathway, we develop four scenarios to depict plausible narratives regarding development pathways of China, each characterizing how key drivers might evolve. We then provide quantifications of these narratives to understand the evolution in key indicators of building sector evolution. Scenario analysis is an important method for exploring uncertainty in future development, often consisting of both qualitative and quantitative components, as in this study (Jones et al., 2014; O'Neill et al., 2015; Raskin et al., 2005; van Vuuren et al., 2012). Although we focus on buildings in this paper, the scenarios are intended to be broadly usable by for studies of other aspects of China's energy and environmental dynamics. The scenarios provide a useful complement to the Shared Socioeconomic Pathways (SSPs). Second, this study explicitly models buildings at the provincial level. As discussed above, provincial heterogeneity may affect regional planning, as well as building energy demand at the aggregate level.

The final chapter (Chapter 5) discusses policy options to improve energy efficiency in buildings and achieve deep decarbonization. It also discusses future research directions emerged from this dissertation work. In addition to methodological contributions that improve the understanding of the Chinese buildings sector and energy outcomes, the three essays in this dissertation also provide insights for policy development. The three essays underscore the importance of the development path. China is experiencing rapid development and transitions, and the transition pathway China choose would have significant impacts on energy outcomes.

Chapter 2. Decomposition Analysis and Drivers of Building Energy Use: Comparison of the United States, Japan, and China

2.1 Introduction

Buildings are the largest end-use sector globally. China is an increasingly important actor in the buildings sector and accounted for 16% of global building final energy use in 2012. Building energy consumption in China grew rapidly in the past decade. Between 2000 and 2012, building energy use in China grew by 37% and building electricity demand increased by more than 200%, highest among all major economies. While at the per capita level building energy consumption in China is still much lower than that of advanced economies, total building energy use is highest among all countries and expected to continue growing in the next few decades due to rapid income growth, increasing comfort levels, and expansion of end-use services. If unaddressed, this would become a challenge to China's infrastructure development, energy system planning, and greenhouse gas and air pollutant emissions reduction. Although improvements in technologies and policies can enhance energy efficiency, whether these improvements can offset the increase in building energy service demand is uncertain. Understanding how the buildings sector evolved in the past and how different drivers affected the development process and building energy use can help inform the future development of the buildings sector in China. Therefore, we examine the historical trends of building energy consumption and explore how energy efficiency improvement and other drivers simultaneously shaped the buildings sector.

The impact of different drivers on building energy consumption has been widely discussed in the literature (Table 2.1). The majority of studies focused on changes in the residential sector and the selection of drivers varied across studies. Population and the number of households were the most commonly used drivers and some studies also considered specific factors such as income and weather effect. In addition, a few studies further disaggregated energy use by different housing type or energy service to understand changes at the subsector level. In terms of the geographic coverage, existing studies focused on a single country or a group of countries at similar development stages (e.g. OECD 10, EU 15, and IEA 18). Two key trends were observed in these studies. First, income growth, the number of households, and floorspace growth had the most significant contribution to the growth in building energy demand, but the growth could be partially or fully offset by the decrease in energy use intensity. Second, the impact of different drivers changed over time, depending on the stage of development and the development path a country pursued (Achão and Schaeffer, 2009; ADEME, 2007; Chung et al., 2011; EECA, 2012; Golove and Schipper, 1997; Greening et al., 2001; Hojjati and Wade, 2012; IEA, 2007a; OEE, 2011; Petchey, 2010; Rogan et al., 2012; Rosas-Flores et al., 2011; Schipper et al., 1997; Shorrock, 2000; Unander et al., 2004; Xu and Ang, 2014).

Table 2.1 Existing studies assessing historical trends of building energy use

Source	Region	Study Period	Activity	Structure	Energy Intensity	Other Factors
Golove et al. (1997)*	USA	1960–1993	P	A_j/P	E_j/A_j	–
Schipper et al. (1997)*	OECD-10	1973–1991	P	A_j/P	E_j/A_j	–
Shorrock (2000)*	UK	1990–2000	N	–	E/N	–
Greening et al. (2001)*,#	OECD-10	1970–1993	P	A_j/P	E_j/A_j	–
Unander et al. (2004)#	Scandinavia	1973–1990	P	A_j/P	E_j/A_j	–
ADEME (2007)	EU-15	1990–2004	N	A_j/N	E_j/A_j	–
IEA (2007)	IEA-18	1990–2004	P	A_j/P	E_j/A_j	–
Achão et al. (2009)#	Brazil	1980–2007	P	P_r/P	E_r/P_r	–
Petchey (2010)	Australia	1990–2008	P	A_j/P	E_j/A_j	–
Zha et al. (2010)*,#	China	1991–2004	P	–	E/Y	Y/P
Chung et al. (2011)#	Hong Kong	1990–2007	N	N_i/N	E_i/N_i	–
OEE (2011)	Canada	1990–2009	N	N_i/N	E_{ij}/A_{ij}	A_{ij}/N_i
Rosas-Flores et al. (2011)#	Mexico	1996–2006	P	A_j/P	E_j/A_j	–
EECA (2012)	New Zealand	1990–2011	P	N/P; F/N	E_f/F	E_f/E
Hojjati and Wade (2012)#	USA	1980–2005	N	$N_{i,r}/N$	E_i/F_i	F_i/N_i
Rogan et al. (2012)#	Ireland	1990–2008	P	–	E_i/N_i	N_i/P
Zhao et al. (2012)#	China	1998-2007	P	Ex/P	E_j/Y	Y/Ex
Fan et al. (2013)*,#	China	1996–2008	P	A_j/P	E_j/A_j	–
Xu and Ang (2014)#	Singapore	2000-2010	P	$P_i/P;A_{ij}/N_i$	E_{ij}/A_{jj}	N_i/P_i
Nie and Kemp (2014)#	China	2002-2010	P	F/P	E_j/F	–
Zhou and Chen (2015)	China	1996-2013	P	F_i/P_i	E_i/F_i	–

Note: This table is adapted from Xu and Ang (2014). * indicates studies on CO_2 emissions as they are a direct extension of energy studies. # indicates studies on residential buildings. i: building or house type; j: end-use; r: region/income group; f: fuel type; E: energy consumption; Y: residential sector value added; P: population; N: number of households; F: total floor area; Ex: household expenditure; A: energy service driven measurement by end-use, e.g. floorspace for space heating/cooling end uses, number of appliances for appliance end uses, etc.

Five studies, in particular, focused on building energy consumption in China. These studies investigated changes in the Chinese buildings sector in the past two decades. Zha et al. (2010) examined impacts of population, household income, energy intensity (energy use per unit of income), energy structure (percentage of total energy expenditure), and CO_2 emission coefficient in urban and rural residential buildings between 1990 and 2004. They found that the income effect contributed most to the increase in CO_2 emissions, and improvement in energy efficiency and carbon emission coefficient was not enough to offset the increase due to population, income, and energy structure effect. Zhao et al. (2012) studied urban residential building energy use between 1998 and 2007, and further disaggregated energy use into 17 different end-use services. They found that per capita household expenditure, larger share of energy expenditure, and population growth contributed to the growth in urban residential energy consumption, while higher energy prices contributed negatively to urban residential energy consumption. Fan et al. (2013) assessed China's residential carbon emissions between 1996 and 2008 and found that the fuel mix of primary and final energy had insignificant effect on residential carbon intensity and the mix of residential energy services had the highest contribution to the increase in carbon intensity. Nie and Kemp (2014) studied residential energy consumption in China between 2002 and 2010. They added additional factors to understand the floorspace effect as well as impact of five end-use services. Nie and Kemp (2014) found that the increase in appliances was the biggest contributor to the increase in residential energy consumption, but the effect declined over time due to energy efficiency improvement. Per capita floorspace was the second largest contributor, followed by population. Energy mix was the least important factor. Zhou and Chen (2015) extended the study scope to include both residential and commercial buildings and considered four factors: population, proportion of urban population, per capita floorspace, and energy use intensity. Their results indicated that per capita floorspace was the primary contributing factor to the growth in China’s building energy consumption during 2004-2013 and the increasing ratio of urban population was the secondary factor. Although improvement in energy use intensity had a negative contribution rate of -33%, it was not enough to offset the rapid growth driven by floorspace expansion and urbanization.

Building on the previous research, we examine the driving forces of building energy consumption in a more comprehensive way. First, we look beyond China and examine and compare the historical growth in China, Japan, and the United States. The historical analysis of developed countries can shed light on alternative development paths China might pursue. Japan and the United States, among the largest building energy consumers in the world, both experienced dramatic growth in building energy consumption in the past few decades, but had distinct growth patterns. Japan had relatively low per capita household energy consumption, compared to other countries in the Organisation for Economic Co-operation and Development (OECD). In 1988, annual energy use per household in Japan was approximately one-half of that in France, United Kingdom, and Germany, and about one-third of that in the United States. Although the gap has been narrowed, the Japanese household energy use is still much lower than that of the United States (Dzioubinski and Chipman, 1999; Howarth et al., 1993; McDonald, 1990; Pérez-Lombard et al., 2008). Japan and the United States represent two different development models, providing insights on structural and intensity changes at different levels of gross domestic product (GDP) and under different development paths.

Second, this paper uses a longer time series of historical data than the existing studies. The longer time series can help assess transitions in policies, socioeconomic conditions, and lifestyles, as well as their impact on building energy consumption. The analysis of China’s historical growth starts in 1978, when the economic reform started. The analysis of Japan and the United States goes back to 1963, when the per capita GDP in Japan is similar to the current level in China. The analysis of all countries extends to 2013. Using long time series data, we are able to capture the impact of major societal and policy changes in the development process, such as oil crises in the 1970s, the introduction of one child policy in China in 1979, shift in lifestyle in Japan in the 1960s and 1970s, the implementation of energy efficiency standards in the 1990s and 2000s, and the Fukushima nuclear disaster in 2011.

Third, we assess the impact on both residential and commercial buildings. The majority of the previous decomposition analysis of China's buildings sector focused on residential buildings. Although Zhou and Chen (2015) included public buildings in their analysis, they used the same drivers for residential and commercial buildings. Here we use different sets of indicators for residential and commercial buildings, as the key driving forces of growth in these two types of buildings are different (Hong et al., 2016; Ürge-Vorsatz et al., 2015).

The paper proceeds as follows. Section 2.2 describes key factors contributing to building energy consumption, decomposition method, and data sources. Section 2.3 depicts how the driving forces shaped energy use in different countries at different stages. Section 2.4 discusses policy implications and concludes.

2.2 Method and Data

2.2.1 Drivers of building energy consumption and decomposition method

Building energy consumption is affected by socioeconomic factors, climate, culture and lifestyle, technologies, and policies (Haas, 1997; Xu and Ang, 2014). However, not all these factors are needed for assessing building energy consumption and only some have been used in the literature.

We select a list of drivers used in this study based on two conditions: data availability and impact of these drivers. For example, the mix of fuel, housing type, and region showed insignificant effect on building energy consumption in the previous studies, and therefore excluded from our study (Hojjati and Wade, 2012; Nie and Kemp, 2014). Similar to Ürge-Vorsatz et al. (2015), we use the number of households, household size, floorspace, and energy use intensity as key drivers for the residential sector and GDP, floorspace, and energy use intensity as key drivers for the commercial sector. The change in building energy use can be decomposed using different drivers. Better data availability and would allow application of alternative drivers and to more countries in the future.

Index decomposition analysis is a commonly used method to conduct decoupling analysis of energy consumption and greenhouse gas emissions. Compared to other decomposition methods, index decomposition analysis has the advantage of processing time series data and better captures changes over time (Ma and Stern, 2008; Nie and Kemp, 2014). In particular, we use the logarithmic mean Divisia index (LMDI) approach in this paper to understand how drivers changed over time and their impacts on the buildings sector. The LMDI method has been extensively used in the literature to study changes in the energy system and emissions due to its theoretical foundation, adaptability, easy to interpret, and zero residuals (Ang, 2004, 2005; Lu et al., 2016; Pachauri, 2014).

The annual final energy consumption in residential buildings is disaggregated into four drivers: number of households, average number of people per household, floorspace per capita, and energy use per unit of floorspace.

$$E_{res} = N \times H \times F_{res} \times I_{res} \qquad \text{(Equation 2.1)}$$

Where

E_{res} is total final energy use in residential buildings;
N is the total number of households;
$H = \frac{P}{N}$ is household size measured in the average number of people per household, where P is the total population;
$F_{res} = \frac{FS_{res}}{P}$ is residential building floorspace per capita, where FS_{res} is total residential floorspace;
$I_{res} = \frac{E_{res}}{FS_{res}}$ measures energy use intensity, represented by residential building energy use per unit of floorspace.

The change in residential building energy consumption between time period *t-n* and *t* can be decomposed into changes in these four factors:

$$E_{res}^{t} - E_{res}^{t-n} = \Delta E_{res} = \Delta E_{res,N} + \Delta E_{res,H} + \Delta E_{res,F_{res}} + \Delta E_{res,I_{res}} \qquad \text{(Equation 2.2)}$$

Where

$$\Delta E_{res,N} = L_{res} \times \ln \frac{N^{t}}{N^{t-n}}$$

$$\Delta E_{res,H} = L_{res} \times \ln \frac{H^{t}}{H^{t-n}}$$

$$\Delta E_{res,F_{res}} = L_{res} \times \ln \frac{F_{res}^{t}}{F_{res}^{t-n}}$$

$$\Delta E_{res,I_{res}} = L_{res} \times \ln \frac{I_{res}^{t}}{I_{res}^{t-n}}$$

$$L_{res} = \frac{E_{res}^{t} - E_{res}^{t-n}}{\ln E_{res}^{t} - \ln E_{res}^{t-n}}$$

Each of the four terms in Equation 2.2 represents the contribution to change in building energy use triggered by one factor while keeping the rest of variables constant. For example, $\Delta E_{res,N}$ represents the change in residential building energy use due to changes in the number of households, with all other variables remaining constant. Similarly, $\Delta E_{res,H}$, $\Delta E_{res,F_{res}}$, and $\Delta E_{res,I_{res}}$ represents the change in residential building energy use due to changes in the household size, per capita floorspace, and energy use per unit of floorspace, respectively, while holding all other variables constant. L_{res} is the logarithmic mean of changes in residential building energy use between time period *t-n* and *t*.

The annual final energy consumption in commercial buildings is disaggregated into three drivers: GDP, floorspace per unit of GDP, and energy use per unit of floorspace.

$$E_{com} = G \times F_{com} \times I_{com} \qquad \text{(Equation 2.3)}$$

Where

E_{com} is total final energy use in commercial buildings;
G is the total GDP of the country;
$F_{com} = \frac{FS_{com}}{G}$ is commercial floorspace per unit of GDP and represents use intensity, and FS_{com} is total commercial floorspace;
$I_{com} = \frac{E_{com}}{FS_{com}}$ measures energy use intensity represented by commercial building energy use per unit of floorspace.

The change in commercial building energy consumption between time period *t-n* and *t* can be decomposed into changes in the three factors:

$$E_{com}^{t} - E_{com}^{t-n} = \Delta E_{com} = \Delta E_{com,G} + \Delta E_{res,F_{com}} + \Delta E_{res,I_{com}} \qquad \text{(Equation 2.4)}$$

Where

$$\Delta E_{com,G} = L_{com} \times \ln \frac{G^{t}}{G^{t-n}}$$

$$\Delta E_{com,F_{com}} = L_{com} \times \ln \frac{F_{com}^{t}}{F_{com}^{t-n}}$$

$$\Delta E_{com,I_{com}} = L_{com} \times \ln \frac{I_{com}^{t}}{I_{com}^{t-n}}$$

$$L_{com} = \frac{E_{com}^{t} - E_{com}^{t-n}}{\ln E_{com}^{t} - \ln E_{com}^{t-n}}$$

$\Delta E_{com,G}$ represents the change in commercial building energy use due to changes in GDP, with all other variables remaining constant. $\Delta E_{com,F_{com}}$ represents the change in commercial building energy use due to changes in floorspace per unit of GDP, with all other variables remaining constant. $\Delta E_{com,I_{com}}$ represents the change in commercial building energy use due to changes in energy use per unit of floorspace, while holding all other variables constant. L_{com} is the logarithmic mean of changes in commercial building energy use between time period *t-n* and *t*.

We use results from the decomposition analysis to calculate how much of the change in China's building energy use between 1978 and 2012 was attributable to changes in each of the driving factors. We then divide the change in building energy use caused by each factor by the total change in China's building energy use to estimate the percentage contribution to the change in total building energy use by each factor (see Section 2.3.4 for results).

2.2.2 Data

Data on building energy consumption in residential and commercial buildings are collected from the Energy Balances complied by the International Energy Agency (IEA, 2015a). Population data are from the United Nation's World Population Prospects (UN, 2015a). GDP data are from the World Bank's World Development Indicators database (World Bank, 2015).

Data on floorspace and the number of households are from statistics of individual countries. The Japan Statistical Yearbook includes data on the number of households and total residential floorspace every five years since 1963 (MIAC, 2015). Data on the Japanese commercial building floorspace are collected from the EDMC Energy and Economic Statistics Book, available annually since 1973 (ECCJ, 2013). The number of households and residential floorspace in the United States are from Moura et al. (2015), which consolidated data from the Residential Energy Consumption Survey and the American Housing Survey and included data since 1891. Data on commercial floorspace in the United States are based on Belzer (2007), supplemented by data from the Building Energy Data Book and the EIA Annual Energy Outlook for the recent years (DOE, 2012; EIA, 2014a). Data on residential floorspace in China and the number of households between 1978 and 2013 are collected from the Comprehensive Statistical Data and Materials on 60 Years of New China and the China Statistical Yearbook (NBSC, 2009, 2014). Data on commercial building floorspace are available in the China Statistical Yearbook between 1996 and 2006 and data before and after these years are estimated based on annual new constructions reported by the China Statistical Yearbook and the China Statistical Yearbook on Construction (NBSC, 1988-2013, 1997-2008).

2.3. Results

2.3.1 Driving forces and trends of building energy use in China

From 1978 to 2013, residential building energy use in China increased by 60%, corresponding to the increase observed in the major drivers: the number of households, household size, per capita floorspace, and energy use intensity. The number of households doubled between 1978 and 2013, as a result of increasing population and decreasing household size. Per capita residential floorspace has strong growth during this time period, increasing from 8 m^2 in 1978 to 35 m^2 in

2013. Although energy use intensity has decreased steadily, it was not enough to offset the increase in energy service demand driven by the growth in the number of households and per capita floorspace.

The decomposition analysis shows that per capita floorspace made the largest contribution to increasing residential building energy use in China, as noted by Nie and Kemp (2014) and Zhou and Chen (2015) (Figure 2.1). Growth in the total number of households also had a positive contribution to the growth in final energy use during this period. Household size decreased from 4.4 to 3 persons per household between 1978 and 2013 and this contributed negatively to the change in energy use but the impact was relatively small compared to floorspace and the number of households. Energy use intensity had a large negative effect on energy use growth between 1978 and 2013, especially in the early years. This was primarily due to fuel switching in residential buildings, from traditional biomass to commercial fuels and from coal to electricity, liquefied petroleum gas (LPG), and natural gas. Improvement in energy-efficient technologies and the implementation of building energy policies also led to reduction in energy use intensity, but the effect was not as substantial as fuel switching.

China has introduced building energy efficiency policies since the early 1980s, initially targeting residential buildings in the Northern China and gradually expanding to all building types in all climate zones. Chinese building energy codes require the design of new buildings today to be 50-65% more efficient than typical buildings in the 1980s (Evans et al., 2010; Shui, 2012; Shui et al., 2009; Yu et al., 2014a). China also developed the minimum energy performance standards (MEPS) and information labels for appliances. As of 2013, there are MEPS for over 50 products and mandatory information labels for 28 products. Standards and labels significantly increase energy efficiency of appliances. However, the rapid increase in appliances ownership and equipment use in Chinese buildings outpaced the increase in efficiency. The ownership of major appliances increased dramatically in the past three decades. For example, the number of televisions, washing machines, and refrigerators in 100 urban households increased from 0.59, 6.3, and 0.22 in 1980 to 110, 88, and 89 in 2013, respectively. The number of computers per 100 urban households increased from 2.6 in 1997 to 71.5 in 2013 (NBSC, 2009, 2014; Nie and Kemp, 2014). China surpassed the United States and became the world's large electricity consumer in 2011 (Khanna et al., 2013; Lin, 2002; Zeng, 2015; Zhou, 2010).

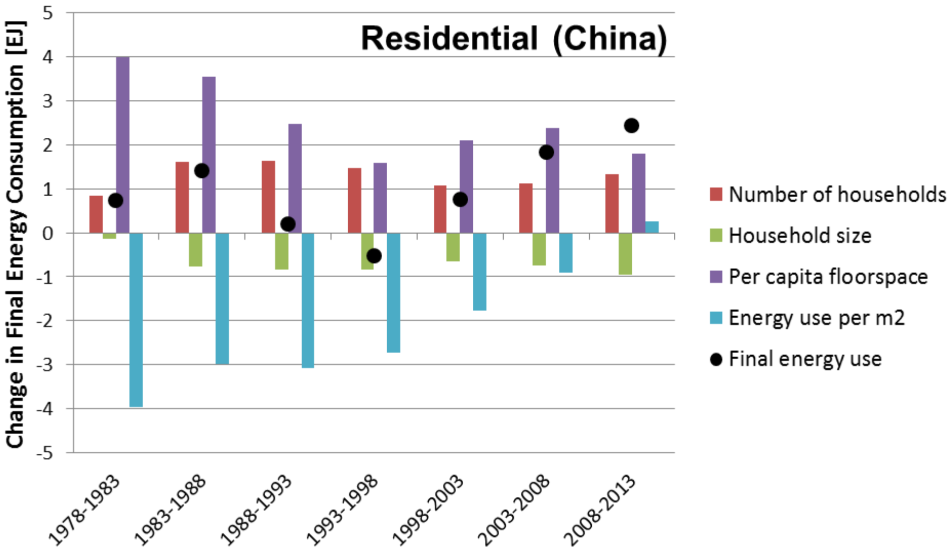

Figure 2.1 Decomposition of changes in final energy use in Chinese residential buildings (1978-2013)

Note: The bars represent the change in final energy use due to each factor, while holding other factors constant. The figure shows relative impacts of different drivers on the change in building energy use.

Compared to residential building energy use, energy consumption in commercial buildings has experienced a much faster growth. Between 1978 and 2013, it grew by more than 10 times. GDP grew substantially, and this was mostly caused by the increase in economic activities as population only grew by 40% during the same time period. Energy use intensity and floorspace per GDP decreased, but changes were relatively small compared to changes in economic activities.

Commercial building energy use grew slowly before 1990. Starting from the early 1990s, when China further opened up the market, commercial building energy use grew rapidly. Economic activity, represented by GDP, was the largest contributor to the rise in building energy use in commercial buildings. Different from trends observed in residential buildings, energy use intensity in commercial buildings did not change significantly between 1978 and 2013, because there was less fuel switching opportunities in commercial buildings. Although energy use intensity negatively contributed to growth in commercial building energy use, its impact was smaller compared to other factors, especially over the past two decades (Figure 2.2).

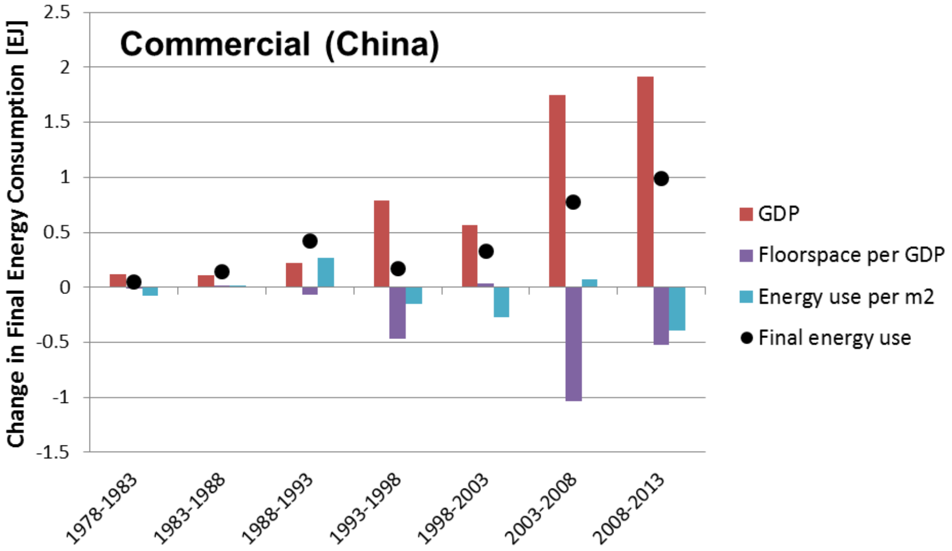

Figure 2.2 Decomposition of changes in final energy use in Chinese commercial buildings (1978-2013)

2.3.2 Driving forces and trends of building energy use in Japan

Japan experienced extreme rapid growth in building energy consumption between 1963 and 2013. The growth of the Japanese buildings sector could be divided into two periods: significant increase in building energy services between 1963 and the early 1990s, and rapid efficiency improvement and stabilized energy consumption from the late 1900s to the present. We examine building energy use of Japan from 1963 to 2013, as per capita GDP of Japan in 1963 is comparable to that of China today (FRED, 2014). From 1963 to the early 1990s, Japan was experiencing rapid economic growth, and the Japanese society was shifting towards western lifestyle, characterized by rapid increase in demand for energy services, decline in household size, and increase in per capita floorspace. During this period, energy use intensity increased dramatically in both residential and commercial buildings. From the late 1990s to 2013, with economic slowdown, rising awareness of energy efficiency, and policies to improve building energy performance, the Japanese buildings sector showed rapid efficiency improvement (especially after 2000) and slow growth in appliance ownership; the floorspace growth also slowed down during this period (Hinge et al., 2004; IEA, 2014a; MIAC, 2015; Nakagami et al., 2008; Wilhite et al., 1996a; Wilhite et al., 1996b).

The decomposition analysis shows that increasing energy use intensity, per capita floorspace, and the number of households contributed to the growth in residential building energy use in Japan in the early years (Figure 2.3). It is worth nothing that although per capita floorspace and the number of households continued to be the main factors driving the growth in residential building energy use, energy use intensity had negative contributions to the change in building energy use since the early 1990s. The negative contribution of energy use intensity and household size together decreased building energy use in Japan in the recent years. In addition, although per capita floorspace in Japan is expected to continue rising, the number of households is projected to decrease in the near term, which may lead to further decline in residential building energy use in Japan (NRI, 2013).

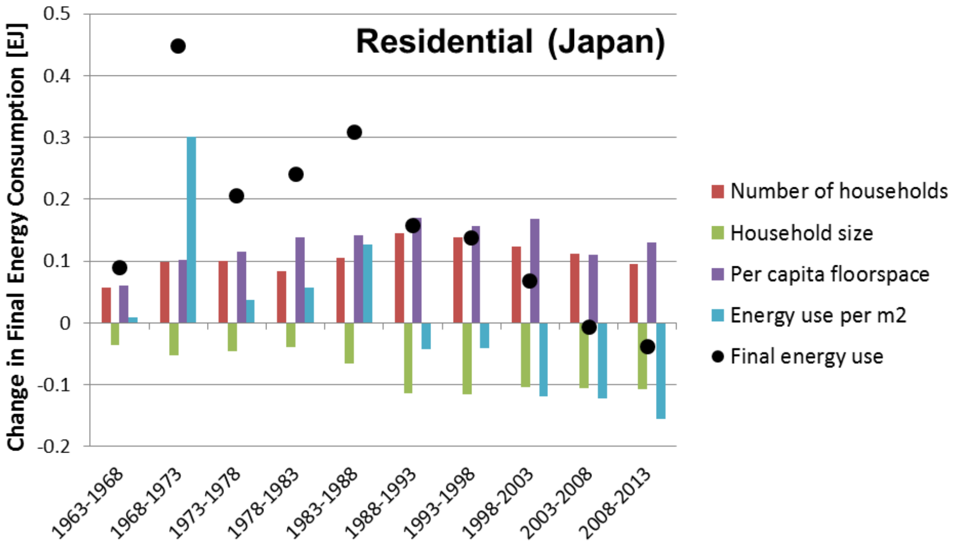

Figure 2.3 Decomposition of changes in final energy use in Japanese residential buildings (1963-2013)

In commercial buildings, GDP growth has been the main contributor to the rise in commercial building energy use before the early 1990s, and the relationship changed after Japan's economy slowed down significantly and the country entered the "Lost Decade" (Hayashi and Prescott, 2002; Ohno, 2006). Similar to trends observed in residential buildings, commercial buildings also showed decreasing energy use intensity, which happened in the past decade. The decrease in energy use intensity was even more substantial after the Fukushima Daiichi nuclear disaster in 2011 (Figure 2.4).

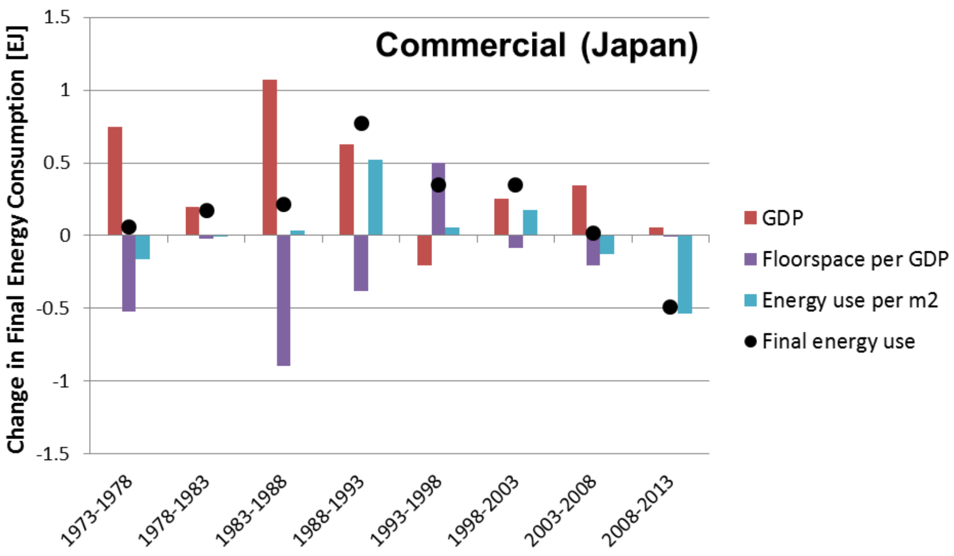

Figure 2.4 Decomposition of changes in final energy use in Japanese commercial buildings (1973-2013)

The change in energy use intensity is a combination of increasing energy service demand and improving energy efficiency. The relative impact of these two factors changed over time. The oil crises in the 1970s helped shape energy policies in Japan. In response to the oil crises, Japan developed the Energy Conservation Law in 1979 and adopted its first energy efficiency standards for commercial and residential buildings in 1979 and 1980, respectively. However, the development and implementation of energy efficiency standards were not enough to offset the growth in energy service demand. Before the early 1990s, along with the rapid economic growth, the demand for end-use services also increased drastically. For example, the number of televisions owned by a household has increased from less than 0.5 in 1970 to 2 in 1992; there was also a rapid increase in the ownership of other appliances such as refrigerators and washing machines (Sugiura et al., 2013). As a result, energy use intensity in Japanese residential buildings increased by 100% between 1963 and 1990 (see Figure S1).

Since the early 1990s, energy use intensity in the Japanese residential sector started to decline. This could be explained by the slow growth in appliances due to the saturation effect and energy efficiency improvement from stringent energy efficiency standards and programs (e.g. the amendment of the Energy Conservation Law and the Creation of the Top Runner Program in 1999) (Cadavid and Giraud, 2010). The Top Runner standards aimed to improve energy efficiency of major appliances (e.g. television, refrigerator, and air conditioner) by 17-60% in 2004 compared to the 1997 levels, and the stringency of standards continued to increase (Ito et al., 2006; Komiyama and Marnay, 2008). The New National Energy Strategy adopted in 2006 set a target of improving the country's energy efficiency by at least 30% by 2030 compared to 2003 levels. With these energy efficiency policies and programs in place, Japan now is one of the world's most energy-efficient economies (Kallakuri et al., 2016; Slusarska and Orlando, 2016).

The combination of stabilized demand and fast efficiency improvement led to decline in energy use intensity since the early 1990s. This trend has been accelerated by the Fukushima nuclear disaster, when electricity generation capacity dropped dramatically. Shortage in energy supply resulted in a large amount of energy savings from both government policies and voluntary actions to reduce energy demand, known as the Setsuden (energy conservation) campaign. Examples of energy conservation measures taken include limiting air conditioning use, setting a high room temperature, and reducing standby power use. As a result, electricity consumption dropped significantly. For example, electricity use (mostly from buildings) in the Tokyo metropolitan area was reduced by 16% in the summer of 2011 and 2012 compared to the summer of 2010 (Lun and Ohba, 2012; Matsukawa, 2016; Skea et al., 2013).

2.3.3 Driving forces and trends of building energy use in the United States

The United States entered the industrialization process earlier than Japan and China, and per capita GDP in the United States in 1895 is similar to that of Japan in 1963 and China in 2013. Examining how building energy consumption changed in the United States can provide an overview of building energy profile of a well-developed country. From 1963 to 2013, residential and commercial building energy use in the United States increased by 60% and 150%, respectively, much less than the growth rate in Japan's building energy use.

The growth of the U.S. residential buildings sector could be divided into three periods (Figure 2.5). Before the first oil crisis in 1973, energy use in U.S. residential buildings showed strong growth, and the increase in energy use intensity and the number of households were the primary contributors to the rising residential building energy use. The second period started after the first oil crisis, residential energy use decreased substantially during this period, mostly due to the decline in energy use intensity, especially after the second oil crisis in 1979. Although the number of households and per capita floorspace continued to increase and positively contributed to building energy use, the decline in energy use intensity was more significant and offset the impact of these two factors. From 1990 and onwards, strong and continuous improvement in energy efficiency was the predominant characteristic of the U.S. residential sector. Even though new electric end uses, such as personal computers and cable televisions, kept expanding, technology efficiency improvement and the implementation of energy efficiency standards and demand side management programs were able to decrease energy use intensity, which contributed negatively to building energy use (ASE, 2013; DOE, 2008; EIA, 2015; Hinge et al., 2004; Hojjati and Wade, 2012; Moura et al., 2015).

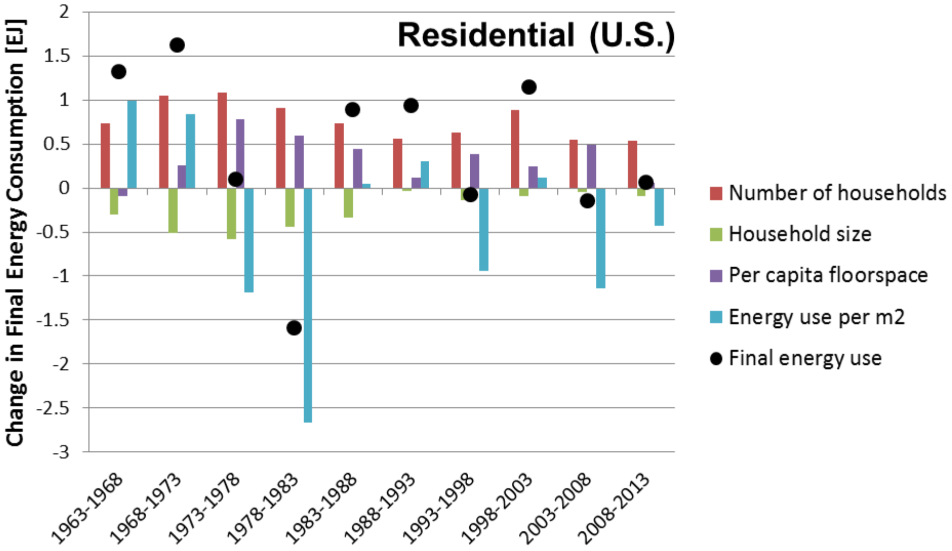

Figure 2.5 Decomposition of changes in final energy use in U.S. residential buildings (1963-2013)

Commercial building energy use in the United States grew steadily between 1963 and 2013 and GDP growth was the primary contributor to the rise in commercial building energy use (Figure 2.6). Similar to trends in the residential sector, commercial building energy use increased rapidly before the first oil crisis and rising energy use intensity and GDP both contributed to this growth. After the oil crises in 1973 and 1979, energy use intensity negatively contributed to commercial building energy use and resulted in minimal growth and even decline in commercial building energy use in the late 1970s and early 1980s, although GDP still grew rapidly. Then energy use intensity of commercial buildings slightly increased in the late 1980s and 1990s as a result of strong increase in office equipment, and this positively contributed to building energy use. This trend has been reversed in the 2000s due to the implementation of energy efficiency standards and various building energy programs (Andrews and Krogmann, 2009; Matt et al., 2013; Wang and Brown, 2014).

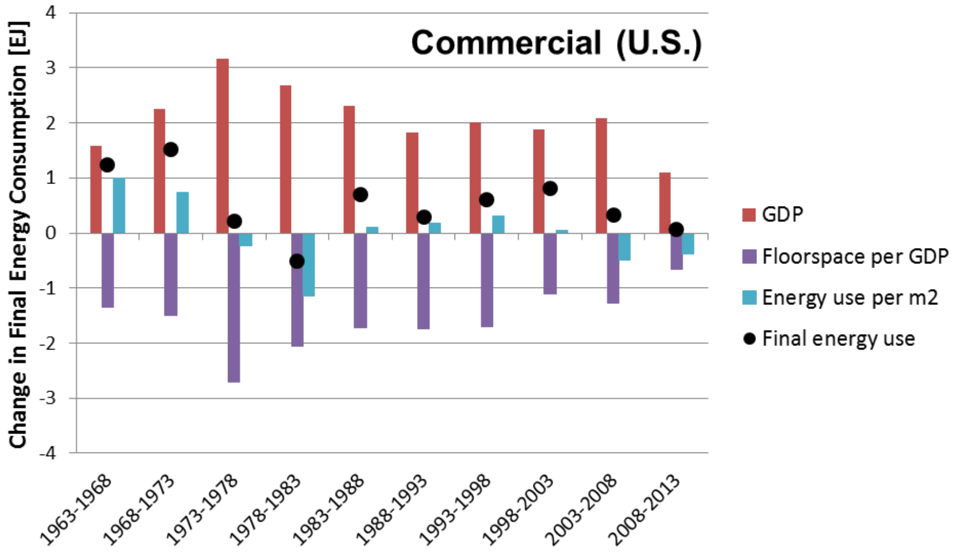

Figure 2.6 Decomposition of changes in final energy use in U.S. commercial buildings (1963-2013)

Compared to China and Japan, per capita GDP in the United States was much higher back to the 1960s and 1970s and the use of appliances reached the saturation level earlier. In the wake of the oil crises in 1973 and 1979, the United States started to develop energy efficiency policies and programs and energy use intensity of U.S. residential buildings continued to drop since 1979 (see Figure S3). Improvement in energy efficiency was a critical contributor to the decline in energy use intensity. The American Council for an Energy-Efficient Economy estimated that energy efficiency improvement accounted for 60% of reduction in economy-wide energy intensity between 1980 and 2015. Similar impacts were also observed in the buildings sector. Energy use intensity in homes built in the past decade is around 20% less than homes built in the 1970s (Nadel et al., 2015). Progressively tighter energy codes and appliance standards are likely a significant contributor to energy efficiency improvement. States and cities have been adopting building energy codes since the 1970s. Building energy codes are minimum energy efficiency requirements for new constructions and buildings with major renovations, and energy efficiency requirements in building codes have become more stringent over time. The 2012 residential energy code is 40% more efficient than the 1980 baseline and the 2010 commercial code is 50% more efficient than the 1980 baseline (Livingston et al., 2014). In terms of appliance standards, California and several other states started to adopt minimum energy performance standards for appliances in the 1970s and federal appliance standards took effect in 1990. As a result, average energy efficiency of appliances improved significantly between 1980 and 2015, such as 50% improvement in air conditioners, 65% improvement in refrigerators, and nearly 75% improvement for cloth washers (Doris et al., 2009; Nadel et al., 2015).

2.3.4 Cross-country comparison and implications for China

Energy use in China's buildings sector continued to grow from 1978 to the present. Similar to the buildings' growth in Japan in the 1960s and 1970s, the growth of the Chinese buildings sector was accompanied by fast expansion in floorspace and shift towards the western lifestyle. During 2000-2012, China has the fastest growth in per capita building energy use among all major economies. While per capita building energy use in the United States, Japan, and most OECD European countries declined, per capita building energy use in China grew by more than 25% (Nakagami et al., 2008; OECD and IEA, 2015).

Per capita floorspace was the largest contributor to the growth in residential building energy use in China between 1978 and 2013, whereas the number of households played a larger role in increasing residential building energy use in the U.S. and in a global analysis by Ürge-Vorsatz et al. (2015) (Figure 2.7). The number of households contributed to around 140% of the change in residential building energy use in China, but the impact was still less substantial than that from per capita floorspace (around 290%). China has experienced a real estate boom, adding around 2 billion m^2 of residential floorspace annually in the past decade. The growth in per capita floorspace was driven by multiple factors, such as income growth, increasing comfort level, construction practices, and land use policies (Chivakul et al., 2015; Chow and Niu, 2010). Without policy interventions, the demand for real estate in China is expected to remain strong (Glaeser et al., 2016). If this trend continues, it could drive significant growth in China's residential building energy use.

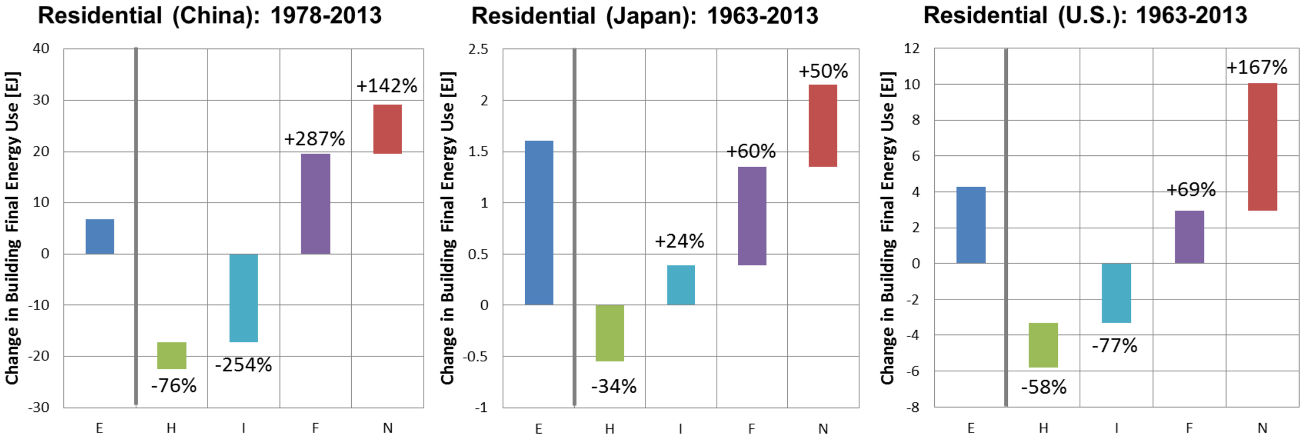

Figure 2.7 Decomposition of changes in residential building energy use in China, Japan, and the United States

Note: Results of the decomposition analysis for changes in final energy use (E) of residential buildings into four factors – average number of people per household (H), energy use per unit of floorspace (I), floorspace per capita (F), and the number of households (N) – are shown in Figure 2.7. The percentage contribution of each effect to the total change in final energy use of residential buildings is also marked on each bar.

The number of households and household size are correlated and can drive building energy use in two different directions. All three countries had a rapid increase in the number of households and a continued shrinking in household size. While the number of households positively contributed to building energy use, household size negatively contributed to the change in residential building energy use in all three countries. The change in household size and the number of households was affected by both population growth and societal change. For example, in China household size declined dramatically since the introduction of the one child policy in 1979. However, whether household size would continue to decline in the future is uncertain, as it will be affected by several factors such as fertility rate, population mobility, aging, the improvement in housing conditions, and the recently introduced two-child policy (Hu and Peng, 2015). Understanding potential changes in household characteristics and uncertainties would help estimate future building energy demand in China.

Energy use intensity negatively contributed to changes in residential building energy use in China during 1978-2013 and the United States during 1963-2013, whereas in Japan it positively contributed to the growth in energy use during 1963-2013 (Figure 2.7). As discussed earlier, the positive contribution of energy use intensity in Japan was caused by the rapid increase in end-use services between 1963 and the early 1990s, as the Japanese society shifted toward western lifestyle. The decrease in energy use intensity in China was mainly driven by fuel switching. For example, between 1992 and 2002, coal used in Chinese residential buildings decreased by 50%, while building electricity consumption and LPG tripled and increased by 4 times, respectively. However, this fuel switching opportunity was mostly exploited, as shown in Figure 2.1, and the negative contribution of energy use intensity has decreased over time.

Reducing energy use intensity is the most important strategy to curb building energy demand in China. Without energy efficiency improvement, even though decreasing household size helped to reduce building energy use, China's residential building energy use would have increased by 3 times between 1978 and 2013, 80% higher than the actual residential building energy use in 2013, as shown in Figure 2.7. With less opportunity in fuel switching and increasing demand of end-use services and comfort levels, energy use intensity in China might increase and positively contribute to the growth in building energy use in the future, as observed in Japan in the early years. However, the historical analysis also demonstrates that technology improvement and strong policies to promote the deployment of energy-efficient technologies can help lower energy use intensity and offset the growth in energy service demand, as observed in the United States and Japan in the past two decades.

Although energy use in Chinese commercial buildings is currently low, there is a strong growth potential. Since energy use in commercial buildings is driven by economic activities, in the developed countries like Japan and the United States, commercial building energy use accounts for around half or more than half of total building final energy consumption. In China, energy us in commercial buildings only accounted for 16% of total building energy use in 2013. In addition, energy use intensity may increase and result in growth in China's commercial building energy use. Currently, energy use intensity in Chinese commercial building is 0.23 GJ/m^2, much lower than that of Japan and the United States (around 1.24 GJ/m^2). Without policies to promote low-carbon, energy efficient buildings, energy use intensity in Chinese commercial buildings may experience rapid growth.

GDP was the main contributor to the growth in commercial building energy use in all three countries and is expected to continue rising in the future (Figure 2.8). However, the GDP driven growth in commercial buildings can be offset by declining energy use intensity. As shown in the experience of Japan and the United States in Section 2.3.2 and 3.3, energy use intensity negatively contributed to the change in commercial building energy consumption in the last decade, and the impact was significant. In Japan, influenced by energy efficiency improvement, commercial building energy use started to decrease even before the Fukushima accident.

Therefore, with technology improvement and building energy efficiency policies in place, it is possible to decouple economic growth and commercial building energy use.

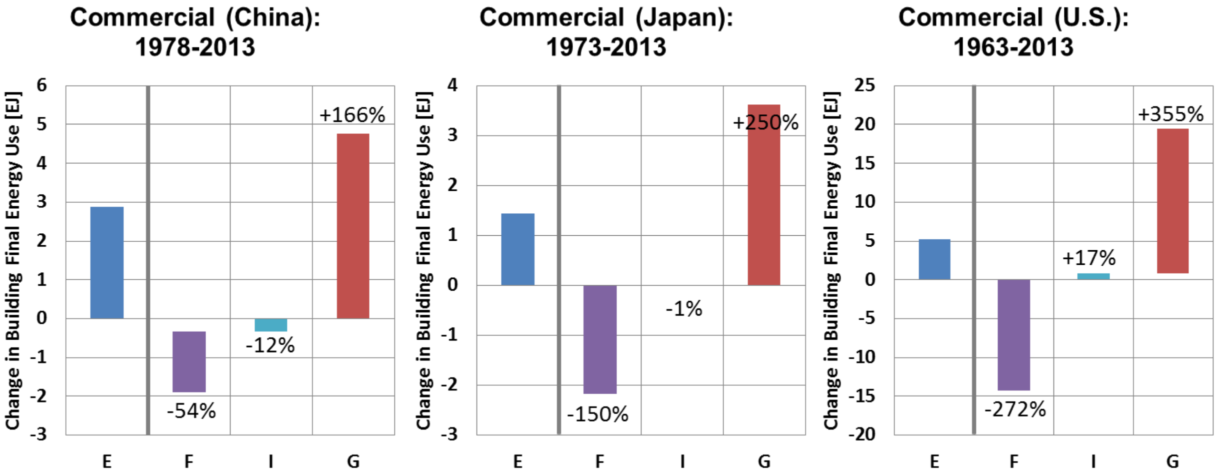

Figure 2.8 Decomposition of changes in commercial building energy use in China, Japan, and the United States

Note: Results of the decomposition analysis for changes in final energy use (E) of commercial buildings into three factors – service use intensity represented by floorspace per GDP (F), energy use per unit of floorspace (I), and GDP (G) – are shown in Figure 2.8. The percentage contribution of each effect to the total change in final energy use of commercial buildings is also marked on each bar.

2.4. Conclusions

Total building energy use in China almost doubled between 1978 and 2013, increasing from 10 EJ to nearly 20 EJ. Several factors can affect the growth in building energy use, and if unaddressed, China may continue its rapid growth in the buildings sector, especially in commercial buildings. Growth in building energy use is also associated with massive infrastructure development, air pollutant emissions, and more pressure on the energy supply system, which would pose challenges to China's development and mitigation efforts.

The development path a country pursues and the stage of development both affect building energy demand. As shown in the historical analysis of the three countries, policy and technology choices can affect the profile of building energy use. China is undergoing rapid growth and transitions. Policies the Chinese government develops and the effectiveness of policy implementation will shape the development path and determines future sustainability.

Growth in building energy consumption is affected by economic activities, technology improvement, consumer behavior, and culture and lifestyles. It is also influenced by building energy policies, as well as policies beyond the buildings sector. Changes in the societal structure would affect household size and the number of households, and therefore impact future building energy demand in China. Understanding the linkage between social policies, societal changes, and these drivers and how they might affect future building energy demand is critical. Per capita floorspace was a key driver of building energy consumption in China and is expected to continue growing. The development of future housing and land use policies also need to consider the potential impact on the energy system.

Improvement in building energy efficiency has the potential to offset the growing energy service demand and decouple building energy use from economic growth. As noted in the experience of Japan and the United States, stringent energy efficiency standards, utilities programs, and incentives to encourage the development and deployment of energy-efficient technologies are needed to promote energy efficiency in buildings.

Chapter 3. Uncertainty in China's floorspace growth: provincial-level analysis and implications on building energy demand

3.1 Introduction

China is undergoing rapid economic growth and structural changes. The process of industrialization and modernization is accompanied by rising energy demand. China overtook the United States as the world's largest carbon dioxide emitter in 2007 and the top building energy consumer in 2012 (Fridley et al., 2011; IEA, 2007b, 2014a). China also has the world's largest construction market. The building floorspace of China in 2010 is around 50-56 billion m^2,[1] compared to 25 billion m^2 of the United States and 24 billion m^2 of the European Union (Economidou et al., 2011; EIA, 2011; Eom et al., 2012; Jiang et al., 2014; Moura et al., 2015; Zhou et al., 2014). In 2013, China built 3.5 billion m^2 of new buildings, which was around seven times of floorspace additions in the United States of the same year (EIA, 2014a; NBSC, 2014).

Floorspace is a key driver of the buildings sector growth (Hong et al., 2016; Yu, 2017). Developing countries like China are expected to experience rapid floorspace growth in the next several decades, which has the potential to shape the energy system. Growth in floorspace affects future energy demand of the buildings sector; it also has strong linkages to upstream and downstream industries and influences the energy demand of the industrial sector. Therefore, understanding future growth in building floorspace is critical to assessing future energy demand and greenhouse gas emissions in China.

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[1] The estimates of total building floorspace in China in 2010 vary across studies, ranging from 50 to 56 billion m^2. The difference is mainly caused by different estimates of commercial building floorspace, as there are no official statistics or survey data on it.

Building floorspace growth is dynamic and there are huge uncertainties in the projection of China's floorspace. First, provinces have disparate growth patterns, as region-specific characteristics, such as income level, people's lifestyle, population density, and land use policies, can affect floorspace expansion. Second, the trajectories of growth in the near and long term are different. Factors affecting near-term growth such as housing price may not play a substantial role in the long term. How to derive the long-term growth trajectory from the historical trend and near-term data is challenging. Third, previous studies suggested the relationship between income and floorspace is a key element in floorspace projection, but the elasticity of per capita floorspace to income is different at different income levels. The income elasticity increases at low income levels until it reaches a maximum level, and then declines steadily. Finally, floorspace growth may not be unbounded. Empirical evidence suggested that per capita floorspace reaches a saturation level even if income continues to grow. However, the level of saturation and when the saturation level is reached are highly uncertain and different by region (Eom et al., 2012; Hong et al., 2016; U.S. Congress Office of Technology Assessment, 1992).

Existing studies did not fully address these dynamics in floorspace growth. One group of studies estimated future building floorspace demand using regression analysis (Berkelmans and Wang, 2012; Chivakul et al., 2015; Shen and Liu, 2004). These studies estimated the relationship between floorspace and income, while controlling for other determinants such as housing price, urbanization rate, and urban population. These studies mostly concerned about growth in urban residential buildings and did not provide a full picture of the buildings sector. In addition, they estimated fixed income elasticity and did not consider variations between near and long term growth patterns. Another group of studies estimated China's future floorspace through 2050 using stock turnover model; however, they did not consider heterogeneity across provinces and regions (Hong et al., 2016; Hu et al., 2010; Jiang et al., 2014). Although the national level analysis can provide information on an overall trend, regional dynamics are critical to understanding development in a large country like China. Growth patterns differ between urban and rural areas, between northern and southern provinces, and between high and low income provinces. As shown in Hu et al. (2010), the relationship between per capita floorspace and income in Beijing is significantly different from that at the national level.

This study estimates future building floorspace of rural residential, urban residential, and commercial sectors for individual provinces in China. It aims to improve the understanding of floorspace growth in China and implications for building energy use in the following ways. First, we draw on historical experience and derive the relationship between floorspace and income growth at the provincial level. Second, we consider how urban planning and development path would shape the evolution of the buildings sector and develop alternative floorspace projections that span a range of uncertainties in the saturation level. Third, we explore how different floorspace pathways affect future building energy demand in China. It is worth noting that the methodology used in this paper can be extended to study building floorspace growth across countries and at the global scale.

This paper proceeds as follows. The next section shows historical growth trends in developed countries and Chinese provinces. Section 3.3 explains the methodology used to estimate future floorspace, as well as data and assumptions. Section 3.4 examines results of floorspace projections and implications for building energy use. Section 3.5 discusses conclusions, limitations, and directions of future research.

3.2 Historical Trends of Per Capita Floorspace Growth across Regions

3.2.1 Historical floorspace growth in OECD countries

Understanding how floorspace evolved in the past can help make better future projections. Per capita floorspace follows an upward growth trend in most OECD countries but the growth rate and per capita floorspace vary across countries. Per capita residential floor space is in the range of 35–55 m^2 in most developed countries, with notable exceptions in the United States, Canada, and Australia with 70-80 m^2. Per capita residential floorspace in major cities also has high variations. At the high end is Sydney with close to 55 m^2 and at the low end are Hong Kong and London with less than 20 m^2. Different from the residential sector, divergence in per capita commercial floorspace between regions is smaller. Italy, Spain, and London have low levels of per capita commercial floorspace, which are less than 10 m^2, and the United States and Denmark with over 20 m^2 are at the high end. Most regions fall within a range of 10-20 m^2 of per capita commercial floorspace (Center for Sustainable Systems, 2016; Council of Australian Governments, 2012; ENTRANZE, 2013; Hong Kong Housing Authority, 2015; Kennedy et al., 2015; MIAC, 2015; Moura et al., 2015; Natural Resources Canada, 2011; Odyssee, 2009; Rector, 2007; U.S. Census Bureau, 2013).

For the purpose of considering possible trajectories of Chinese floorspace growth, three trends of growth in floorspace across countries are observed (Figure 3.1). One group of countries shows rapid growth in per capita floorspace along with income growth (e.g. the United States, Canada, New Zealand, Japan, Spain, the United Kingdom, and France for residential buildings and New Zealand, Japan, and France for commercial buildings). A second group also shows an upward growth trend but the rate of growth is much slower, such as Denmark, Norway, and Netherlands for residential buildings, and Denmark, Norway, and the United States for commercial buildings.

Per capita floorspace growth of the third group stabilizes and does not change with income growth, and only very few countries fall into this category. This trend is observed in Sweden for both residential and commercial buildings[2] and the United Kingdom for commercial buildings between 1999 and 2004 (Dol and Haffner, 2010; ENTRANZE, 2013; Odyssee, 2009). Floorspace projection for Chinese provinces needs to consider these possible development paths, as individual provinces may ultimately follow one of these paths.

Building floorspace data can be collected through different channels such as census, housing surveys, and national registers. Countries also have different methods to define building floorspace and collect data. Different data sources and data collection methods may result in different levels of floorspace, but key trends observed for a given country or region may not vary significantly by using different data (Dol and Haffner, 2010).

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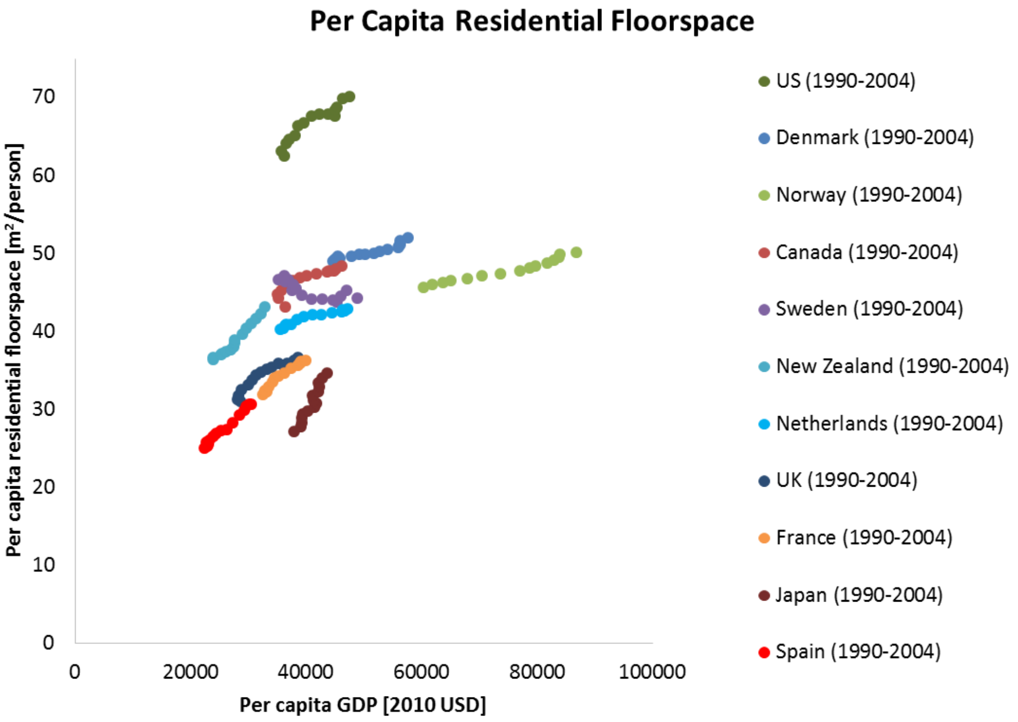
[2] Data source of housing statistics in Sweden changed in 1995, from census to administrative registers; as a result, there are discrepancies in floorspace data. We cross-check per capita floorspace in Sweden with data in the *Housing Statistics in the European Union* and the ENTRANZE database for recent years and confirm the stabilizing trend, as per capita floorspace in 2004 and some recent years in Sweden are around the same.



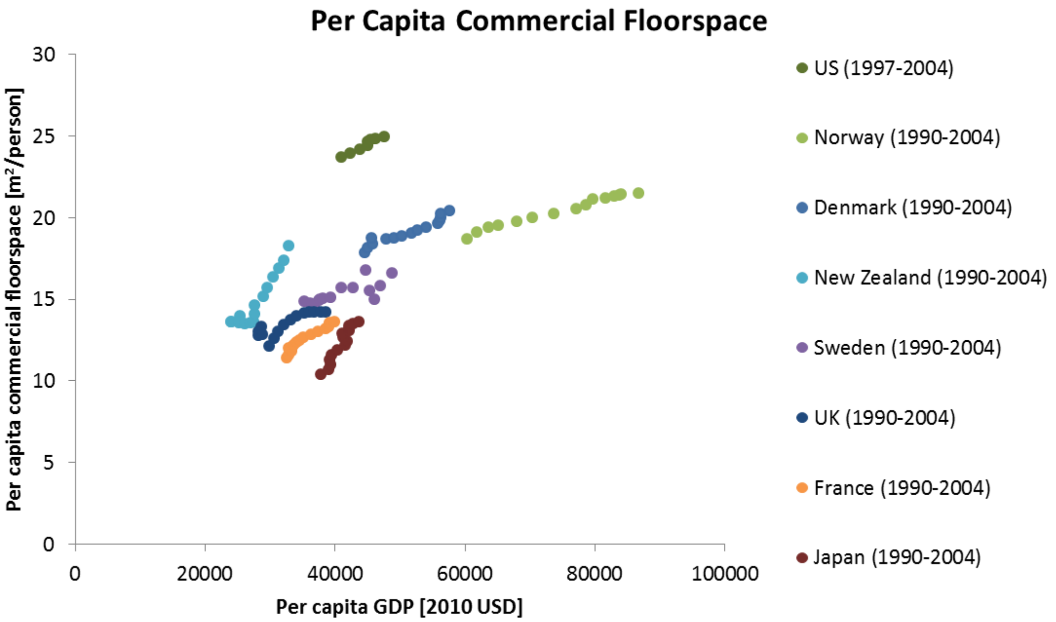


Figure 3.1 Per capita GDP and per capita residential (top) and commercial (bottom) floorspace in OECD countries (1990-2004)

Data sources: (Odyssee, 2009; World Bank, 2015).

3.2.2 Historical floorspace growth in China

All provinces in China experienced significant growth in per capita floorspace, as demonstrated in Figure 3.2 and 3.3. Per-capita residential floorspace grew 3-5 times between 1978 and 2010 and per capita commercial floorspace grew 2-3 times between 1996 and 2006[3].

Per capita floorspace growth shows diverse patterns across provinces and building types. The average annual growth rate of per capita floorspace varies considerably: from 1% to 7% in residential buildings and 0% to 11% in commercial buildings (Table A1). Across geographical areas, provinces in southern China have experienced the strongest growth in recent years and now have the highest levels of per capita floorspace, whereas provinces in the North and Northwest have low levels of per capita floorspace.

The relationship between income and per capita floorspace varies by province. At similar income levels, provinces show different levels of per capita floorspace. For example, at $7,000 per capita GDP level, per capita floorspace in Zhejiang was 1.5 times higher than that of Beijing in urban residential buildings and doubles in rural residential buildings. The income level at which saturation is approached also varies by province. For instance, in urban residential buildings, growth in per capita floorspace in Jiangxi slowed down at per capita GDP of less than $5,000, whereas in Tianjin and Shanghai, with per capita GDP higher than $10,000, per capita floorspace are still growing rapidly.

Growth in per capita floorspace is affected by multiple factors. As discussed above, income is a key driver of building floorspace growth and the relationship between floorspace and income growth changes over time. In addition, housing market conditions, land use policies, population

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[3] Data on commercial floorspace by province are only available between 1996 and 2006.

density, local economy, construction practices, and consumer preference, among other factors, can also impact the development of the buildings sector and floorspace evolution. As a result, provinces and countries show wide divergence in their per capita floorspace levels.

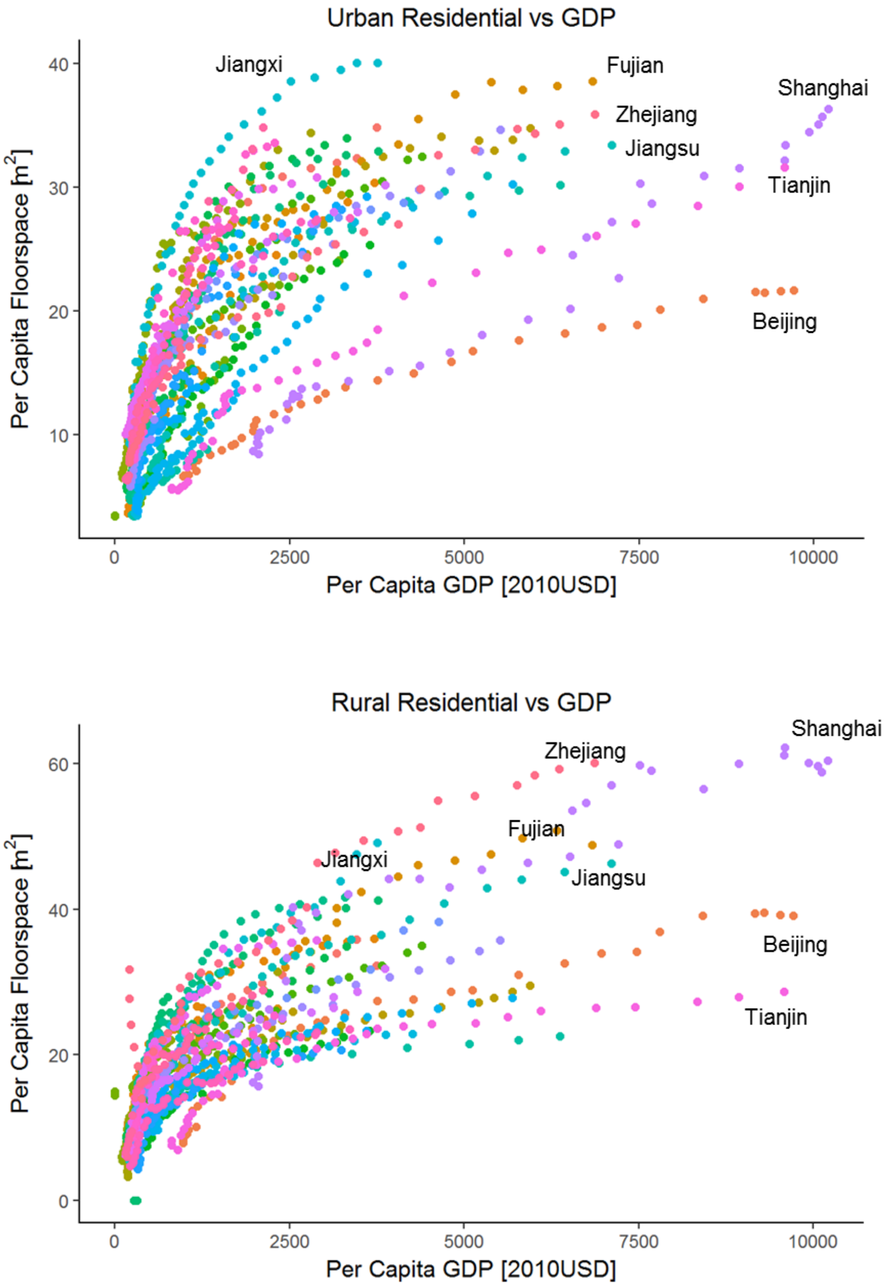

Figure 3.2 Relationship between per capita residential floorspace and per capita GDP by province (1978-2010)

Per capita residential floorspace growth in most Chinese provinces shows different patterns from the ones observed in recent years in OECD countries. Although several provinces show a continuous upward growth trend, most provinces experienced extremely fast growth in per capita residential floorspace at low income levels and then the growth slowed down as income increases or per capita floorspace even stabilized in a few places, such as Jiangxi, Fujian, and Beijing (Figure 3.2).

Several factors may contribute to different growth patterns between China and OECD countries. First, most growth in per capita floorspace in China happened at low income levels. For example, at around $2,500 per capita GDP level, several provinces have per capita residential floorspace over 30 m^2, which is greater than that of Japan at $40,000 per capita GDP level. Second, per capita residential floorspace in China today is higher than several OECD countries. The average per capita residential floorspace in China in 2012 is 33 m^2 in urban areas and 37 m^2 in rural areas (NBSC, 2014). This is close to the current level of per capita residential floorspace in Western Europe. Moreover, per capita residential floorspace in rural areas in some southern provinces, such as Zhejiang and Shanghai, is close to 60 m^2, exceeding that of most countries but the United States and Australia. Chinese provinces have reached high levels of per capita floorspace at relatively low income levels; given land use constraints and saturated consumer demand for floorspace, residential floorspace in China may follow a slow, continuous growth path observed in some OECD countries.

Different from residential buildings, per capita floorspace of commercial buildings shows linear, continuous growth (Figure 3.3). This is because per capita commercial floorspace in Chinese provinces is low and has strong growth potential. Per capita commercial floorspace in most provinces is less than 5 m^2, compared to 7-26 in developed economies (ENTRANZE, 2013;

Hong Kong Housing Authority, 2015; MIAC, 2015; Moura et al., 2015; U.S. Census Bureau, 2013). As the Chinese economy continues to expand, per capita floorspace of commercial buildings may grow at a slower rate or reach a saturation level.

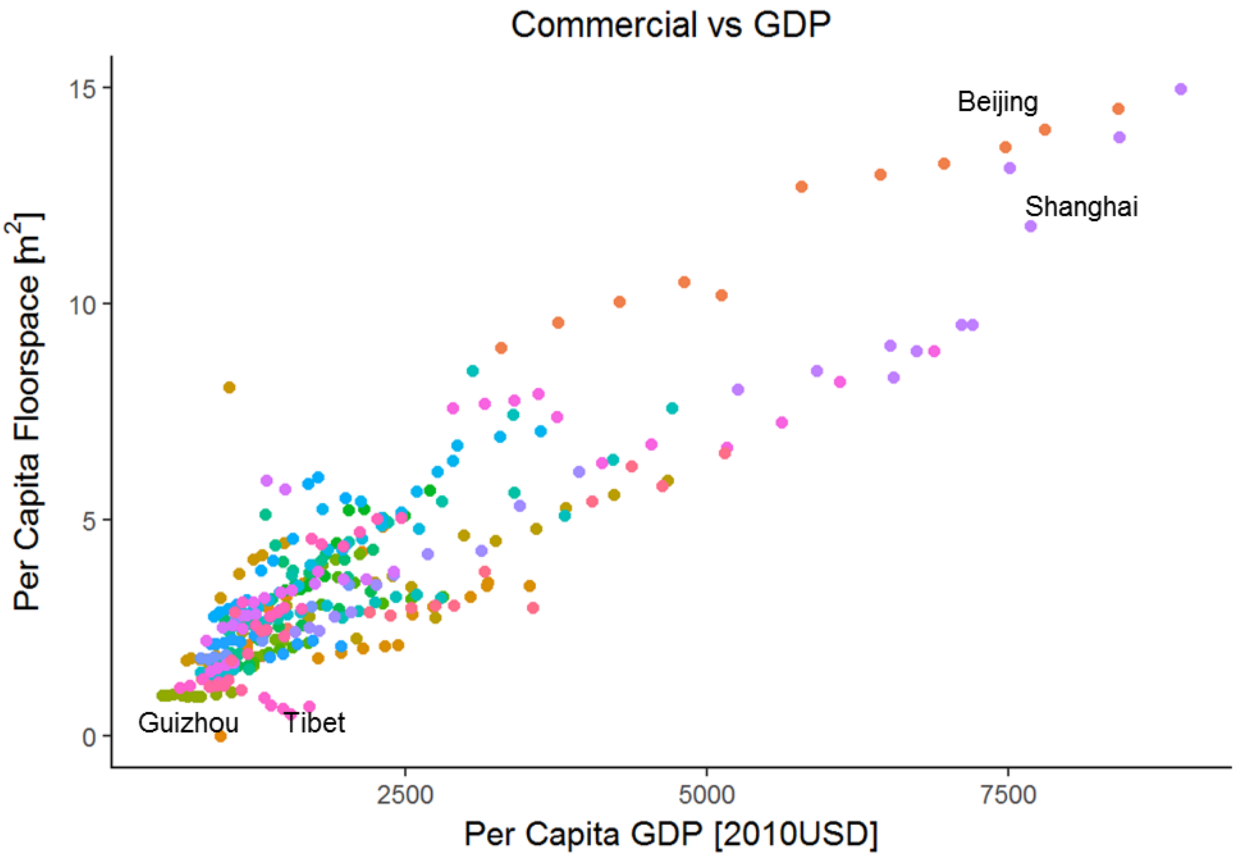

Figure 3.3 Relationship between per capita commercial floorspace and per capita GDP by province (1996-2006)

Note. Provinces in Figure 3.2 and Figure 3.3 are represented by different colors.

3.3 Methodology and Data

3.3.1 Selection of the floorspace model

Previous studies suggested that income is a key driver of floorspace growth (Berkelmans and Wang, 2012; Chivakul et al., 2015; Hong et al., 2016). As shown in the historical analysis, the relationship between per capita floorspace and income in Chinese provinces changes over time. Per capita floorspace increases at low income levels and the growth slows down as income rises; in a few provinces, growth in per capita floorspace stabilizes as it approaches the saturation level. In OECD countries, at high income levels per capita floorspace either continues to increase or stabilizes.

To develop a good understanding of future floorspace growth, the floorspace model needs to have four key characteristics. First, it needs to fit the historical data reasonably well and the estimated floorspace for the historical period needs to reflect the actual historical trend. As shown in Figure 3.2 and 3.3, historical data do not show one consistent trend and the pattern of floorspace development changes over time; we will discuss the choice of fitting period in detail in Section 3.3.3. It is also worth noting that model fit is only one aspect and future development may depart from the past, and therefore the model should also have the capability of reflecting different future trends (Hardie et al., 1998; Meade and Islam, 2006).

Second, it needs to capture the relationship between income and floorspace growth. Income is a key driver of per capita floorspace growth and has been used as the key independent variable to study future floorspace growth (Berkelmans and Wang, 2012; Chivakul et al., 2015). As shown in OECD countries and Chinese provinces, per capita floorspace usually increases along with income growth.

Third, it needs to reflect the changing relationship between income and per capita floorspace, which varies over time and with income levels. The model needs to reflect the changing elasticities of per capita floorspace with respect to income. As observed in the historical analysis, the rate of floorspace growth with respect to income changes over time and at different income levels. For example, per capita floorspace growth slows down as income reaches high levels.

Fourth, there needs to be an obvious upper bound where people's demand for floorspace is saturated. Having the saturation level in the floorspace model helps contextualize different development pathways and also provides a capability to link the floorspace model with broader modeling and scenario analyses. Even though some countries do not seem to come to a final saturation level, having saturation levels from real-world analogs can supplement the statistical model with real-world analysis and help understand real-world implications of different floorspace growth pathways.

Logistic and Gompertz functions are the most frequently referenced curves in projecting future growth (EIA, 2013a, b; Hong et al., 2014; Hu et al., 2010; IEA, 2012; Marnay et al., 2008; McNeil et al., 2012; Trappey and Wu, 2008). Although these functions can describe similar behavior in some phases of development, one important distinction is that the Gompertz curve is asymmetric while the logistic curve describes a symmetric development process. Compared to the logistic function, the Gompertz function is more flexible and allows for variation in curvatures at different income levels (Dargay and Gately, 1999). This is the key reason we use the Gompertz function in this analysis. Neither the Gompertz nor logistic function is structural; therefore, we accompany the statistical model with some real-world analysis, such as picking saturation levels from real-world analogs.

The Gompertz curve meets all four characteristics listed above for a good model to estimate China's future floorspace growth. It is often used to estimate growth in vehicle ownership and its relationship with income (Dargay and Gately, 1999; Huo and Wang, 2012; Wu et al., 2014). The approach presented in this paper is similar to the method used by Dragay and Gately (1999) to estimate car and vehicle ownership across countries. Per capita floorspace is estimated as a function of income and saturation demand (see Equation 1).

$$F_{it} = \gamma \times e^{\alpha_i e^{\beta_i GDP_{it}}} \qquad \text{(Equation 3.1)}$$

Where

F_{it} is the per capita floorspace at time t for province *i*;

γ is the saturation level of per capita floorspace, which is related to population density, land supply, people’s preference, and housing and land use policies;

GDP_{it} is the per capita GDP at time t for province *i*;

α_i, β_i are parameters defining the shape of the function (i.e. the speed of reaching saturation) for each province *i* and they both have negative values. α_i determines the maximum income elasticity, which is different by province and building type. β_i determines the per capita GDP level at which floorspace reaches the saturation level; the smaller β in absolute value, the greater per capita GDP at which elasticity reaches the maximum value.

The long-run elasticity of per capita floorspace to per capita GDP (E_{it}) is not constant and varies with income levels (see Equation 2).

$$E_{it} = \alpha_i \beta_i GDP_{it} e^{\beta_{ii} GDP_{it}} \qquad \text{(Equation 3.2)}$$

In addition to income, several other factors could affect growth in per capita floorspace. Such factors include housing price, energy price, population density, land use policy, mortgage rate, and purchase restriction, but empirical data for these factors for 31 provinces across multiple years are scarce. Therefore, these factors are not included in the model but considered when selecting saturation levels for provinces (see Section 3.3.3). Given that income is the key determinant of per capita floorspace growth, the simplification of the function should not impair the validity of the projection.

To estimate per capita floorspace in China, we need to estimate parameters α, β, and γ for individual provinces, separately for urban residential, rural residential, and commercial buildings. Due to the non-linear nature of the Gompertz function, we estimate the model described in Equation 1 using the Levenberg-Marquardt method, which solves nonlinear least squares problems (Marquardt, 1963).

3.3.2 Data and assumptions

In order to estimate future floorspace growth, we need to understand historical data. For residential floorspace, we use a dataset with provincial-level information between 1978 and 2010. Per capita floorspace of urban and rural residential buildings between 1978 and 2008 for 31 provinces is obtained from the Comprehensive Statistical Data and Materials on 60 Years of New China and these data are supplemented by data from provincial statistical yearbooks for the latest years (NBSC, 2009). For a few places where there are missing data, we linearly interpolate data between missing years. The data of per capita floorspace exhibit a large change between 2002 and 2003 due to changes in the statistical method. Because the pre-2002 data capture the historical trend, we do not discard them. Instead, we smooth the full dataset by extracting the trend throughout the entire time period. Similar adjustments have been made by Berkelmans and Wang (2012) to estimate urban residential floorspace in China.

The China Statistical Yearbook does not directly report data on commercial building floorspace, but it includes data on total and residential floorspace in urban areas. Here we assume that commercial buildings only exist in urban areas and the difference between total and residential floorspace is commercial floorspace. We collect data on commercial floorspace for 31 provinces between 1996 and 2006, as statistical categories in the China Statistical Yearbook changed in 2009 and do not include relevant data afterward (NBSC, 1997-2008).[4]

Historical population, urbanization, and GDP data for individual provinces are obtained from the China Statistical Yearbook and statistical compilation of the Chinese National Bureau of Statistics (NBSC, 2009, 2014). Growth in urbanization and GDP for individual provinces follows historical trends and eventually converges to the same national growth rate by the end of the century as shown in the shared socioeconomic pathway 2 (Dellink et al., 2016; Kc and Lutz; O'Neill et al., 2015). Population growth of individual provinces follows historical trends and eventually converges to the same national rate by 2070, which equals the growth rate in the 2015 UN medium-variant population projection (UN, 2015a).

To understand potential saturation levels of per capita floorspace, we collect historical floorspace data of developed countries from various sources. For per capita floorspace in cities, we use data collected by Kennedy et al. (2015) in their study of megacities, supplemented by city-level statistics of New York, Sydney, Berlin, and Copenhagen as per capita floorspace in Chinese cities already exceeded that of many megacities (CBRE, 2013; City of Sydney, 2012; Parshall et al., 2011; Xue, 2011). For per capita floorspace at the national level, we use data of ENTRANZE (2013) for European countries and national statistics in the United States, Japan, Canada, and Australia (Council of Australian Governments, 2012; EIA, 2014a; MIAC, 2015; Natural Resources Canada, 2011).

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[4] The 2008 China Statistical Yearbook reports on total and residential floorspace in urban areas in 2007; however, these data are the same as those in 2006. We did not use data in 2007 because of the potential error in statistics.

3.3.3 Selection of different floorspace pathways

3.3.3.1 Three growth scenarios

The choice of saturation level helps contextualize floorspace pathways, for example, whether China would evolve toward the U.S. or Japanese lifestyle. There are many potential drivers affecting floorspace growth and saturation levels, such as macro-economic drivers (e.g. disposable income, inflation, and unemployment), housing market variables (e.g. mortgages and housing prices), land policies (e.g. land use restrictions and land values), and social, demographic, and behavioral factors (e.g. lifestyle and population density). The distribution of growth (e.g. compact or dispersed development) can also influence the level of floorspace demand (Güneralp et al., 2017; Kennedy et al., 2015; Moura et al., 2015). Here we develop three growth scenarios to reflect different choices in development paths.

We use three growth scenarios – low, medium, and high – to estimate per capita floorspace growth under different development patterns. In these scenarios, per capita floorspace reaches low, medium, and high saturation levels (see Table 3.1 and 3.2). The scenario analysis is used to illustrate implications of possible development paths. The low growth scenario portrays the growth in Western Europe or Japan with limited expansion of per capita floorspace. To follow this path, the Chinese buildings sector experiences significant adjustments and substantial contraction of new construction. The medium growth scenario follows the trend in Nordic countries. This assumes slow adjustments in the real estate market to prevent overheating while ensuring sufficient living and working space for all people. The high growth scenario resembles the U.S., Canadian, or Australian pattern with high levels of per capita floorspace. Under this scenario, in rural areas people continue to pursue large living spaces without land use restriction.

In urban areas, the construction boom continues with high demand for living spaces and rapid growth in the service industry.

Table 3.1 Saturation levels of per capita residential floorspace in three growth scenarios (unit: m^2)

Growth Pattern	Country Analogs for Provinces	Residential
High Growth	Australia	80
	United States	70
	Canada	60
Medium Growth	Denmark	55
	Norway	50
	Italy/Sweden	45
Low Growth	Japan/France/Germany	40
	Belgium	35
	UK	30

Growth Pattern	City Analogs	Residential
High Growth	Sydney	55
	Copenhagen	50
Medium Growth	Berlin	45
	Osaka/New York/Los Angeles	40
Low Growth	Tokyo	35
	Paris	30

Table 3.2 Saturation levels of per capita commercial floorspace in three growth scenarios (unit: m^2)

Growth Pattern	Country Analogs for Provinces	Commercial
High Growth	United States	26
	Canada/Denmark	23
	Finland	20
Medium Growth	Sweden/Netherlands	18
	France/Japan/Germany	15
	UK	12
Low Growth	Belgium/Portugal	10
	Spain/Italy/Australia	7

Growth Pattern	**City Analogs**	**Commercial**
High Growth	Los Angeles	30
	Copenhagen	25
Medium Growth	New York	20
	Osaka	18
Low Growth	Tokyo	15
	London	10

3.3.3.2 Choice of fitting period

The estimated floorspace based on the Gompertz function needs to fit the historical trend reasonably well; however, historical data do not show one consistent trend and the pattern of floorspace development changes over time. In the early stage of development, floorspace grew drastically at low income levels in most provinces, but the growth slowed down in recent years.

Instead of fitting the model with the entire time series of historical data, we use data after 1999 to fit the model and estimate future growth in floorspace at the provincial level for three building types. Using data from 2000 and afterward has two advantages. First, future growth is more likely to build on the recent growth trend. Unlike OECD countries, China's per capita floorspace grew several times at low income levels; this trend is unlikely to be repeated as the basic housing demand is met and the national and local governments are adjusting policies to reduce vacancy rate and speculation in the real estate industry (Glaeser et al., 2016). Second, we have a more consistent dataset by using data from recent years. There were unexplained changes in statistical methods, and data of earlier years might be collected using different methods.

3.3.3.3 Customizing saturation levels for provinces

Given there are multiple factors influencing floorspace growth, regions are likely to pursue development paths specific to their characteristics and have different floorspace saturation levels. In this paper, we customize development paths for individual provinces in three ways.

First, we apply different saturation levels for provinces and four municipalities (i.e. Beijing, Tianjin, Shanghai, and Chongqing), as population densities and development patterns are different between provinces and cities. Floorspace growth in major cities, such as Paris, Tokyo, and Los Angeles, provides analogs for saturation levels of the four municipalities, whereas saturation levels of provinces follow the national average per capita floorspace in developed countries.

Second, we use different saturation levels for residential and commercial buildings, as the dynamics between these two sectors are different. As shown in Figure 1, per capita floorspace in residential buildings is much higher than that of commercial buildings, because these two types of buildings have different functions and serve different needs. Therefore, we apply different saturation levels for different building types based on the levels of historical growth observed in major developed countries.

Third, we customize saturation levels to every region based on four factors that affect future supply and demand of floorspace: historical floorspace, local economy, land supply, and local policies. This is a subjective exercise in some cases, while in other cases it is more obvious. Some provinces have already surpassed the given saturation level in the low and/or medium growth scenarios; in these cases, we use the next saturation level to estimate future floorspace growth. For example, per capita rural residential floorspace in Shanghai and Zhejiang in 2010 is around 60 m^2, much higher than per capita residential floorspace in most OECD countries and greater than saturation levels in the low and medium growth scenarios; therefore, we only use saturation levels in the high growth scenario to estimate rural residential floorspace in these two provinces.

Historical floorspace, local economy, land supply, and local policies affect regions in different ways; as a result, regions reach different saturation levels in the same growth scenario (Table 3.3). Here we discuss how these factors influence floorspace expansion in different building types and Appendix A discusses in detail how we customize saturation levels to individual provinces in different scenarios.

Four factors listed above all influence the growth in urban residential floorspace. For example, although major cities like Beijing have high economic growth and income levels, limited land areas constrain floorspace expansion and result in low levels of per capita urban residential floorspace. Local land polices and financing/mortgage policies also play an important role in shaping the housing market in China. Because the local government can increase revenues through land sales and expand economic output and employment through investment in new construction, it has strong incentives to encourage floorspace expansion. One striking fact of the floorspace growth in China is that local governments with weak economies are often most aggressive in promoting new construction. However, this growth is not sustainable and building construction started to slow down in some places. For example, western provinces lacking major cities and key industries started to experience oversupply of building stock[5] and contraction in new construction (Chivakul et al., 2015; Ding and Chen, 2015; Zhao et al., 2014).

Local economic development and increase in income are the key drivers of floorspace growth in rural areas. Although there are policies to limit land areas used for building construction per household at the local level, they do not regulate floor area ratio and thus do not constrain available building floorspace. In addition, as land in rural areas and rural houses are not tradable

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[5] In some western cities, the housing inventory ratio, measured by the ratio of floorspace unsold to floorspace sold during the same period, is as high as 24 months.

in most cases, there is less investment-driven building construction in rural areas compared to urban areas. Typical policies to adjust housing demand in urban areas, such as tightening monetary policies and house purchase restrictions, do not apply to rural housing. Currently, per capita residential floorspace in rural areas is higher than that in urban areas at the national level and in most provinces; only in a few places with low income levels and/or special living conditions (e.g. Gansu, Qinghai, Inner Mongolia, and Tibet) per capita residential floorspace in rural areas is lower than that in urban areas.

The growth in commercial floorspace is driven by local economy, in particular service sector GDP. The Chinese government does not apply as many counter-cyclical policies to influence the development of commercial buildings as it has for urban residential buildings. The market of commercial buildings is highly differenced by city tier. There is a strong demand for commercial floorspace in large cities like Beijing and Shanghai, but in most cities there are signs of oversupply of commercial buildings as vacancy rates are up to 40% in second or third tier cities like Chongqing, Chengdu, and Changsha (Miner, 2015).

Table 3.3 Saturation levels by province in three growth scenarios (unit: m^2)

Building Type	Urban Residential			Rural Residential			Commercial		
Scenario	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Anhui	40	50	60	35	45	60	7	12	20
Beijing	30	40	50	45	55	70	18	20	25
Chongqing	35	45	50	40	50	60	10	18	25
Fujian	40	55	70	55	60	70	7	12	20
Guangdong	40	50	60	35	45	60	10	18	26
Gansu	35	45	60	30	45	60	10	15	20
Guangxi	40	45	60	40	55	60	7	12	20
Guizhou	35	45	60	30	45	60	7	12	20
Henan	40	45	60	40	45	60	7	12	20
Hubei	40	50	60	45	55	70	10	18	23
Hebei	35	45	60	40	45	60	7	12	20
Hainan	30	45	60	30	45	60	10	15	20
Heilongjiang	30	45	60	30	45	60	10	12	20
Hunan	40	50	60	45	55	70	10	15	20
Jilin	30	45	60	30	45	60	10	12	20
Jiangsu	40	55	70	60	70	80	10	18	26
Jiangxi	45	50	60	55	60	70	7	12	20
Liaoning	35	45	60	30	45	60	10	15	20
Inner Mongolia	35	45	60	30	45	60	10	15	20
Ningxia	35	45	60	30	45	60	10	12	20
Qinghai	35	45	60	30	45	60	7	12	20
Sichuan	35	45	60	40	45	60	10	12	20
Shandong	40	50	60	40	50	60	10	18	26
Shanghai	45	50	55	70	75	80	18	20	30
Shaanxi	35	45	60	45	55	70	10	15	23
Shanxi	35	45	60	35	45	60	7	12	20
Tianjin	35	45	50	35	45	60	15	18	25
Xinjiang	30	45	60	30	45	60	7	12	20
Tibet	40	50	60	35	45	60	7	12	20
Yunnan	40	50	60	35	45	60	7	12	20
Zhejiang	40	55	70	70	75	80	10	18	26

3.3.4 Model estimation

We use the Levenberg-Marquardt method to estimate parameters α, β in three scenarios for urban residential, rural residential, and commercial buildings. The estimates of α, β are of the correct sign and within a reasonable magnitude. α determines the maximum income elasticity, which is different by province and building type. The maximum income elasticity is highest in commercial buildings, as the development of the service sector is strongly correlated with economic development. The maximum income elasticity is close to 1 in urban residential buildings, 0.7 in rural residential buildings, and 2.4 in commercial buildings. β determines the income level where the income elasticity reaches the maximum value and also varies widely across provinces and scenarios. Using α, β, we estimate per capita floorspace for individual provinces by building type.

The estimated per capita floorspace at the provincial level is consistent with historical data. Four provinces shown in Figure 3.4-3.6, Beijing, Qinghai, Inner Mongolia, and Jiangsu, are at different income levels and have different levels of historical floorspace and growth trajectories. The comparison between estimated and actual values in these four provinces shows that the model in Equation 3.1 fits historical data well at various income and per capita floorspace levels.

3.4. Results and Discussion

3.4.1 Per capita floorspace at the provincial level

Per capita floorspace expansion differs by province and growth path. In the low growth scenario, as there is only limited expansion of floorspace, the saturation level is close to per capita floorspace in several provinces today and growth in per capita floorspace slows down in the near term. In the medium growth scenario, per capita floorspace continues to grow for some time and then gradually slows down, with exceptions in places with relatively low levels of per capita floorspace today. For example, per capita floorspace in urban residential buildings in Beijing and in rural residential buildings in Inner Mongolia continues to increase for several decades before approaching the saturation level (Figure 3.4 and 3.5). In the high growth scenario, most provinces continue to expand floorspace until the end of the century with notable exceptions in rural residential buildings in Zhejiang and Shanghai, where per capita floorspace already exceeds that of most OECD countries.

Although income is a major driver of floorspace growth, other factors also influence floorspace growth trajectory. As a result, provinces with similar levels of per capita GDP have different levels of floorspace demand. For example, Inner Mongolia and Jiangsu have similar levels of per capita GDP and growth rate but different levels of per capita floorspace. Inner Mongolia has abundant natural resources and large land areas for farming and grazing. Resource-intensive industry and agriculture contribute to a large share of its economy. Due to lack of major cities and service industry, Inner Mongolia has low levels of per capita floorspace. In addition, because of different lifestyle, traditional dwellings in Inner Mongolia are different from those in coastal and inland regions. Economic structure, the size of cities, and cultural factors lead to different growth paths between Inner Mongolia and Jiangsu historically and possibly in the future.

It is worth nothing that in our analysis historical growth trajectories have strong influence on future growth. The model we choose fits reasonably well with the historical data, and the future growth is extrapolated based on the historical trend while constrained by saturation demand. As a result, provinces with fast growth in the past continue to grow rapidly in the near term and approach the saturated demand at a fast rate. Even though some of them have higher saturation levels than provinces with slow growth, they may still approach saturation levels earlier. Provinces with slow past growth continue the trend and experience slow growth in per capita floorspace in the coming decades, as shown in commercial floorspace in Qinghai (Figure 3.6). As discussed earlier, different from OECD countries, per capita floorspace in Chinese provinces grew rapidly at low income levels. However, whether the growth will continue in the future is unknown. As China is also adjusting its economic structure and housing policies, the future may diverge from the past, which is not captured in the current analysis.

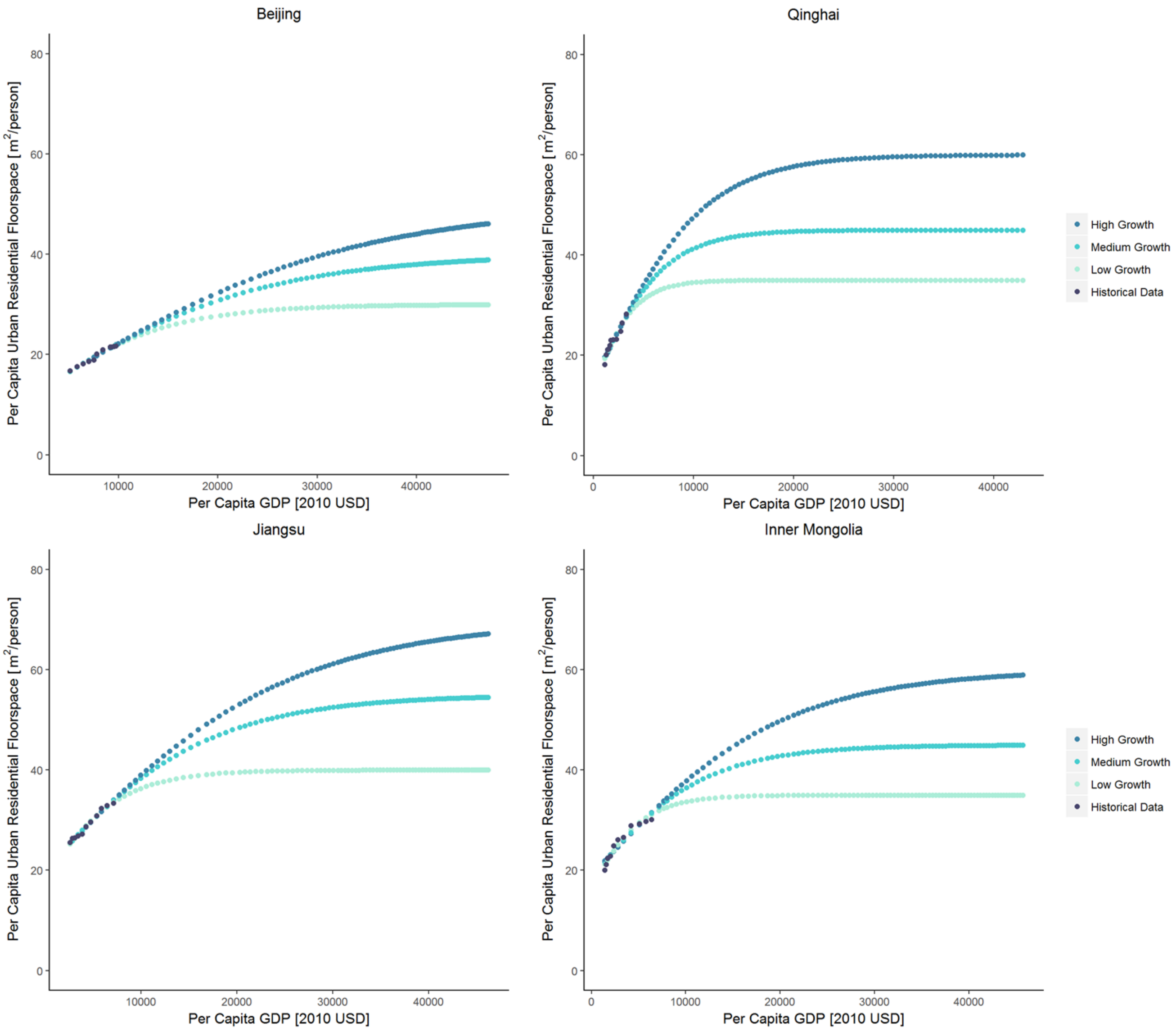

Figure 3.4 Per capita urban residential floorspace and per capita GDP in selected provinces (2000-2100)

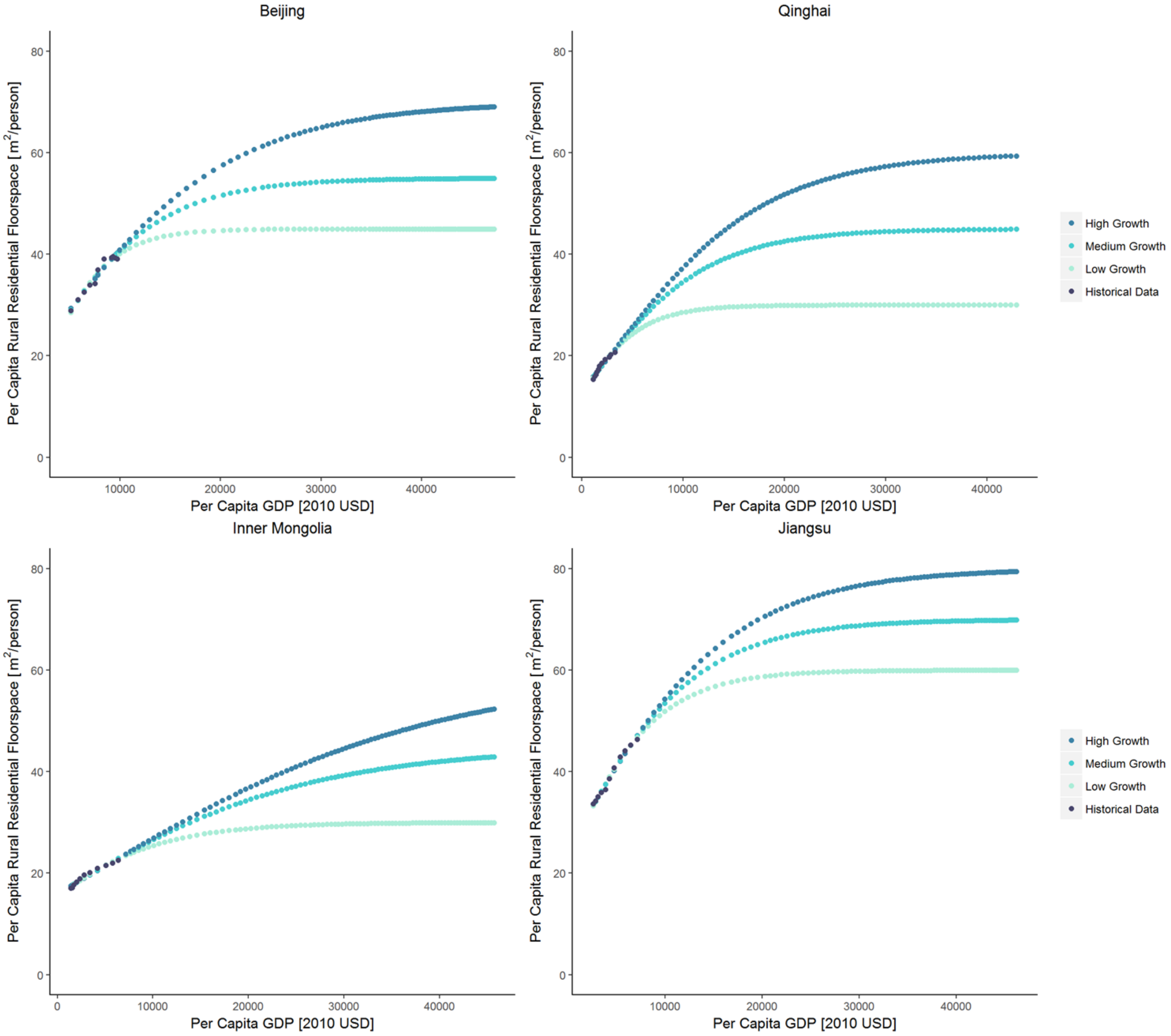

Figure 3.5 Per capita rural residential floorspace and per capita GDP in selected provinces (2000-2100)

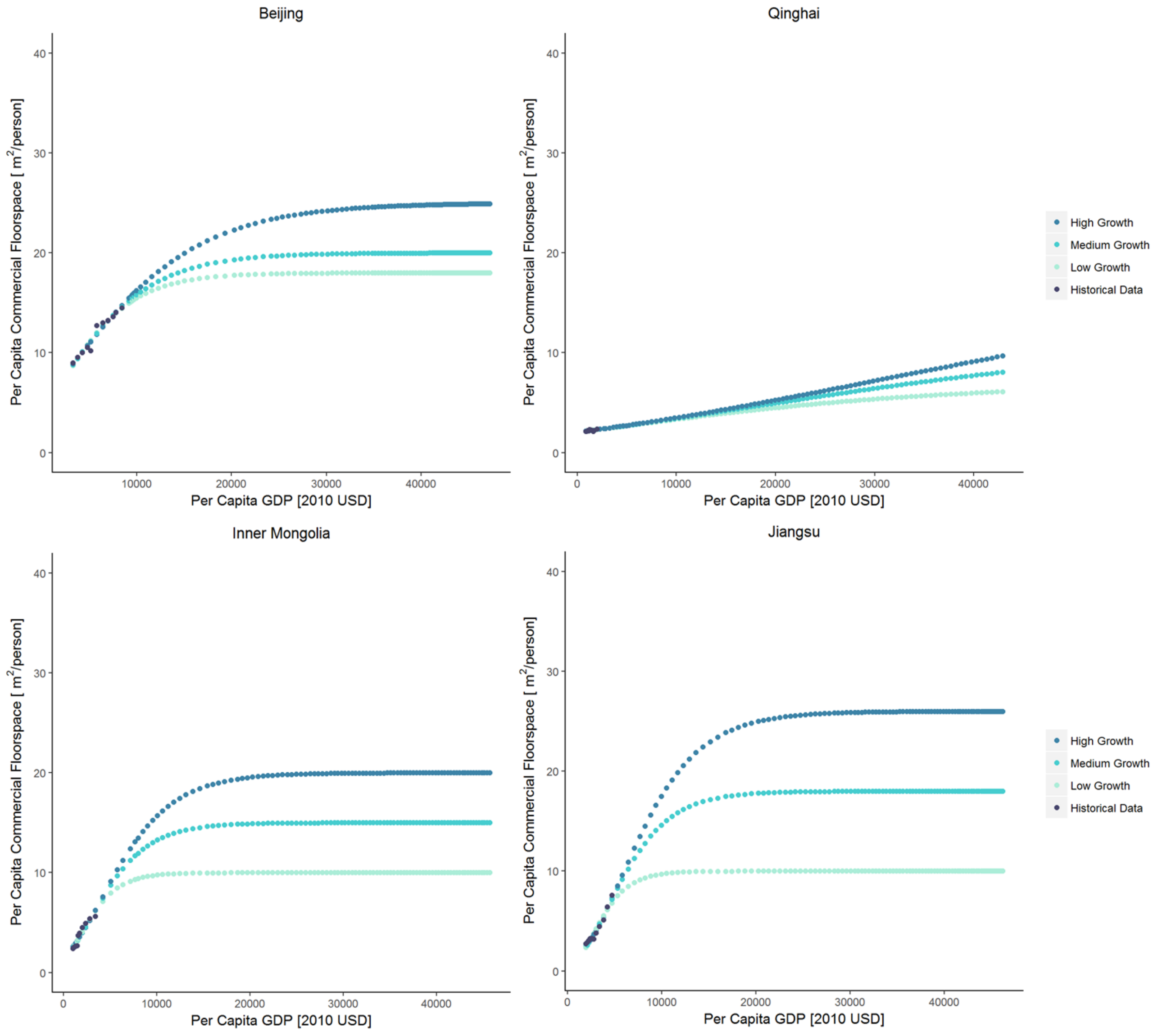

Figure 3.6 Per capita commercial floorspace and per capita GDP in selected provinces (2000-2100)

The income elasticity of floorspace demand changes at different income levels. As shown in Figure 3.7, the income elasticity increases at the low income level and then reaches a maximum level, and then it steadily declines. Most previous studies only estimated fixed income elasticity based on historical data. For urban residential buildings, the estimated income elasticities in the literature are between 0.2-1, which are shown in the accelerating stage in our estimate (Chivakul et al., 2015; Chow and Niu, 2010; Chow and Niu, 2015; Shen and Liu, 2004).

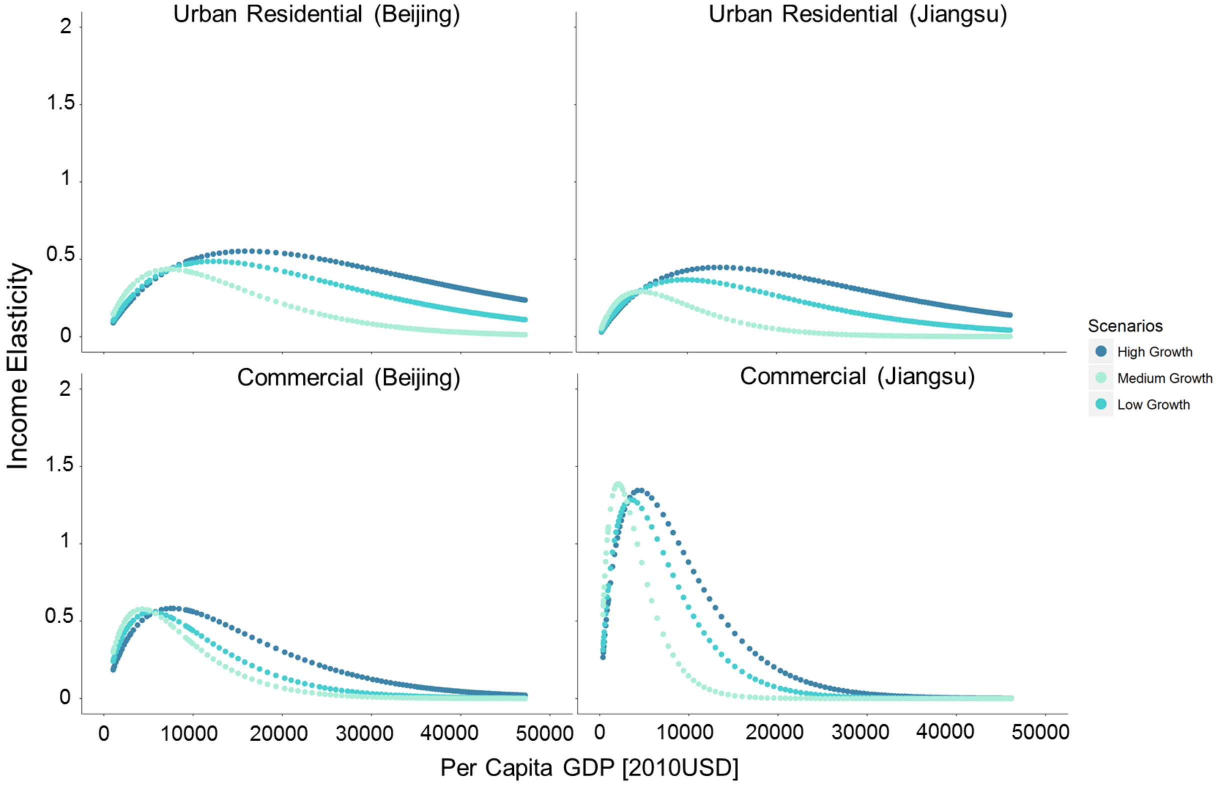

Figure 3.7 Income elasticity of demand for urban residential and commercial floorspace in selected provinces (1978-2100)

The income elasticity of floorspace demand also varies by building type. The maximum income elasticity of commercial buildings is between 0.5-2.4 across provinces, with most provinces greater than 1 in all scenarios. This means that 1% increase in per capita GDP would increase per capita commercial floorspace by 0.5-2.4%. The income elasticity in residential buildings is lower, 0.2-0.7 in rural residential and 0.2-1 in urban residential buildings. This means that people's demand for housing is less responsive to changes in per capita GDP, compared to demand for service floorspace, as factors beyond income also affect people's housing choice.

3.4.2 China's floorspace growth in different scenarios

Our analysis shows strong growth in China's building floorspace in all scenarios. However, the level of total building floorspace varies widely across scenarios, between 65 to 110 billion m^2 in 2050. Even with limited floorspace expansion in the low growth scenario, the total building stock in China still increases by 20% between 2010 and 2050. In the medium growth scenario, total floorspace grows by more than 50% between 2010 and 2050. The high growth scenario is an extreme case with the assumption of material intensive lifestyle and little land use restriction and provides the upper boundary of the total building stock in China; the total floorspace nearly doubles between 2010 and 2050 in this scenario.

Long-term projections of building floorspace can be evaluated against historical experience, implications on other variables (e.g. floorspace additions), and other projections. The wide range of floorspace projections is consistent with the historical experience. The estimated results of total floorspace fall within the range of +/-1% of historical data when comparing total floorspace in the base year 2006[6].

To further understand the plausibility of floorspace projections, we estimate annual floorspace additions implied by our floorspace projections. This information is also valuable for estimating industrial energy demand, as the amount of new construction is closely linked with the demand for iron and steel and cement. We use a stock turnover model to estimate the annual new

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[6] We use 2006 as the base year, as this is the last time period that statistical data on total building floorspace are available.

construction, which equals the total floorspace of the current year minus the total floorspace of the previous year and then plus the demolished floorspace at the current year. All previous studies pointed out that the demolition rate in China was higher than that of developed countries because of lower quality construction and shorter life span (Berkelmans and Wang, 2012; Cai et al., 2015; Hong et al., 2016; Woetzel et al., 2009). We assume that the demolition rate is 2% per year, similar to the long-term demolition rate estimated by Berkelmans and Wang (2012) and the observed demolition rate in China by Woetzel et al. (2009). The implied new construction differs significantly across scenarios, but is within ranges of historical growth and estimates of the literature (Berkelmans and Wang, 2012; Hong et al., 2016; Hu et al., 2010; NBSC, 2015; Woetzel et al., 2009) (Table A2). The floorspace addition in the high growth scenario is slightly higher than most existing studies. However, this shows a continuation of the historical growth trend. The Chinese statistics show an upward trend in new construction, rising from 2.1 billion m^2 in 2006 to 3.6 billion m^2 in 2014. If the growth continues, it is likely to reach the floorspace level shown in the high growth scenario. Jiang et al. (2014) also pointed out if the current level of construction continues, China's floorspace would reach 120 billion m^2 in 2050.

Other projections of total building floorspace in China used by the modeling community generally fall between the low and medium growth scenarios before 2030, and then converge toward the floorspace level in the medium growth scenario (Figure 3.8). The main reason for this convergence is that most studies used similar assumptions as we make in the medium growth scenario and assume that per capita floorspace demand (including both residential and commercial) would reach around 60 m^2 in the long term (Hong et al., 2016; Jiang et al., 2014).

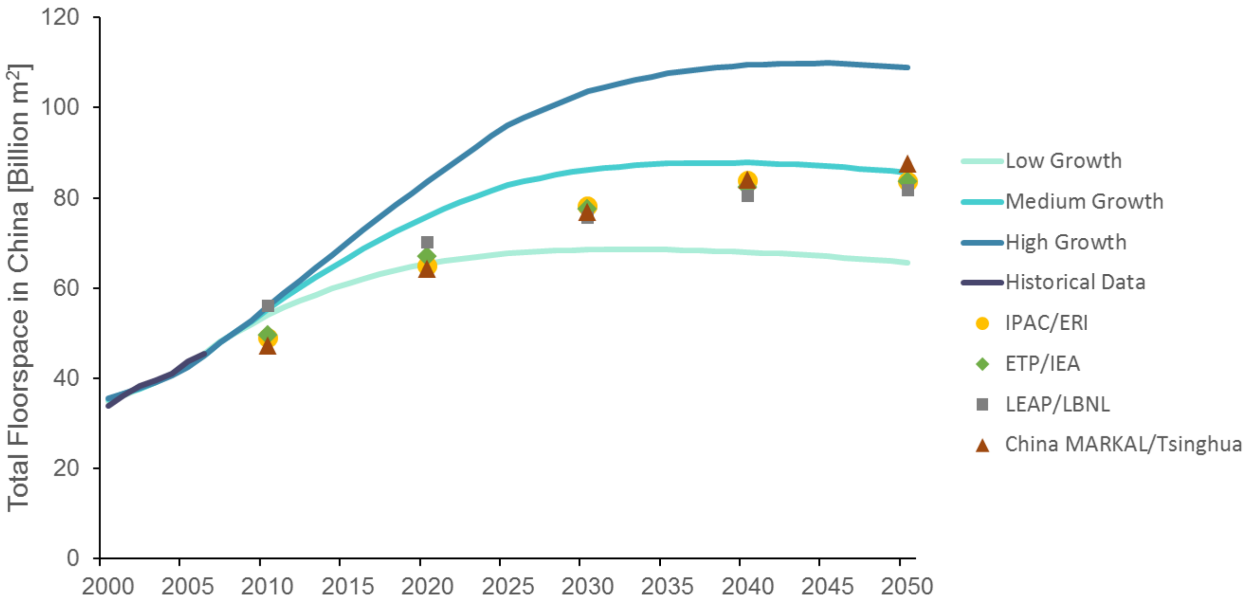


Figure 3.8 Total building floorspace in China (2000-2050)

Although models show similar levels of total floorspace in the long term, pathways to reach it are different. The China MARKAL model shows continuous rapid growth in floorspace, whereas growth in total floorspace slows down in IPAC, ETP, and our projections between 2040 and 2050. This uncertainty would have strong implications for future energy demand and climate change mitigation. Therefore, it is important to understand where the difference comes from and how it may affect building energy demand and emissions.

Three key factors contribute to the difference in growth trajectories across models. First, per capita floorspace in 2010 is different across models. For example, per capita residential floorspace in 2010 is around 30 m^2 in ETP, whereas in our analysis it is around 35 m^2, the same as the value in the China Statistical Yearbook. Even though various models have the same saturation level, different starting points may lead to different pathways to the saturation level. Second, varying population assumptions across models lead to different levels of total floorspace. Population used in this study is the same as the 2015 UN medium-variant population projection, in which China's population peaks in 2028 at 1.42 billion and then gradually declines to 1.35 billion in 2050. Although per capita floorspace continues to increase at both provincial and national levels in our analysis, total floorspace in China grows slowly after 2030 and then declines due to reduced population. Population decline is slower in other models compared to the 2015 UN projection; in 2050 China's population reaches 1.38 billion in TIMES, 1.39 billion in ETP, 1.41 billion in LEAP, and 1.46 billion in IPAC. Third, the regional modeling in this analysis provides additional insights, as where the growth in floorspace happens can affect total floorspace and cannot be observed when modeled at the national level. For example, three provinces, Zhejiang, Shandong, and Jiangsu, account for 17% of total population in China and all have high levels of per capita floorspace today. Per capita rural residential floorspace in Zhejiang is over 60 m^2, and even if it follows a high growth path, the room for future growth is limited. The current high levels of per capita floorspace in high-population provinces limit future growth and often lead to approaching saturation levels early in these places. As a result, our projection has higher total floorspace before 2030 compared to other models (Figure 3.8).

Different from previous research, our analysis shows that total floorspace peaks in China before 2050. The timing of peaking is affected by the saturation level. In the low growth scenario, total floorspace peaks between 2030 and 2035, as there is only limited floorspace expansion and total population starts to decline before 2030. In the medium growth scenario, total floorspace peaks around 2040 and then declines due to the decrease in population, although per capita floorspace continues to grow in all provinces. In the high growth scenario, floorspace continues to grow for several decades and then the total floorspace peaks around 2045.

Population decline contributes significantly to the floorspace peak in China. As discussed earlier, in our analysis, China's population peaks before 2030 and then declines; difference in China's total population in 2050 across models is between 30 and 110 million. Different population projections would affect the timing of peaking, as well as the level of peak floorspace and associated energy demand. Considering some recent policy changes, population projection could be more uncertain. China recently ended its one-child policy and none of population projections used in these previous studies reflects changes in the population policy. Zeng and Hesketh (2016) estimated that if a universal two-child policy is implemented, population peaking would be postponed by 6 years and the population size in the peak year would increase by 0.05 billion. The impact is more substantial toward the mid-century. With a universal two-child policy in place, population declines slowly after peaking. The estimate of Zeng and Hesketh (2016) showed that population under a universal two-child policy in 2050 would be 0.15 billion more than that under a continuing one-child policy scenario. Moreover, this change in China's policy would have impact beyond population and also result in greater consumption, service demand (e.g. floorspace), and energy demand.

3.4.3 Implications for building energy use

The different level of building floorspace would have implications for building energy consumption. Using GCAM-China, we conduct a brief analysis on building final energy use in China under different floorspace growth scenarios (see Chapter 4 for the description of GCAM-China). Final energy use in Chinese buildings reaches 21-35 EJ by 2050, depending on the growth scenario (Figure 3.9). In all three scenarios, building energy use peaks before 2050, between 2030 and 2035 in the low growth scenario, between 2035 and 2040 in the medium growth scenario, and between 2045 and 2050 in the high growth scenario. Although the floorspace peak contributes to the peak in total building final energy, there are other factors affecting energy use, such as energy efficiency improvement, change in fuel profile, and increase in energy service demand. As a result, the timing of building energy peaking and floorspace peaking can be different. For example, in the medium growth scenario, building energy peaks before floorspace peaks.

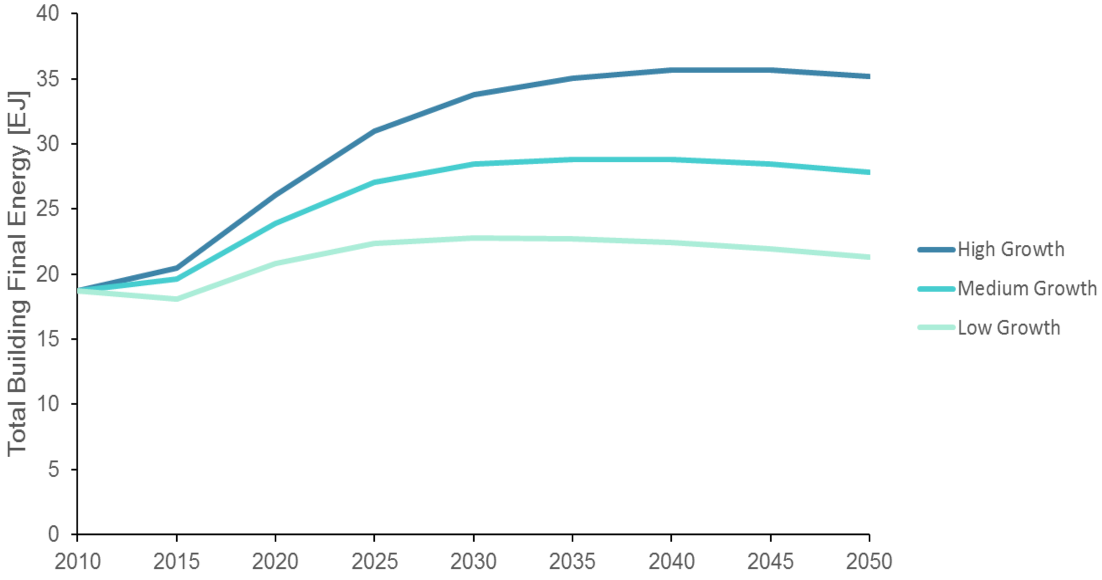


Figure 3.9 Total final energy consumption in Chinese buildings (2010-3050)

According to the estimate of the International Energy Agency (IEA), building final energy use in China would reach 31 EJ and 22 EJ in 2050 in the 6-degree and 2-degree scenarios, respectively (IEA, 2015b). To limit building energy use to 22 EJ in IEA's 2-degree scenario, energy use per unit of floorspace, or energy use intensity, needs to be reduced to 0.33, 0.26, and 0.2 GJ/m^2 in the low, medium, and high floorspace growth scenarios, respectively. Energy use intensity is an indicator of building energy performance relative to building space and it provides information on trends in building energy use that are affected by factors beyond building floorspace.

To reach the 2-degree target, it would require further reduction in energy use intensity of Chinese buildings. Reduction in building energy use intensity can be achieved by a mix of measures, such as switch from traditional biomass to commercial fuels, improvement in the stringency of building energy policies, technology advancement, and efficient energy use behavior. It is also worth noting that factors other than energy efficiency can also contribute to the change in building energy use. Increase in residential floorspace, for example, has the potential to reduce energy use intensity, as energy use in appliances and equipment does not grow proportionally to building floorspace. However, countries with large floorspace such as the United States still have high energy use intensity due to high energy service demand. Therefore, it is critical to ensure that energy efficiency improvement due to technology and policy advancement can offset the increase in floorspace and energy service demand in China.

3.5 Conclusions

This is the first study projecting China's building floorspace growth at the provincial level with three building types. It takes a closer look at variations in provincial characteristics, as well as their impact on future building floorspace growth and energy demand. It focuses on the key relationship between income and per capita floorspace and estimates the changing income elasticity over time. The same methodology can be applied to study floorspace growth in other regions and countries.

Future research can improve and extend this work in several ways. First, although the choice of saturated floorspace has impact on future floorspace demand, floorspace growth in this analysis, as well as in most previous research, is strongly affected by the historical growth trend. However, future growth can be different and may significantly deviate from the past. China is adjusting its economic structure and provincial and local governments are also attempting to modify land use and housing policies, which can lead to new development in the buildings sector. Future analysis needs to consider the possibility of dramatic change in the built environment and infrastructure and how it affects energy demand and emissions. Second, several factors can slow the change in per capita floorspace to the change in income, such as the necessary build-up of savings to afford housing and the gradual change in land use practices. Future analysis can add an adjustment factor to account for lags in the adjustment of floorspace to income growth. Third, population density and urbanization appear to affect the saturation level of per capita floorspace, and can be explicitly accounted for in the estimation of the saturation level. Finally, we only consider the change in the saturation level across scenarios, and income and population are fixed across all scenarios. Future work can explore how income, urbanization, and population change under different pathways and how these changes affect floorspace expansion and energy consumption, particularly the timing and level of peak floorspace and building energy demand.

Chapter 4. Transition pathways and scenarios for climate change mitigation in China: evolution of the buildings sector

4.1 Introduction

China, as the world's largest energy consumer and greenhouse gas (GHG) emitter, also has the world's largest construction market. In 2012, China surpassed the United States as the world's largest building energy consumer (IEA, 2014a). Energy use in buildings (including traditional biomass) constitutes 28% of total final energy consumption in China (IEA, 2014a; Jiang et al., 2014). Driven by economic growth, urbanization, lifestyle changes, and changes in the economic structure, building energy consumption is expected to continue grow rapidly. Buildings will therefore be an important element of efforts by the Chinese government to plan infrastructure, constrain energy growth, or meet a range of related sustainability goals such as local air pollution and GHG reductions (Daioglou et al., 2012; Delmastro et al., 2015; IEA, 2014b; McKinsey & Company, 2009; Shi et al., 2014; Ürge-Vorsatz et al., 2012; WBCSD, 2009).

Although the importance of buildings in China is well-understood, there is a high uncertainty in the evolution of these drivers and future building energy demand from China's dynamic growth and rapid social and economic changes. Studies have shown high variations in the future building energy consumption (22 EJ to 31 EJ in 2050 across models) (IEA, 2015c; Jiang et al., 2014). These differences arise from different assumptions about socioeconomic drivers, technology, and building sector policies, among other things.

In addition, conditions vary a great deal across provinces. The degree to which this heterogeneity persists will have important implications. There is a wide disparity in energy consumption patterns and socioeconomic conditions across provinces. For example, per capita GDP of coastal provinces are four times higher than that of western provinces (NBSC, 2014). The composition of building energy consumption varies across provinces, reflecting different housing size, occupancy density, income level, climate, lifestyle, and use of appliances (Büchs and Schnepf, 2013; Dai et al., 2012; Isaac and van Vuuren, 2009; Olonscheck et al., 2011; Rosas-Flores et al., 2011; Zhou et al., 2013b). In the northern provinces, a significant portion of building energy consumption is used for heating, while buildings in the central China with hot summers and cold winters only have modest heating loads. The regional heterogeneity in socioeconomic drivers and energy use patterns would have strong impact on technology and options for energy efficiency improvement and carbon emissions abatement.

This study aims to better understand and characterize the uncertainty in China’s building energy demand. The research is motivated by the following questions: What is the overall range in key indicators of building sector evolution (energy consumption, floorspace, fuel mix)? What assumptions might drive differences in these possible futures? How will these dynamics vary across provinces? Where are hot spots for growth in the future? To investigate the Chinese buildings sector at a high resolution, we use a 31-province China model embedded in the Global Change Assessment Model (GCAM-China) in this study. GCAM-China takes into consideration of provincial specific conditions and has the capability to represent energy supply and demand at the provincial level under varying development paths.

A range of models have examined long-term growth of the Chinese buildings sector through various scenario analyses. Zhou et al. (2013; 2014; 2008) used the China End-Use Energy Model to analyze China’s energy demand and emissions in two scenarios with varying technologies and efficiency improvement rates. Using the Integrated Policy Model for China (IPAC), Jiang et al. (2014; 2006) assessed the future trajectory of the Chinese buildings sector in four scenarios with different rates of deployment of low-carbon technologies. The Energy Technology Perspectives (ETP) of the International Energy Agency is a global model with detailed end-use modules for China. It investigated energy consumption in the buildings sector in China under the 6°C, 4°C, and 2°C scenarios, where the world is on the path toward a 6°C, 4°C, and 2°C rise in average global temperature, respectively (IEA, 2015c). The World Energy Outlook (WEO) estimated China's future energy demand in three scenarios: new policies, current policies, and 450 scenarios, which have different assumptions on policy implementation and mitigation target (IEA, 2015d).

This study builds on this previous research in two main ways. First, rather than focusing on a single possible pathway, we develop four scenarios to depict plausible narratives regarding development pathways of China, each characterizing how key drivers might evolve. We then provide quantifications of these narratives to understand the evolution in key indicators of building sector evolution. Scenario analysis is an important method for exploring uncertainty in future development, often consisting of both qualitative and quantitative components, as in this study (Jones et al., 2014; O'Neill et al., 2015; Raskin et al., 2005; van Vuuren et al., 2012). Although we focus on buildings in this paper, the scenarios are intended to be broadly usable by for studies of other aspects of China's energy and environmental dynamics.

The scenarios developed in this study provide a useful complement to the Shared Socioeconomic Pathways (SSPs). SSPs, developed at the global level, lack the consideration of heterogeneity within a country. This analysis expands the mitigation challenge dimension of the SSP framework and considers the heterogeneity across Chinese provinces. It provides a more complete scenario framework, as heterogeneity does not only affect the distribution of development across regions, but also has implications for aggregate, national-level energy consumption and emissions. The approach used in this chapter for scenario development provides a useful way to apply SSPs and global scenarios to national and subnational levels.

Second, this study explicitly models buildings at the provincial level. Although there were attempts to study China's energy issues at the provincial level, none of them explicitly consider the uncertainty in the scale of the energy system and how the drivers of building energy use would evolve. In addition, these models did not have comprehensive details of the buildings sector. The China Regional Energy Model (C-REM), a China-specific general equilibrium model, runs at the provincial level, but it lacks sectoral and technology details to fully capture the growth of the buildings sector (Luo et al., 2014; Qi et al., 2014). In a recent study, Xing et al. (2015) estimated the future energy service demand in Chinese urban residential buildings and the analysis was downscaled to the provincial level. However, it did not provide a full picture of China's buildings sector, as rural residential and commercial buildings were not studied.

The paper is structured as follows. In section 4.2, we explain the model used in this paper. Section 4.3 describes the development of scenarios, consisting of both qualitative narratives and quantitative components. Section 4.4 examines results from different scenarios and implications on China's building energy demand. Section 4.5 discusses limitations and future research and concludes.

4.2 Global Change Assessment Model – China (GCAM-China)

This study uses a detailed building energy model nested in GCAM to investigate future energy demand of the Chinese buildings sector. GCAM is a partial equilibrium integrated assessment model, capable of representing the development of the energy system and its associated GHG emissions. The model is global in scale, with 32 energy-economy regions and 283 land regions.

GCAM runs in 5-year time step from 1990 to 2100. Previous work of Edmonds and Reilly (1983), Clarke and Edmonds (1993), and Clarke et al. (2007) discusses GCAM structure in detail.

GCAM-China, an extension of GCAM, is a fully global integrated assessment model with additional detail for 31 provinces in China. Thirty one Chinese provinces are modeled individually in GCAM-China, along with 31 global regions (See Table B1). The energy system of each province is represented in terms of electricity generation, other transformation, and end-use sectors (i.e. building, industry, and transport). GCAM-China has the capability of modeling provincial level energy supply and demand within a consistent global modeling framework. GCAM-China uses province-specific socioeconomic conditions, climate, and energy use patterns to allow for a more detailed evaluation of future evolution of the energy system in China.

The building energy model used in this study is fully nested in GCAM-China, so that fuel prices in the buildings sector are cleared in the GCAM global or provincial markets. The model explicitly accounts for key drivers that affect the growth of the buildings sector: the increase in building floorspace with population and economic growth, the demand for building energy services, and the fuel and technology competition within the services. The model comprises three building types: urban residential, rural residential, and commercial buildings, with detailed representation of energy services, fuels, and end-use technologies (Figure B1). Changes in building energy services is represented as a function of income, fuel prices, and climate (Chaturvedi et al., 2014; Eom et al., 2012; Yu et al., 2014b).

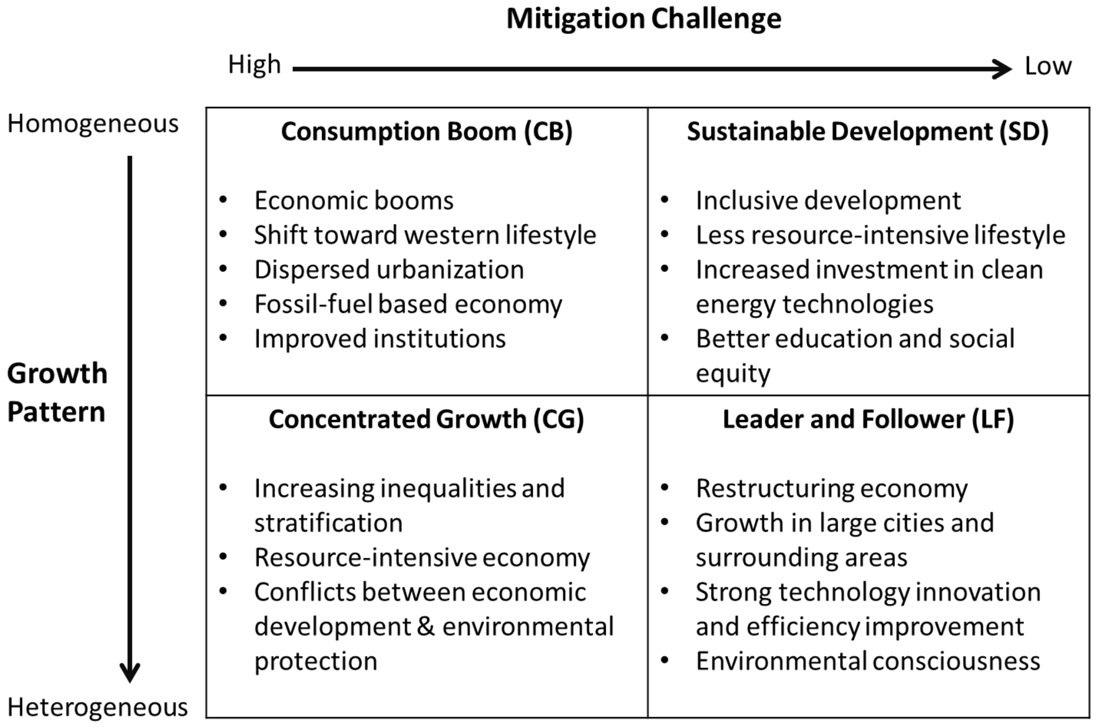
4.3 Scenario Development

4.3.1 Scenario narratives

To answer the question of the evolution of the Chinese buildings sector, we explore four different pathways using GCAM-China. Alternative scenarios are a useful way to explore uncertainty in future changes, describing plausible pathways in societal development (Jones et al., 2014; O'Neill et al., 2015; Raskin et al., 2005; van Vuuren et al., 2012).

The development of scenarios in this paper was informed by the pre-existing scenarios developed by the climate change community, especially the shared socioeconomic pathways (SSPs) (Kriegler et al., 2014; O'Neill et al., 2015; Riahi et al., 2016). The SSPs, as global scenarios, lack country-specific details and are not able capture changes within a country. There are uneven development and regional inequalities within China, as China is characterized as "a group of disparate economies rather than a homogenous entity" (Hubacek and Sun, 2001). In addition to the scale of development, the form of development and the spread of the development affect future energy demand. Therefore, we build on SSPs and contextualize it within China, considering the possible divergence across regions.

We develop four scenarios along two dimensions: energy future and growth pattern (Figure 4.1). The energy future dimension portrays China with varying challenges to mitigation, similar to one of the dimensions of the SSP framework. The high energy future scenarios, consumption boom and concentrated growth, correspond to the SSP5 fossil-fueled development scenario and depict two SSP5 worlds without and with subnational heterogeneity. The low energy future scenarios, sustainable development and leader and follower, are developed based on the SSP1 sustainability scenario, and help understand how development at the subnational level can affect sustainability in provinces and at the national level. The growth pattern dimension considers the form of development, whether it is concentrated or dispersed and whether the regional gap would become wider or narrower. The scenario narratives are grounded on historical and current trends in China as well as historical development pathways of industrialized countries. Although the focus of this paper is to analyze the evolution of the buildings sector, the four scenarios developed here can also be used in other analyses on China's energy future and climate strategies.



Consumption Boom (CB)

- Economic booms
- Shift toward western lifestyle
- Dispersed urbanization
- Fossil-fuel based economy
- Improved institutions

Sustainable Development (SD)

- Inclusive development
- Less resource-intensive lifestyle
- Increased investment in clean energy technologies
- Better education and social equity

Concentrated Growth (CG)

- Increasing inequalities and stratification
- Resource-intensive economy
- Conflicts between economic development & environmental protection

Leader and Follower (LF)

- Restructuring economy
- Growth in large cities and surrounding areas
- Strong technology innovation and efficiency improvement
- Environmental consciousness

Figure 4.1 Illustration of four scenarios depicting plausible development pathways in China

In the consumption boom (CB) scenario, China continues the fast pace of economic development with gradually integrated market and participatory society to pursue rapid technological progress and development of human capital. The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyle. There is little effort to avoid environmental impacts due to a perceived tradeoff with economic development, although technology innovation can partially address environmental impacts. The high economic growth also leads to improvement in institutions and an emerging middle class that requires better institution and deeper social reform. This helps improve equality and bridge the gap between coastal and western provinces. Increasing equality across regions maintains more labor force at the local level, with a dispersed urbanization pattern and emerging midsized cities, small cities, and big towns[7]. In the long term, regional disparity declines and the level and speed of development are similar across provinces.

The CB scenario focuses on development, including improvement in economy, welfare, institution, and equity. There are only a few nations achieved such development path in the past (Lane and Montgomery, 2014; McNeill, 2008). China is in the process of transition to a market economy and has seen rapid growth in people's income and urban population in the past two decades. This also led to increasing service demand and comfort level, and people in China started to pursue the western lifestyle with increasing energy service demand, smaller household size, and higher per capita floorspace. This pattern of changing lifestyle as income grows was also observed in Japan between the 1960s and 1990s, in the United States after the depression, and in Europe after World War II (Barton et al., 2013; Grumbine, 2007; Hinge et al., 2004; Nakagami et al., 2008; Tsang and Lee, 2013; Wilhite et al., 1996a). During 2000-2012, China had the fastest growth in per capita building energy use among the major economies. While per capita building energy use in the United States, Japan, and most European countries declined, per

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[7] According to the Mckinsey report, the Chinese cities are divided into five categories, mega (over 10 million people), big (5-10 million people), midsized (1.5-5 million people), small (0.5-1.5 million people), and big town (less than 0.5 million people). For details, see Woetzel, J., Mendonca, L., Devan, J., Negri, S., Hu, Y., Jordan, L., Li, X., Maasry, A., Tsen, G., Yu, F., 2009. Preparing for China's Urban Billion McKinsey Global Institute, Shanghai, China, p. 520.

capita building energy use in China grew more than 25% (Nakagami et al., 2008; OECD and IEA, 2015). Transition to a market economy in China led to widening gaps between rich and poor, costal and western provinces. However, some recent policy development and societal changes suggest a potential break from past trends. One recent change is the emergence of middle class in China that not only demands for services and goods but also puts pressure on institutional changes (Barton et al., 2013; Kharas, 2010; Li, 2010). The other factor is the recent policy change; the Chinese government has put forward the "Western Development Strategy" and the "Belt and Road Initiative" to retain labor at the local level and stimulate development in the western provinces (NDRC et al., 2015).

In the sustainable development (SD) scenario, China shifts toward a more inclusive development path, emphasizing human well-being, social equity, and sustainability. The Chinese government restructures the economy and moves away from the resource-intensive growth, even at the expense of slower economic growth. Increasing investment in energy efficiency and renewable energy technologies spurs innovation of low-carbon technologies. Meanwhile, with rising environmental awareness, people gradually move toward less resource-intensive lifestyles. Emphasis on inclusive growth and increasing investment in health and education accelerate the demographic transition and lead to a relatively low population growth. With the focus on sustainable development, inequality across regions and between urban and rural is reduced and a pattern of more dispersed growth emerges. In the long term, all provinces converge toward a low-carbon development path at the same speed.

The SD scenario constitutes a break with recent history of industrialized countries that took the resource-intensive development model. Under the great pressure of curbing air pollution, China is now pursuing a more sustainable growth pattern and the economic structure and industry development are subject to considerable changes – moving away from heavy industry, more stringent policies on air pollution control, and increasing investment in clean energy (Green and Stern, 2016). The KPMG poll in 2015 showed that Chinese outward direct investment activities were increasingly driven by the need for sustainable growth (Feng and Yu, 2013; Huang et al., 2013; KPMG, 2015; Wang, 2014b). The aggravated air pollution problem and environmental degradation also raise awareness among the Chinese people. Although green consumerism is still a marginal phenomenon in China, polls showed growing level of environmental consciousness and change in consumer attitudes toward environmentally friendly products (Kan, 2010; Wang, 2014a).

The concentrated growth (CG) scenario depicts increasing disparities in economic opportunities and human capital, with investments and resources concentrated in large cities. This leads to increasing inequalities and stratification both across and within provinces. Mega cities and big cities keep expanding in population and size, while small cities and towns face significant development challenges. The economic growth in China is driven by growth in the coastal and wealthier regions and the development rarely spreads to the inland areas. Motived by economic opportunities, migrants move from inland to high-income, coastal regions, resulting in high population growth in these provinces. In low-income provinces, demographic changes are shaped by high fertility rate and fast emigration. The effort of improving institution and equity is limited, as elites fear that social reform threatens their power.

The CG scenario shows a development pathway consistent with historical growth patterns in China in the past three decades. Development and income growth proceed unevenly, with a widening gap between urban and rural households and between western and eastern provinces (Dollar, 2007). The use of energy followed a resource-intensive path. The urban and wealthier households tended to acquire larger living spaces and more appliances and equipment (Li and Yao, 2009). Even though fossil fuel dependency decreased slowly and China set the target of 20% non-fossil fuel by 2030, there was no strong incentive to use unconventional and clean resources, as provincial and local governments constantly faced the pressure of economic development. As a result, the deployment of clean energy technologies grew moderately.

The leader and follower (LF) scenario is characterized by transition in social, economic, and technological trends. Although the development is still concentrated, a cluster of medium-sized cities develop around larger ones, marked by the continuation of fast urbanization. Investment in education and health leads to low fertility rate and slow population growth. With improved education and institution, there is a growing number of middle class in China, who are conscious of the environment and pursue efficient lifestyle. The middle class has high demand for protecting its right, prosperity, and property ownership. Health can be considered as a fundamental right; air pollution in China threatens this right and may trigger high awareness of environmental protection. In addition, as pointed out by Goodman (2016) and Nathan (2016), the Chinese middle class has strong support to the Chinese government, and along with the push from the Chinese government toward clean energy, the Chinese middle class may support more efficient and environmentally friendly lifestyle. China restructures the economy, with a focus on shifting the growth from manufacturing and construction sectors to service industry and clean energy.

The LF scenario depicts a new normal path, a combination of productivity gains, technology innovation, and cultural and institutional changes. It reflects the recent growth trend. The economic slow-down and the decline of construction and manufacturing industries shown in 2014 and 2015 are expected to be long-term trends (Qi et al., 2016). In addition, current policies on air pollution control and clean energy would help foster the transition. Even with improving institutions and high income growth, regional disparities could still exist, as seen in some Organisation for Economic Co-operation and Development (OECD) countries (Ballas et al., 2014; Whyte, 2014; Xie and Zhou, 2014).

4.3.2 Scenario Quantification

In order to capture different growth patterns across provinces, we divide provinces into two groups based on their per capita GDP in 2015: high-income and low-income provinces (Figure 4.2). High-income provinces concentrate in coastal areas, whereas most western provinces are in the low-income group. In the CB and SD scenarios, growth is dispersed, and therefore, high-income and low-income provinces converge to the same rate of growth in the long term. The CG and LF scenarios depict a world that growth is concentrated in a few regions, and thus the uneven development across regions continues in these two scenarios.

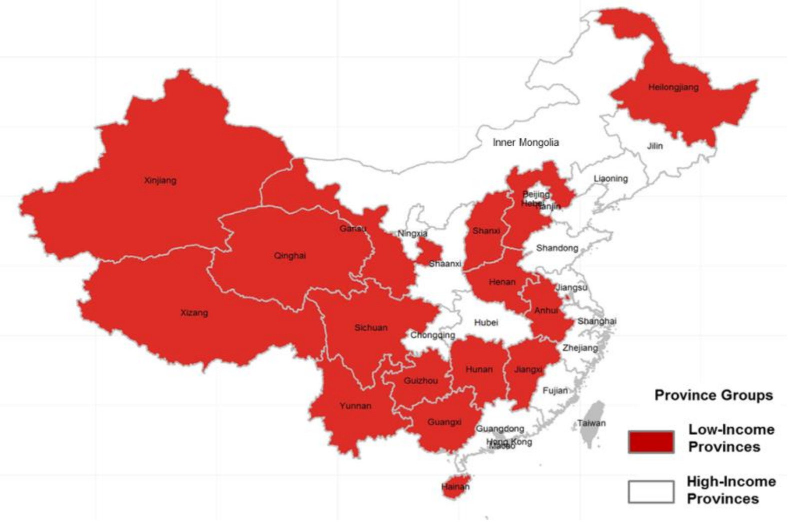

Figure 4.2 High-income and low-income provinces in this study

The scenarios are developed based on the hypotheses about key elements that drive China's future energy demand. These factors include population growth, income growth, urbanization, choice of lifestyle, and technology improvement (Guan et al., 2008; Hubacek et al., 2007; Rosa and Dietz, 2012). To create projections of these drivers, we assign either a fast, central, or slow growth rate of individual drivers for each income group under each scenario based on scenario narratives. Table 4.1 summarizes the qualitative description of these drivers across scenarios and income groups.

Table 4.1 Assumptions for the four scenarios

Scenarios	**Consumption Boom (CB)**		**Sustainable Development (SD)**		**Concentrated Growth (CG)**		**Leader and Follower (LF)**	
Provincial groups	Low-income	High-income	Low-income	High-income	Low-income	High-income	Low-income	High-income
Population growth	Medium		Low		Medium	High	Low	Medium
Urbanization rate	High		Medium		Low	High	Medium	High
Per capita GDP	High		Medium		Low	High	Low	High
Choice of lifestyle	High-energy		Low-energy		Medium	High	Low	Medium
Clean energy technology	Medium		High		Medium	Medium	High	High

The historical population, urbanization, and GDP data for individual provinces are obtained from the China Statistical Yearbook and statistical compilation of the Chinese National Bureau of Statistics (NBSC, 2009, 2014). The growth in population, urbanization, and GDP for individual provinces follows its historical trends and eventually converges to the same national growth rate, but convergence levels vary across scenarios and provinces as shown in Table 4.1.

Each scenario assumes either a fast, central or slow population growth. Projections of low, medium, and high population growth rate are consistent with the UN population projections (UN, 2015a). It is worth noting that the drivers of population growth at the national and provincial levels are different. Population growth at the national level is driven by fertility rate and high-income countries often have low fertility rate and low population growth, whereas population growth in Chinese provinces is mostly driven by migration and high-income provinces often experience high population growth. The migration effect is considered when quantifying population growth across scenarios. For example, in the two heterogeneous scenarios, high-income provinces experience higher population growth than low-income provinces.

Total population sizes across scenarios cover a wide range. Consistent with the narratives, population growth is the slowest in the SD scenario reaching 597 million in 2100 and highest in the CG scenario reaching 1389 million in 2100. The CB and LF scenarios depict medium growth, with 1067 million and 842 million in 2100, respectively. The year of reaching peak population also varies by scenario. In the SD and LF scenarios population peaks around 2025, whereas population in the CB and CG scenarios reaches the peak in 2030 and 2040, respectively.

China continues to urbanize in all scenarios, but urbanization rates differ widely across scenarios. The medium urbanization pathway follows UN's World Urbanization Prospects (UN, 2015b), while the low and high growth pathways are similar to the slowest and fastest urbanization pathways shown in the SSPs (Jiang and O'Neill). Urbanization rates in the CB and SD scenarios are high (84% in CB and 76% in SD by 2100), as development between provinces becomes more balanced and provinces converge toward the same growth rate. In the scenarios where provinces follow heterogeneous development paths, urbanization rates are lower (69% in CG and 71% in LF by 2100), because the low-income provinces are still left behind and show slower rate of growth.

Growth in per capita GDP at the provincial level ranges from low to high level, reflecting the low, medium, and high GDP grow rates of the SSPs developed by Dellink et al. (2016). GDP growth also differs widely across scenarios, especially in the second half of the century. The CB scenario depicts very fast development and has the highest GDP level and per capita GDP. The SD and LF scenarios describe a world focusing on inclusive growth and the growth of per capita GDP is moderate. With decline in population, in the SD scenario, the total GDP starts to decline toward the end of the century.

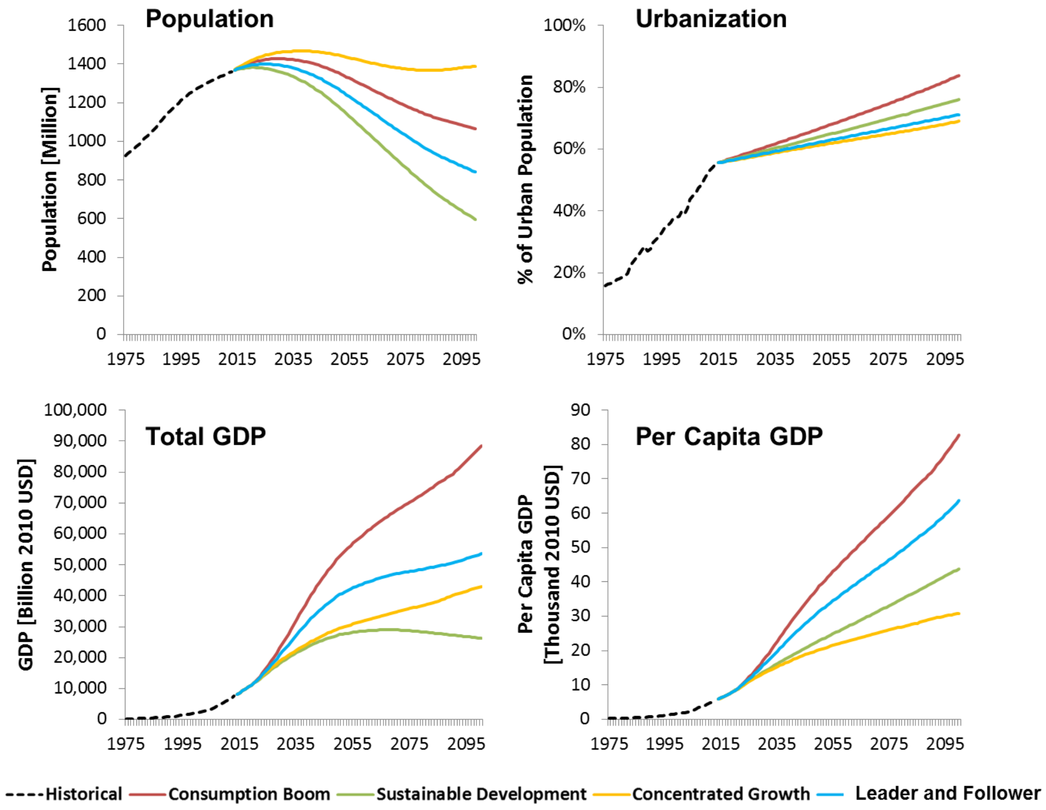

Figure 4.3 Population, urbanization, and GDP assumptions for China

Because the focus of this study is the evolution of the buildings sector, we limit the lifestyle change to the key parameter related to building energy use – per capita floorspace. Floorspace is a key driver of building energy demand and is growing rapidly in China. Historical data on per capita floorspace for urban residential, rural residential, and commercial buildings in each province are collected from Chinese statistics (NBSC, 1991-2014, 2009). It is worth noting that the statistical method for counting building floorspace changed in 2004, and we adjusted data before 2004 to ensure consistency in building floorspace data.

There is a high uncertainty in future floorspace growth in China. Estimated total floorspace of China in 2050 ranges between 75 and 93 billion m^2 in previous studies (IEA, 2013, 2015c). Per capita floorspace has not been specified in the SSP studies and previous global environmental scenarios. Therefore, we conduct our own analyses on the growth of floorspace in China under four scenarios.

Floorspace growth is associated with income growth and constrained by country-specific characteristics such as land use policy and population density. Here we estimate per capita floorspace as a function of income and demand saturation, as shown in Yu et al. (2016). The relationship between per capita floorspace, income, and the saturation level of demand is specific to individual provinces, controlling for provincial-specific characteristics. Per capita floorspace continues to increase as income grows until it reaches the saturation level, at which people do not have incentive to purchase more floorspace. The saturation level of floorspace reflects people’s preference and choice of lifestyle.

To identify meaningful scenarios of the saturation level of demand, we created analogs based on current per capita floorspace in OECD countries. Previous studies made relatively conservative assumptions of future floorspace growth in China and often assumed that per capita floorspace would converge to the current level in Japan. Here we consider more paths, including a situation that China converges toward a U.S. lifestyle. China added over 3 billion m^2 of floorspace per year between 2008 and 2013 and if this trend continues, it is likely to reach the U.S. level of per capita floorspace in the long term. The average per capita floorspace in China is around 35 m^2

for residential buildings and 8 m^2 for commercial buildings in 2013, exceeding that of several countries and cities we surveyed (NBSC, 2014). To create floorspace projections for scenarios, we assign either a fast, central, or slow projections for income-based provincial groups in each scenario. Within the high-income group, we also differentiate between the four autonomous municipalities and provinces. The saturation level of demand for residential buildings is 45, 55, and 70 m^2 per capita for provinces and 40, 45, and 58 m^2 per capita for municipalities in the low, medium, and high projections. Per capita commercial floorspace at the saturation level is 7, 15, and 26 m^2 in provinces and 15, 22, and 30 m^2 in cities. The high, medium, and low levels roughly reflect the current level of per capita floorspace in the United States, Japan, and OECD Europe, respectively.

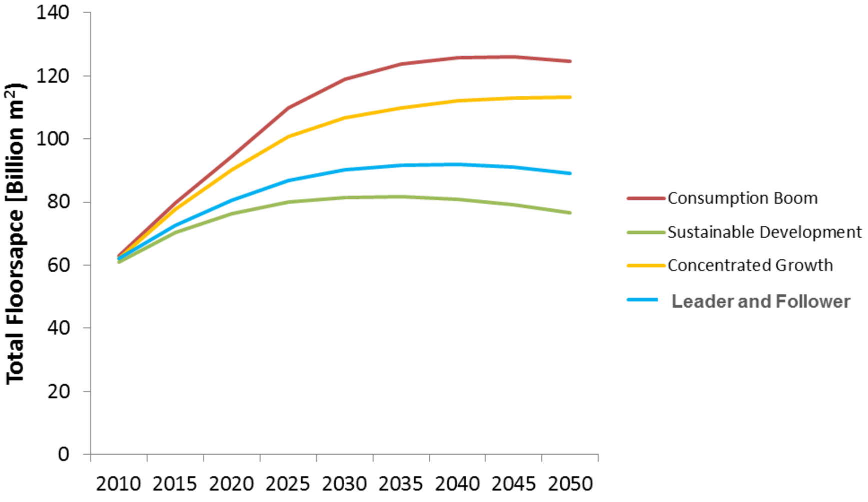

Figure 4.4 Floorspace projections in the four scenarios

Advancement of clean energy technologies is represented as energy efficiency improvement in buildings. The medium level of efficiency improvement assumes autonomous energy efficiency improvement and is consistent with the default values in GCAM (see GCAM documentation: http://jgcri.github.io/gcam-doc/) and is intended to represent technology improvement in a business as usual world without new policies to encourage technology innovation and deployment. The fast technology development or the high case assumes rapid advancement of clean energy technologies and achieves the same level of technology efficiency and cost 15 years earlier than the medium case.

Building energy use by fuel and service is calibrated to the historical data in the model base year (i.e. 2010). China's total building energy consumption by fuel in 2010 is matched with the Energy Balances of the International Energy Agency, and then partitioned to provinces based on fuel shares of provinces in the China Energy Statistical Yearbook (2011). Since China does not have a national or provincial building energy survey collecting data on energy use by service and fuel, energy service profiles of different provinces are developed based on surveys in cities and counties (Brockett et al., 2002; Chen et al., 2006; Hu and Jiang, 2001; Lin et al., 2011; THUBERC, 2011; Tonooka et al., 2006; Tonooka et al., 2003; Wang et al., 2002; Wang and Feng, 1997; Wang et al., 1999; Yu et al., 2008; Zhou et al., 2009).

4.4. Results and Discussion

4.4.1 Total building energy use in China

Energy demand of the buildings sector is associated with population change, economic growth, technology improvement, and lifestyles. Building energy demand in China has grown by 50% in the past decade (2002-2012), with an average annual growth rate of 4% (IEA, 2015d).

Building energy use in China in 2050 ranges between 25 and 42 EJ across scenarios. The average annual growth rate between 2010 and 2050 is less than 2% in all scenarios, lower than the historical growth rate. However, as shown in Figure 4.5, most growth happens before 2030;

all scenarios show a plateau in building energy use between 2030 and 2040 and a decelerating growth afterward as a result of decreasing population and improving efficiency.

In all scenarios, urban residential buildings have the highest share of final energy use (around 40%), given fast urbanization and increasing service demand by urban households. The share of energy use in commercial buildings increases rapidly, especially in the SD and LF scenarios, where the economic structure shifts from manufacturing to service industries.

The CB and SD scenarios reflect potential upper and lower bounds of energy use under different development paths. The high economic growth and resource intensive lifestyle in the CB scenario lead to high building energy use and the annual growth rate between 2010 and 2030 is about 4%, on par with the growth trend in the past decade. The SD scenario sees slow growth in building final energy use with less than 2% growth per year between 2010 and 2030. The CG scenario continues a similar trajectory to the historical path until 2020 (around 4% annual growth) and then the growth slows down as a result of slow growth in low-income provinces. It is also worth noting that the CG scenario is the only one with high population growth and the plateau in final building energy use comes later in the CG scenario compared to other scenarios. The LF and SD scenarios depict inclusive growth and show similar growth pattern, but building energy use in the heterogeneous world grows at a higher rate as exhibited in the LF scenario.

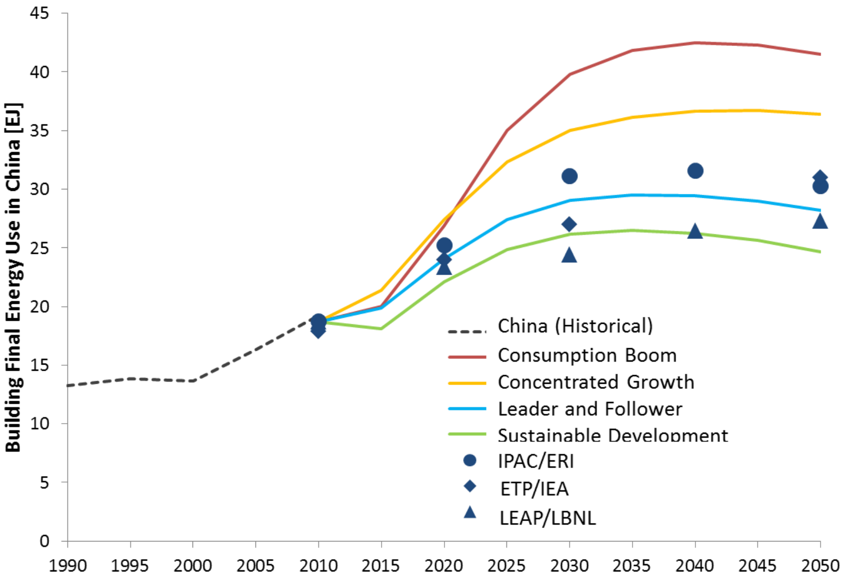

Figure 4.5 Building energy use in China (1990-2050)

Sources: (Jiang et al., 2014; OECD and IEA, 2015; Zhou et al., 2013).

The shape of building energy trajectories and the magnitude of growth differ across studies. This study shows a wider range of building energy use compared to previous studies, as it considers a variety of development paths including the ones with dramatic shift in lifestyle and continuation of rapid floorspace expansion. Studies also show different trajectories of building energy use. The IEA/ETP and LBNL studies exhibit continuous growth until 2050, while the ERI research and all scenarios in this study show a plateau in building energy use before 2050, driven by technological change and decline in population.

4.4.2 Regional trends in final building energy demand

Total building energy use in 2050 varies by more than a factor of 30 across provinces and scenarios. Provinces with large population and economy are generally the large building energy consumers, such as Sichuan, Inner Mongolia, Shandong, and Guangdong.

Regions show different patterns of building energy use in different development paths. In the CB and SD scenarios where provinces converge toward the same level of growth rate at the end of the century, top provinces for building energy use are the same but the development and energy consumption levels differ widely between these two scenarios. In the CG and LF scenarios, provinces pursue heterogeneous development paths and there is a high variation in how individual provinces evolve; top building energy consumers are very different between these two scenarios (see Figure 4.6 and Table B2).

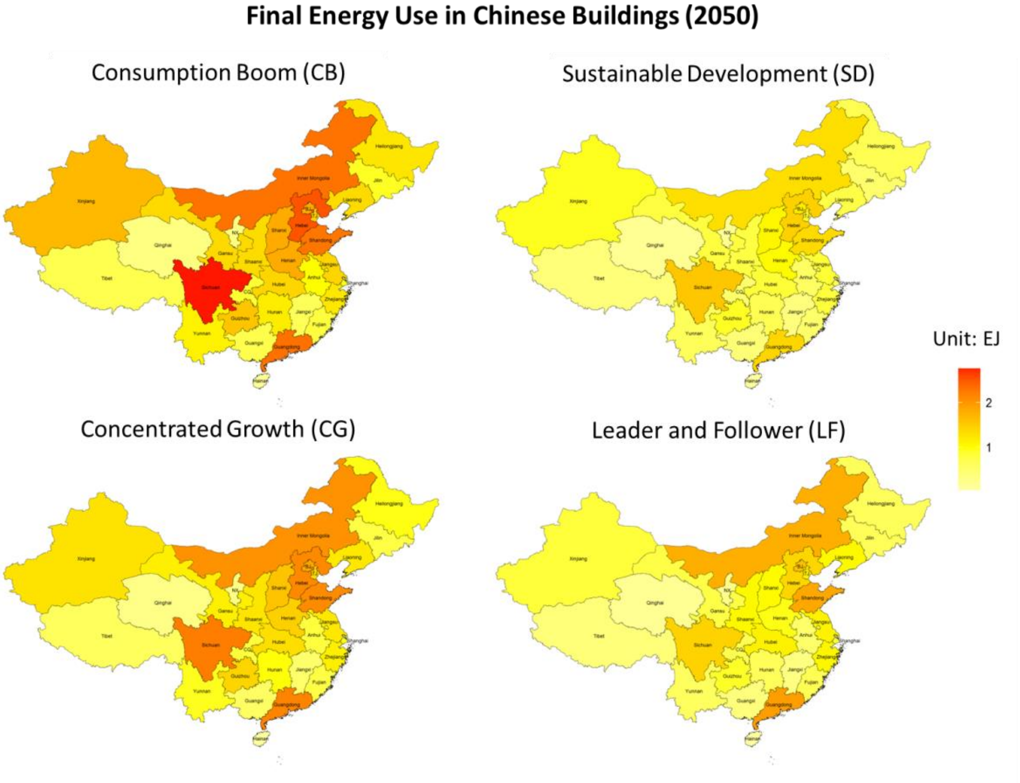

Figure 4.6 Final energy use in Chinese buildings by province (2050)

Building energy demand is normally associated with income growth, but the degree of coupling is uncertain as demographic changes, lifestyles, and technological advancement also affect building energy use (Pérez-Lombard et al., 2008). The four scenarios cover a broad range of alternative development pathways, and therefore, provinces show diverse patterns of coupling between per capita building energy demand and per capita GDP (Figure 4.7).

The coupling between building energy and GDP continues in the next two decades. As observed in all scenarios and all regions, as income grows, building energy consumption grows rapidly before 2030 and then slows down or stabilizes between 2030 and 2050. For example, in the CB and LF scenarios, even though income continues its fast growth track after 2030, per capita energy use only increases slightly. Building energy use is also driven by development pathways; at similar income levels, per capita building energy use and the convergence level across scenarios are different.

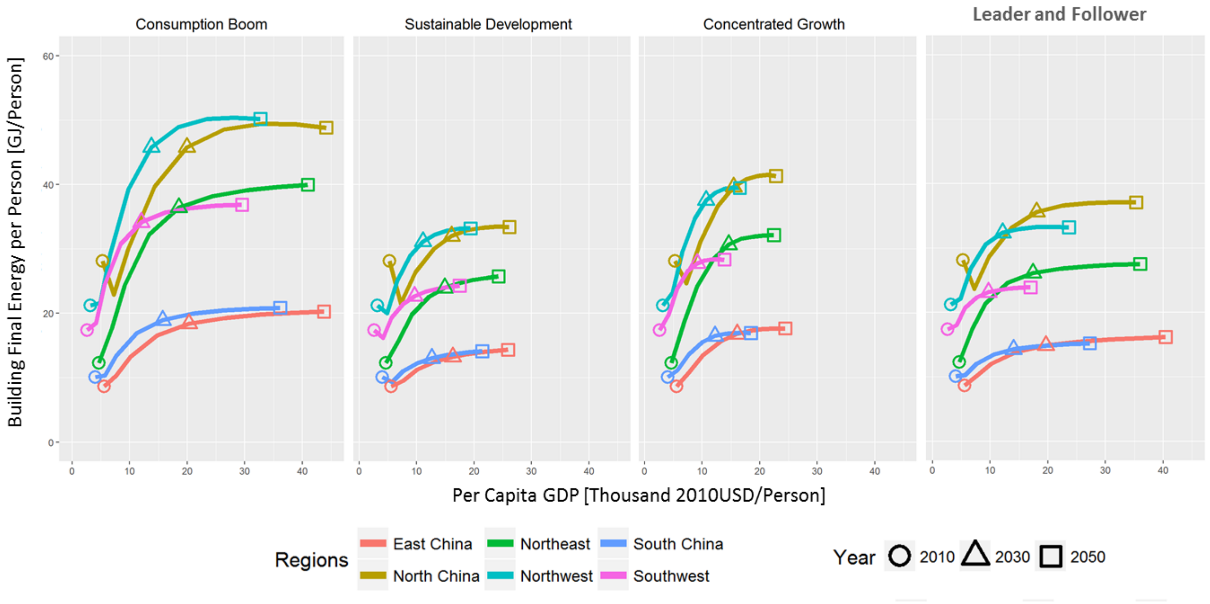

Figure 4.7 Per capita building final energy use and income by region (2010-2050)

Building energy use is climate related. In the warmer regions (e.g. South and East China), the annual building energy use of 10GJ/person is associated with low income levels and 20GJ/person is associated with medium to high income levels. In the colder regions (e.g. North and Northwest China), around 20GJ/person is observed to correlate with low income levels, while 40-50GJ/person is correlated with medium to high income levels[8].

4.4.3 Fuel mix and implications for the electricity sector

Understanding building electricity use is critical to future power system planning. China has experienced the fastest growth in building electricity use among the major economies in the past decade. Between 2010 and 2012, building electricity use in China grew by 3 times. The growing importance of electricity in buildings is associated with rapid increase in the use of appliances and electrical devices. The trend of rapid electrification continues in all scenarios, and electricity become the largest energy source of buildings in 2050, accounting for around 40% of energy used in buildings.

Building electricity use is about half of total electricity use in China in 2050. Although all scenarios show similar trends of rapid electrification, the scale of building electricity consumption is very different across scenarios. Compared to the 15 EJ of building electricity use in 2050 in the CB scenario, building electricity use in the SD scenario is less than 9 EJ in 2050, only 60% of that in the CB scenario. Uncertainty in electricity demand would affect power system planning, investment, and operations. It would also affect China’s mitigation strategies, as the electricity sector is the largest source of GHG emissions in China.

Electricity consumption differs by grid region, reflecting differences in population and GDP as well as economic structure. The North and East China grid regions have the highest level of total electricity consumption, followed by the Central and Southern China grid regions. It is worth noting that the East and North China grid regions also have the highest share of coal-fired power

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[8] Per capita building energy use in North China decreases and then increases, because of fuel switching from traditional biomass to more efficient commercial energy sources.

generation, which associates with high level of GHG and air pollutant emissions. Although the North and East China grid regions have a higher level of total electricity consumption, buildings play a larger role and account for a larger share of electricity use in the Central and Southern China grid regions. Electricity consumption is relatively low in the Northeast and Northwest China grid regions, because of their smaller population scale compared to other grid regions (see Figure 4.8 and Figure B2).

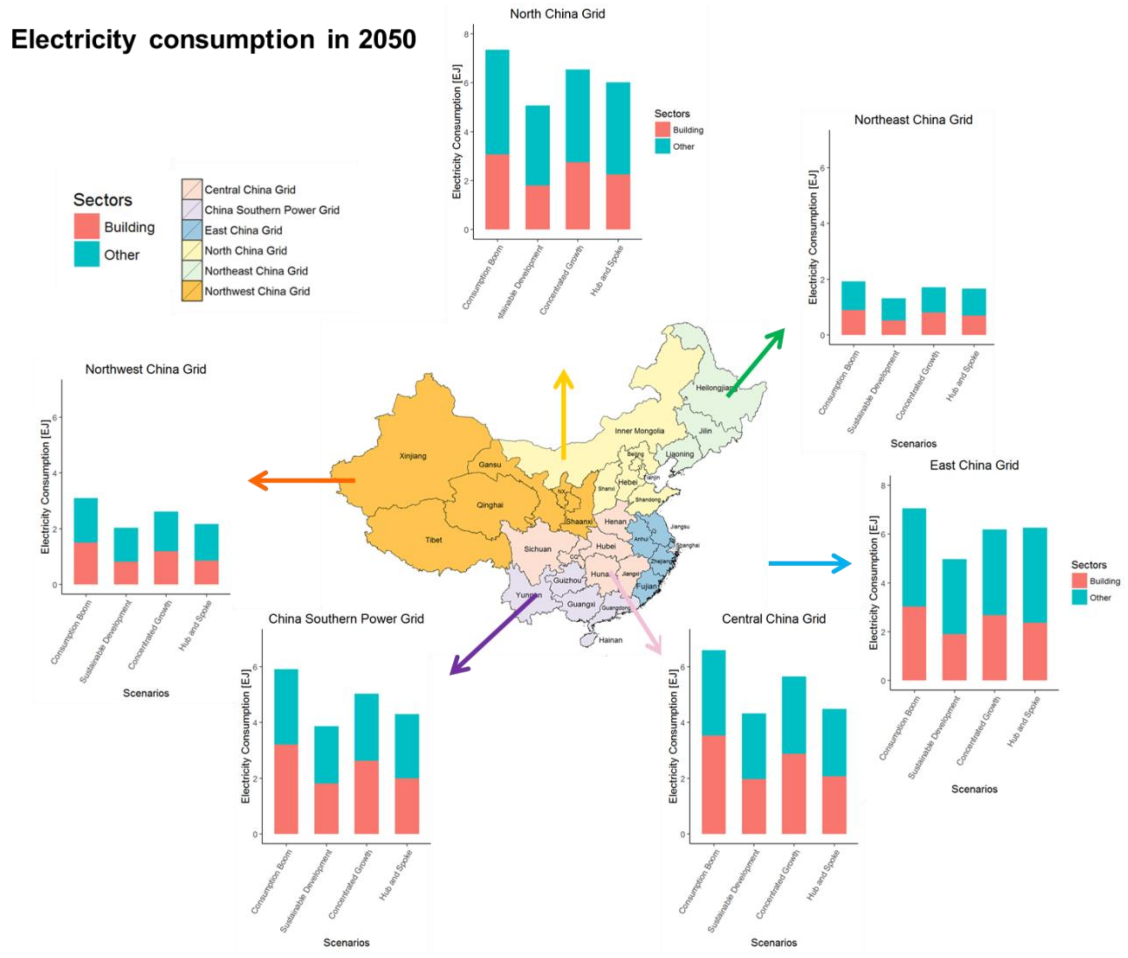

Figure 4.8 Electricity consumption in 2050 by grid region and scenario

Fuel profiles and the level of electrification are different by province, affected by provincial income level, climate condition, end-use service type, and fuel supply. As shown in Figure 4.9, although Beijing and Inner Mongolia are both high-income provinces and fall under the same climate zone, their fuel profiles are very different. In Beijing, 50-60% of building energy is from electricity and natural gas and coal only accounts for 4-8% of total final building energy use, whereas in Inner Mongolia around 20% of building energy is supplied by coal because of its rich coal resources. In Gansu, more than 50% of building energy is from coal, used for space heating, water heating, and cooking services, because Gansu is a low-income province and shifting from fossil fuels to cleaner energy sources happens slower. In Fujian, a southern province without space heating, electricity is the dominant fuel for appliances, lighting, and space cooling, and accounts for 60% of building energy use.

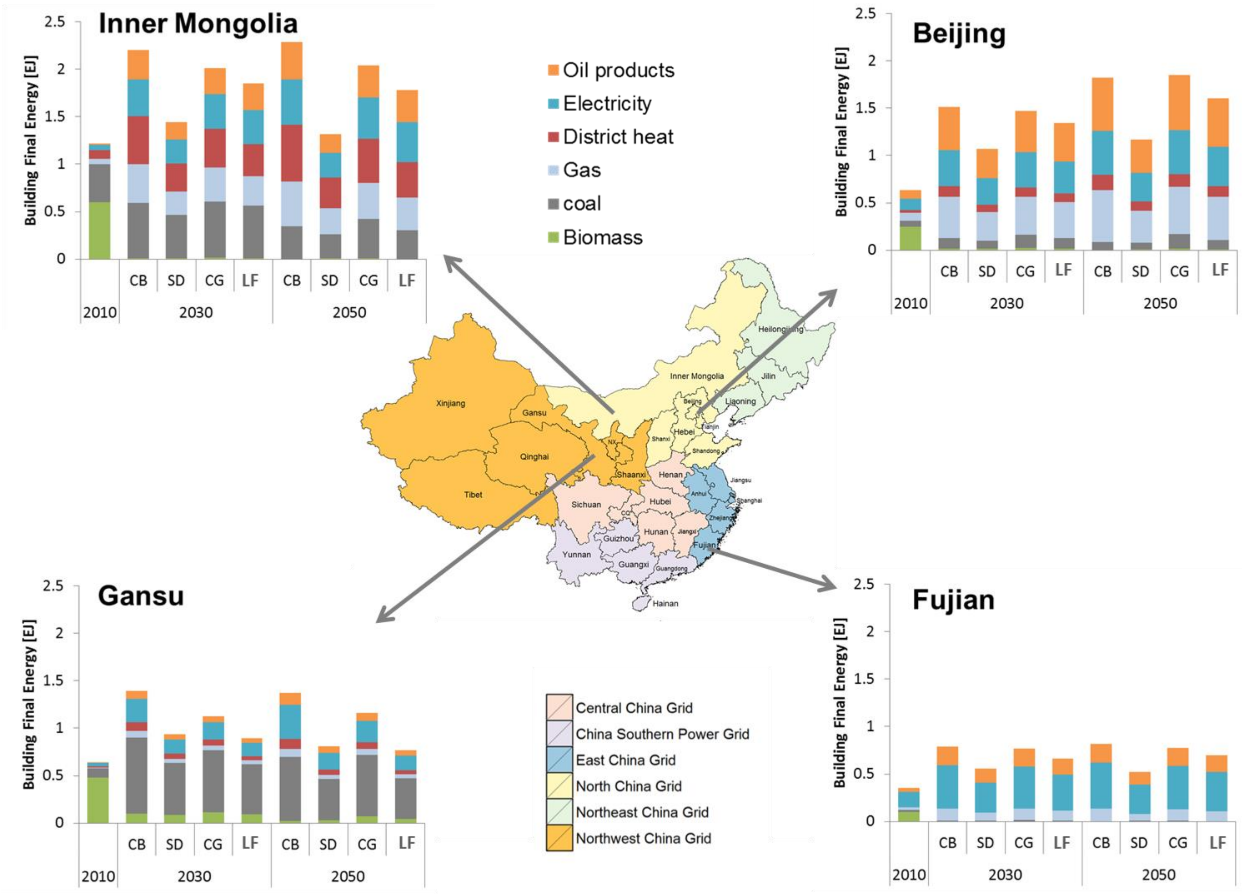

Figure 4.9 Building energy use by fuel at the provincial level

4.5 Conclusions

Understanding the evolution of the Chinese buildings sector is critical but challenging, as China is characterized by very dynamic growth with rapid social and economic changes. Building energy use is also dynamic, affected by architectural design, increasing demand for building services and comfort levels, energy prices, and changes in technologies and their applications; these factors interact and drive building energy consumption in different directions. A thorough analysis of how these factors and China's development would drive building energy use is needed. This paper develops four scenarios depicting plausible paths China would pursue. Distinct development paths would lead to very different levels of building energy consumption in China, ranging between 25 and 42 EJ in 2050.

Some trends are observed across all scenarios. First, there is strong coupling between building energy use and GDP before 2030 and then building energy use would stabilize or decrease even though income continues to grow. Therefore, policy attention needs to be paid to the near to medium term development, as it sets the path for future trajectories of building energy and the level of convergence. Second, the Chinese buildings sector would continue fast electrification and building electricity use would be around half of total electricity use in China. Changing fuel mix in the buildings sector can significantly affect China's future emissions trajectories. Studies have shown that long-term decarbonization in China depends on how fast the end-use sectors switch to electricity and how clean the power sector is. In addition to energy efficiency improvement, the development and analysis of building energy policies need to consider impacts on fuel and service profiles.

The level of future building energy use is strongly correlated with development paths China chooses. The scale of per capita building energy use is very different across scenarios even at the same income level, reflecting the choices of lifestyles, technology advancement, and the style of development. Similarly, although fast electrification is observed across scenarios, the scale of electricity demand is different – ranging from less than 9 EJ in the SD scenario to 15 EJ in the CB scenario. Understanding the evolution of buildings and various pathways is critical to the development of mitigation strategies, as the level of mitigation effort would vary under different development pathways.

Although there are multiple pathways China might pursue, there are two factors that provide impetus for low-carbon growth. One factor is the increasing awareness of air quality. As observed in the historical analysis of Japan and the United States in Chapter 2, major events, such as the oil crises and Fukushima disaster, can help reset the development path by accelerating transition to an energy-efficient economy. Severe air pollution in China might be such opportunity that can help China shift toward low-carbon development. For example, to alleviate air pollution, the State Council of China issued the Air Pollution Prevention and Control Action Plan in 2013 and required key actions to reduce air pollutant emissions, and many of these actions, such as coal control and higher transport efficiency, can also lead to lower energy use and higher energy efficiency. Studies have found that actions for air pollution controls also led to climate change mitigation at the national and local levels (Wang et al., 2016; Zheng et al., 2016). The other driving force is the global effort of climate change. China is seeking a leading role in climate change issues and preparing its industry for next-generation clean energy technologies. In the published 13th Five-Year Plan, China's leadership had identified low-carbon technologies as the technologies for the future, and the advancement of clean technologies can help China become a major supplier and exporter of low-carbon goods in a carbon-constrained world (Hilton, 2016; NDRC, 2016). Although air quality improvement and global climate change mitigation can help motivate China to pursue low-carbon development, there is still an issue in the distribution of development, i.e. whether low-carbon development only occurs in several provinces (i.e. LF scenario) or in all provinces (i.e. SD scenario). Whyte (2014) found out that inequality in China was much more structured by location than by social classes and interest groups, as the market structure left from China's socialist era failed to redirect resources from advanced to backward provinces. Given this institutional barrier, provinces are more likely to follow heterogeneous development paths (i.e. LF scenario) initially and then eventually transition toward the sustainable development path with high economic development and improved institutions.

This study provides a framework of analyzing the future evolution of China at multiple spatial scales. The scenario analysis presented here aims to understand the uncertainty in China's future development and associated energy demand. It serves as a basis for assessing and developing mitigation policies. This study is carried out at a high resolution, providing information at the provincial level, which helps identify hot spots for policy development and implementation. The key findings regarding the future trajectories of the Chinese buildings sector would still hold notwithstanding the assumptions used in this study. However, there are limitations and the study could be improved in the following areas. First, there are multiple ways of quantifying the scenarios. The simplified approach is used in this paper to illustrate how different development paths would result in different levels of energy use and thus require different level of mitigation effort. Future work could consider different approaches of classifying provincial groups to allow for more dynamic changes. Second, this paper focuses on the changes in the buildings sector. While it considers changing energy demand in other sectors in response to population and GDP changes, it does not explicitly consider other drivers such as changes in industrial technology efficiency and penetration of renewable energy technologies in the power sector. Future studies need to specify potential changes in other end-use and energy supply sectors, in order to capture the impact of various development paths on the entire energy system. Finally, this paper does not consider policy impact and the level of effort needed to reach certain climate target. Building on the scenario analysis and the provincial-level modeling developed in this paper, future study can examine impact of energy and climate policies and shed light on the development of building sector policies at national, subnational, and provincial levels.

Chapter 5. Conclusions

5.1 Policy Discussion

Curbing energy consumption in Chinese buildings is critical and creates significant opportunity for global greenhouse gas emissions reduction. It also generates benefits beyond climate change mitigation. Reducing emissions of the buildings sector will have positive impacts on other sectors, most notably the electricity sector, as buildings account for about a quarter of China's electricity consumption and the ratio grows rapidly. Reduction of electricity consumption in buildings could avoid adding capacity in the power sector and translate into additional savings in fossil fuels. Moreover, it can help alleviate the air pollution problem. As the traditional biomass is still the major fuel for rural households in China, switching to cleaner fuels such as natural gas and electricity would alleviate indoor (and local) air pollution and potentially generate significant health impacts. Similarly, reducing coal use in urban households and switching to cleaner fuels in cities will also help improve local air quality. In addition, improving efficiency in urban residential and commercial buildings can reduce cooling loads and associated emissions, as well as mitigate the head island effect.

The Chinese government has developed a wide range of policies to promote building energy efficiency and slow down the growth in building energy use, demonstrated in the Green Building Action Plan and the12th and 13th Five-Year Plans on Building Energy Efficiency (MOHURD, 2012; NDRC and MOHURD, 2013). China's nationally determined contributions also reaffirmed the importance of controlling emissions from the buildings sector through policy measures (NDRC, 2015).

Many studies have indicated that implementing energy efficiency measures in the buildings sector is one of the most cost-effective mitigation options (Lucon et al., 2014; McKinsey, 2010; Ürge-Vorsatz et al., 2015). The wide-scale application of such measures and low-carbon technologies could result in significant emissions reduction. However, achieving large-scale deployment of efficient technologies would require well-designed policies and programs to incentivize and transform the market.

There is a wide range of polices to reduce energy use in buildings at both national and provincial levels. These include mandatory energy codes for urban residential and commercial buildings and a voluntary standard for rural residential buildings. In addition, the Chinese government is also devoting resources to promote green buildings. As one of the world’s largest producers and consumers of appliances, China also developed mandatory minimum efficiency standards for major appliances, lighting, and heating, and cooling equipment, and updated them regularly. China also has voluntary energy efficiency labels and mandatory energy information labels. These policies can help improve the efficiency of the Chinese buildings sector and curb the rising energy use and emissions.

Building energy codes set minimum energy efficiency requirements for building envelope, heating, ventilation, and air conditioning (HVAC) system, power system, and water heating, and the requirements are specific to individual climate zones. The Chinese building energy codes[9], issued by the Ministry of Housing and Urban and Rural Development (MOHURD), are national codes and mandatory for new construction and major renovations in urban residential and

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[9] MOHURD also issued a separate standard on lighting energy efficiency.

commercial buildings[10]. Provinces and cities can issue more stringent building codes themselves. For example, building energy codes in Beijing and Shanghai are more stringent than the national codes applicable to their respective climate zones. Enforcement of buildings energy codes also differs across provinces. Although there are not statistically robust data showing compliance rate for individual provinces, all studies indicated that compliance rates are high in large cities and problematic in smaller cities and towns (Evans et al., 2010; Shui, 2012; Shui et al., 2009).

There are also green buildings rating systems for new construction in China. Two prevailing green building rating systems are the Three-Star certification issued by MOHURD and the Leadership in Energy & Environmental Design certified by the U.S. Green Building Council. The green building rating system goes beyond energy codes requirements and also covers land use, water savings, material savings, indoor environmental quality, and operations and management. Currently, the national and provincial governments provide subsides for green buildings rated by the Three-Star system and the level of subsides varies by province.

The Chinese government has also rolled out large-scale energy efficiency retrofit programs for existing buildings. These programs historically have been focusing on residential buildings in the northern heating zone. During 2005-2010, the Chinese government retrofitted 182 million m^2 of floorspace in 15 northern provinces, and target for 2011-2015 is 400 million m^2. The Chinese government extended the retrofit program and included energy efficiency retrofit of public buildings since 2011. MOHURD also plans to conduct energy efficiency retrofits in 50 million m^2 of building floorspace in residential buildings in the South during 2011-2015 (MOF and

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[10] There are five climate zones in China used for developing standards of the built environment: severe cold, cold, hot summer cold winter, temperate, and hot summer warm winter. The temperate zone is small in terms of geographic areas and does not have its own building energy codes. Buildings in the temperate climate zone follow the energy codes of the hot summer warm winter zone.

MOHURD, 2011; NDRC and MOHURD, 2013). Some provincial governments set more ambitious goal. For example, the Beijing government set the goal of retrofitting 150 million m^2 of building floorspace between 2011 and 2015, roughly equivalent to the total floor area retrofitted in the northern China during 2006-2010 (BMCCAE, 2011; MOHURD, 2012).

China first adopted minimum energy performance standards (MEPS) in 1989. As of 2013, China has MEPS for over 50 products and a mandatory energy information label (i.e. China Energy Label) for 28 products (Khanna et al., 2013; Lin, 2002; Zeng, 2015; Zhou, 2010). China is the largest producers and consumers of lighting products, appliances, and equipment in the world. The rapid uptake of appliances and electronics into Chinese households and offices has driven a sustained increase in Chinese electricity use, and China overtook the United States to become the world's largest electricity consumer in 2011 (Zeng, 2015). The MEPS and energy labels are critical to reducing energy consumption of appliances in China, and these programs are updated and revised regularly to include more product categories and to reflect technology improvement to those products in the market. All provinces follow the same requirements of MEPS and energy labels. The compliance rate, however, differs across provinces, due to local economic situation, level of standardization in energy efficiency labeling in local markets, and the level of law enforcement in local markets (Khanna et al., 2013; Zhou, 2010).

The existing policies, however, may not be enough to achieve deep decarbonization in China. Studies assessing deep decarbonization pathways or options of keeping the global average temperature rise below 2 degrees Celsius all found that together with low-carbon transitions in other sectors, major transformation in the Chinese buildings sector is needed to achieve deep decarbonization globally (IEA, 2016; Jiang et al., 2016; Teng et al., 2015). In particular, two measures would help the transitions in China – promotion of nearly zero-energy buildings and electrification of the buildings sector along with decarbonization of the electricity sector. However, the feasibility of applying these two measures in China at the large scale is unknown and needs to be further studied.

With population and economic growth, and increased demand for energy services, the Chinese buildings sector becomes increasingly important to global climate change mitigation. This dissertation explores the evolution of the Chinese buildings sector under different development pathways, while accounting for provincial heterogeneity. It shows that development pathways and heterogeneity across provinces contribute significantly to building energy consumption. Distinct development paths can lead to very different levels of building energy consumption in China, ranging between 25 and 42 EJ in 2050. Policy options need to be specific to regional conditions as well as development paths.

5.2 Future Work

This dissertation develops a framework to examine the evolution of the buildings sector in China. Building on this framework, future work could be extended to the following areas. First, we can build policy options into the scenario analysis and improve the understanding of policy impacts on future building energy demand and greenhouse gas emissions. In particular, the future study needs to explore how much emissions reduction can be achieved using the existing policies under different development pathways and to what extent the new policy measures are needed to achieve deep decarbonization.

Second, emerging from the scenario analysis, there are several factors that could potentially change the trajectories of building energy but how these factors would evolve and interact with the building energy demand is unclear. These factors include the increasing middle class, aging society, and shift in energy use behavior. Future work can dive into these factors and understand how they can shape the future energy demand in China.

Third, the analysis of this dissertation focuses on the buildings sector, but the scenario framework can also be applied to the whole economy in China. It would be meaningful to advance the scenario work by extending it to other sectors and see the implications for China’s total energy demand and greenhouse gas emissions, as well as impacts on achieving the global mitigation target.

Appendix A. Supporting Information for Chapter 3

Table A1. Historical data on per capita floorspace and income

Province	Code	Per Capita GDP (2010 USD)			Per Capita Urban Residential Floorspace (m^2)			Per Capita Rural Residential Floorspace (m^2)			Per Capita Commercial Floorspace (m^2)		
		1978	2010	Average Annual Growth Rate	1978	2010	Average Annual Growth Rate	1978	2010	Average Annual Growth Rate	1996	2006	Average Annual Growth Rate
Anhui	AH	200	2801	9%	8.3	31.6	4%	8.5	32.1	4%	1.3	2.8	8%
Beijing	BJ	1032	9710	7%	6.7	21.7	4%	9.2	39.1	5%	9.0	14.5	5%
Chongqing	CQ	211	3708	9%	4.8	30.4	6%	11.5	36.0	4%	2.1	4.8	9%
Fujian	FJ	224	5387	10%	10.5	38.5	4%	6.1	47.5	7%	1.8	3.5	7%
Guangdong	GD	303	5949	10%	7.1	34.8	5%	8.7	29.5	4%	2.2	5.9	10%
Gansu	GS	287	2173	7%	5.9	27.5	5%	12.3	20.7	2%	1.7	4.5	10%
Guangxi	GX	184	2802	9%	9.5	34.4	4%	4.4	34.2	7%	1.6	2.8	6%
Guizhou	GZ	144	1786	8%	7.6	28.7	4%	7.3	26.8	4%	0.9	1.0	1%
Henan	HA	190	3314	9%	6.3	34.0	5%	9.5	35.0	4%	1.5	3.4	9%
Hubei	HB	272	3763	9%	6.4	32.9	5%	14.0	41.3	3%	2.7	4.3	5%
Hebei	HE	299	3827	8%	12.9	30.5	3%	8.8	32.2	4%	1.7	3.2	7%
Hainan	HI	256	3207	8%	3.5	24.1	6%	15.3	23.2	1%	1.6	4.2	10%
Heilongjiang	HL	461	3651	7%	6.0	25.3	5%	7.5	23.3	4%	3.4	5.7	5%
Hunan	HN	235	3295	9%	5.4	31.2	6%	10.5	41.7	4%	1.7	3.7	8%
Jilin	JL	315	4259	8%	4.1	28.4	6%	7.8	22.9	3%	2.9	4.8	5%
Jiangsu	JS	353	7106	10%	7.6	33.4	5%	9.7	46.3	5%	2.7	7.6	11%
Jiangxi	JX	226	2859	8%	11.0	38.9	4%	7.4	40.3	5%	1.5	3.0	7%

Liaoning	LN	557	5695	8%	6.5	30.2	5%	10.9	27.9	3%	5.3	7.1	3%
Inner Mongolia	NM	263	6373	10%	3.5	30.2	7%	10.0	22.5	3%	2.4	5.6	9%
Ningxia	NX	302	3603	8%	4.5	29.3	6%	7.9	23.3	3%	2.8	5.5	7%
Qinghai	QH	351	3238	7%	7.3	28.2	4%	5.1	20.7	4%	2.1	2.1	0%
Sichuan	SC	216	2883	8%	11.0	30.8	3%	7.0	35.8	5%	2.2	3.8	6%
Shandong	SD	260	5514	10%	7.1	34.6	5%	9.8	35.7	4%	2.4	6.1	10%
Shanghai	SH	2051	10061	5%	8.4	35.1	5%	15.7	59.7	4%	8.0	15.0	6%
Shaanxi	SN	241	3659	9%	8.7	28.2	4%	8.1	31.7	4%	1.8	3.5	7%
Shanxi	SX	300	3475	8%	12.9	28.0	2%	9.4	28.7	4%	2.5	3.8	4%
Tianjin	TJ	946	9585	8%	5.8	31.6	5%	9.0	28.7	4%	7.6	8.9	2%
Xinjiang	XJ	262	3359	8%	9.6	27.5	3%	5.2	23.5	5%	2.6	5.0	7%
Tibet	XZ	309	2283	6%	9.0	33.6	4%	10.7	25.4	3%	1.1	0.7	-5%
Yunnan	YN	184	2119	8%	6.6	34.9	5%	7.7	28.9	4%	1.1	2.3	7%
Zhejiang	ZJ	273	6870	11%	9.1	35.9	4%	21.1	60.1	3%	2.9	6.5	9%

Sources: (NBSC, 1991-2014, 1999).

Table A2. Annual new construction in China (2010-2050)

Data source		2010-2014	2015-2030	2030-2050
Historical Data	NBSC (2015)	Total: 2.8-3.6 billion m^2 Residential: 1.7-2 billion m^2	--	--
Projections (Literature)	Hong et al. (2016)	--	Total: 2-2.4 billion m^2	Total: 0.7-1.4 billion m^2
	Woetzel et al. (2009)	--	Total Urban: 2.4-3.1 billion m^2 Urban Residential: 1-1.2 billion m^2	--
	Berkelmans and Wang (2012)	--	Urban Residential: 1.5-1.7 billion m^2	Urban Residential: 1.1-1.5 billion m^2
	Hu et al. (2010)	--	Urban Residential: 0.9-1.4 billion m^2	Urban Residential: 0.3-0.9 billion m^2
Projections (This Paper)	Low growth scenario	--	Total: 1.4-2.3 billion m^2 Urban Residential: 0.8-1.1 billion m^2	Total: 1-1.4 billion m^2 Urban Residential: 0.6-0.8 billion m^2
	Medium growth scenario	--	Total: 2-3.3 billion m^2 Urban Residential: 1.1-1.5 billion m^2	Total: 1.3-2 billion m^2 Urban Residential: 0.8-1.1 billion m^2
	High growth scenario	--	Total: 3-4.1 billion m^2 Urban Residential: 1.4-1.7 billion m^2	Total: 1.8-3 billion m^2 Urban Residential: 1-1.4 billion m^2

Sources: (Berkelmans and Wang, 2012; Hong et al., 2016; Hu et al., 2010; NBSC, 2015; Woetzel et al., 2009).

Section A1. Likelihood of Different Floorspace Pathways by Province in Three Growth Scenarios

Anhui

Urban Residential: The current per capita urban residential floorspace in Anhui is around 34 m^2 and shows an upward growth trend. In the low growth scenario, per capita floorspace grows slowly toward the Japanese level. In the medium growth scenario, driven by the development of local economy and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches the Norwegian level. In the high growth scenario, per capita floorspace eventually reaches the Canadian level of around 60 m^2, as Anhui lacks major cities and the demand for floorspace growth cannot be sustained.

Rural Residential: Low income level in Anhui results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and reaches the levels of Belgium, Sweden, and Canada in the low, medium, and high growth scenarios, respectively.

Commercial: Per capita GDP in Anhui is lower than the national average. Low service sector demand results in slow growth in commercial floorspace and per capita commercial floorspace reaches the levels of Italy, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Beijing

Urban Residential: Due to high population density and limited land areas, in all three growth scenarios, per capita urban residential floorspace in Beijing grows slowly and reaches the lower boundaries of the three scenarios, 30, 40, and 50 m^2.

Rural Residential: Rural households in Beijing do not have land supply constraint and have high income levels. As a result, per capita rural residential floorspace is high in Beijing. Currently, it is about 40 m^2, exceeding per capita residential floorspace in most west European countries and Japan. It is expected to continue to grow and reaches the Swedish, Danish, and U.S. levels in the long run in the low, medium, and high scenarios, respectively.

Commercial: Demand for commercial buildings in Beijing grew rapidly in the past few years and is expected to continue to grow due to high growth in the service sector. The current per capita commercial floorspace in Beijing is close to 15 m^2, exceeding that of London and Tokyo. In the low and medium growth scenarios, per capita commercial floorspace in Beijing reaches the Osaka and New York levels, respectively. In the high growth scenario, although the high demand still exists, limited land areas constrain the development, and per capita commercial floorspace in Beijing reaches the Copenhagen level in the long term.

Chongqing

Urban Residential: The current per capita urban residential floorspace in Chongqing is around 30 m^2 and shows an upward growth trend. In the low growth scenario, per capita floorspace grows slowly toward the level of Tokyo. In the medium growth scenario, driven by the development of local economy and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches 45 m^2. In the high growth scenario, per capita floorspace eventually reaches the Copenhagen level of around 50 m^2, as Chongqing has strong policies in place to control the oversupply of floorspace.

Rural Residential: Income growth in rural areas in Chongqing results in moderate growth in per capita floorspace, which reaches the Japanese, Norwegian, and Canadian levels in the low, medium, and high growth scenarios, respectively.

Commercial: Although Chongqing is a major city in Southwest China, the growth in service demand and commercial floorspace is lower than that in Beijing and Shanghai. In addition, the vacancy rate of commercial buildings in Chongqing is high. As a result, per capita commercial floorspace in Chongqing has only limited growth and in the long run reaches lower boundaries of saturation levels in the low, medium, and high scenarios.

Fujian

Urban Residential: The current per capita urban residential floorspace in Fujian is around 39 m^2 and shows an upward growth trend. In the low growth scenario, per capita floorspace reaches the Japanese level of 40 m^2. In the medium growth scenario, driven by high income growth and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches 55 m^2. In the high growth scenario, the income-driven growth in floorspace continues and eventually reaches the U.S. level of around 70 m^2.

Rural Residential: The current per capita rural residential floorspace in Fujian is relatively high, approximately 51 m^2 in 2012, and may continue to grow. The Government of Fujian developed regulations to limit floorspace per rural household to 300 m^2 for new construction (Government of Fujian, 2011). In the low growth scenario, the saturation level is close to the Danish level, higher than per capita residential floorspace in most European countries and Japan. In the medium and high growth scenarios, per capita rural residential floorspace reaches the Canadian and U.S. levels in the long run.

Commercial: Although per capita GDP in Fujian is higher than the national average, the share of service industry in GDP is only 42%. Low service sector demand results in slow growth in commercial floorspace and per capita commercial floorspace reaches the levels of Italy, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Guangdong

Urban Residential: The current per capita urban residential floorspace in Guangdong is around 35 m^2 and shows an upward growth trend. In the low growth scenario, per capita floorspace grows slowly toward the Japanese level. In the medium growth scenario, driven by the development of local economy and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches the Norwegian level. In the high growth scenario, per capita floorspace eventually reaches the Canadian level of around 60 m^2, as the demand for floorspace growth is driven by local economic development and constrained by land supply at the same time.

Rural Residential: Although Guangdong has high income levels, the disparity between coastal and mountain areas results in low per capital floorspace in rural areas, which is lower than the national average. In addition, the limited land supply further constrains future development. Per capita rural residential floorspace in Guangdong is currently 30 m^2, close to the UK level, and in the low, medium, and high growth scenarios it reaches the Belgian, Swedish, and Canadian levels in the long term.

Commercial: Guangdong has high income level and rapid growth in the service sector GDP. As a result, commercial building floorspace in Guangdong grows rapidly. The saturation demand for per capita commercial floorspace is close to the Belgian level in the low growth scenario, the Dutch level in the medium growth scenario, and the U.S. level in the high growth scenario.

Gansu

Urban Residential: The current per capita urban residential floorspace in Gansu is around 31 m^2 and shows an upward growth trend. On the one hand, the real estate sector is one of the major industries in Gansu and contributed to more than 20% of local tax revenues in 2015, which provides incentives for the local government to encourage new construction (Government of Gansu, 2016). On the other hand, lacking major cities and slower economic growth contributed to slower increase in housing demand and the buildup of inventory in the housing market was more than 26 months, which has negative impact on future floorspace expansion. Affected by these factors, per capita urban residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively).

Rural Residential: Low income level results in low housing demand in rural areas. Per capita rural residential floorspace in Gansu has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Gansu is adjusting its industrial structure, and the share of service industry in total GDP continues to rise. In 2015, the service industry accounts for more than 50% of total GDP in Gansu. The demand for commercial floorspace continues to grow, reaching the Belgian level in the long term in the low growth scenario. However, lacking major cities and businesses, the growth is limited. Per capita commercial floorspace in the long term reaches the Japanese level in the medium growth scenario and the Finnish level in the high growth scenario.

Guangxi

Urban Residential: The current per capita urban residential floorspace in Guangxi is around 35 m^2 and expected to continue to grow. However, lacking key cities and industries in Guangxi may limit floorspace growth in the long term. In the low growth scenario, per capita floorspace grows slowly toward the Japanese level. In the medium growth scenario, driven by the demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches the level of Sweden. In the high growth scenario, per capita floorspace eventually reaches the Canadian level of around 60 m^2.

Rural Residential: Per capita rural residential floorspace in Guangxi is 35 m^2 in 2011 and exceeds the current level of floorspace in UK and Belgium. It also grew rapidly, rising from 24 m^2 in 2001 to 35 m^2 in 2011. The high growth is expected to continue. In the low, medium, and high growth scenarios, per capita rural residential floorspace reaches the saturation levels of 40, 50, and 60 m^2, respectively.

Commercial: Per capita GDP in Guangxi is lower than the national average. Low service sector demand results in slow growth in commercial floorspace and per capita commercial floorspace reaches the levels of Italy, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Guizhou

Urban Residential: Similar to Gansu, lacking major cities and low economic growth lead to slow growth in housing demand in Guizhou. Per capita urban residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively).

Rural Residential: Low income level results in low housing demand in rural areas. Per capita rural residential floorspace in Guizhou has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Per capita GDP in Guizhou is lower than the national average. Low service sector demand results in slow growth in commercial floorspace and per capita commercial floorspace reaches the levels of Italy, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Henan

Urban Residential: The current per capita urban residential floorspace in Henan is around 34 m^2 and expected to continue to grow. In the low growth scenario, per capita floorspace grows slowly toward the Japanese level. Per capita GDP in Henan is lower than the national average, and the low economic growth may slow down the demand for housing in the long term. In the medium and high growth scenarios, per capita urban residential floorspace has limited growth and reaches the lower boundaries of 45 and 60 m^2, respectively.

Rural Residential: The current per capita rural residential floorspace in Henan is 35 m^2 and already exceeds per capita residential floorspace in UK and Belgium. However, low income level results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and reaches 40, 45, and 60 m^2 in the low, medium, and high growth scenarios, respectively.

Commercial: Per capita GDP in Henan is lower than the national average. Lacking major cities and businesses results in low demand for commercial floorspace and per capita commercial floorspace reaches the levels of Italy, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Hubei

Urban Residential: Per capita urban residential floorspace in Hubei is 37 m^2 in 2015 and exceeds the current level of floorspace in UK and Belgium (Zeng et al., 2016). In the low growth scenario, per capita floorspace grows slowly toward the Japanese level. In the medium growth scenario, driven by the development of local economy and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches the Norwegian level. In the high growth scenario, per capita floorspace eventually reaches the Canadian level of around 60 m^2.

Rural Residential: Per capita rural residential floorspace in Hubei is high, on average over 41 m^2 in 2010. In some areas, it is even close to 48 m^2 (Wuhan Bureau of Statistics, 2010). As income continues to grow, per capita floorspace in rural areas is expected to keep rising. In the low growth scenario, it reaches the Swedish level, whereas it reaches Danish and U.S. levels in the medium and high growth scenarios.

Commercial: Service industry accounts for more than 50% of Hubei's total GDP. Hubei also has the target of becoming the financial and logistics center of Central China, which contributes to future growth in commercial floorspace. In the low, medium, and high growth scenarios, the saturation level of per capita commercial floorspace is close to the current level in Belgium, Sweden, and Denmark, respectively.

Hebei

Urban Residential: Low income level results in relatively slow floorspace growth in Hebei compared to high-income provinces. Although the Chinese government established a new special economic zone in Hebei, the impact is more likely to be local, not at the provincial level. In the low growth scenario, per capita urban residential floorspace grows slowly toward the Belgium level. In the medium and high growth scenarios, per capita urban residential floorspace has limited growth and reaches the lower boundaries of 45 and 60 m^2, respectively.

Rural Residential: Low income level in Hebei results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and reaches the level of Japan, Sweden, and Canada in the low, medium, and high growth scenarios, respectively.

Commercial: Per capita GDP in Hebei is lower than the national average. Lacking major cities and businesses results in low demand for commercial floorspace and per capita commercial floorspace reaches the levels of Italy, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Hainan

Urban Residential: Low income level and limited land supply constrain floorspace growth in Hainan. Per capita urban residential floorspace in the long term reaches lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2, respectively).

Rural Residential: Low income level and limited land areas constrain housing development in Hainan. Per capita rural residential floorspace in Hainan has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Service sector is the backbone of the industrial sector in Hainan, accounting for more than half of the province’s total GDP. The demand for commercial floorspace continues to grow, reaching the Belgian level in the long term in the low growth scenario. However, lacking major cities and businesses other than tourism, the growth is limited in the long term. Per capita commercial floorspace in the long term reaches the Japanese level in the medium growth scenario and the Finnish level in the high growth scenario.

Heilongjiang

Urban Residential: Northeast China, as a base for heavy industry, suffered high unemployment and slow economic growth in the past two decades, which resulted in low demand for housing. The situation may persist as over-capacity in heavy industry is pervasive and the share of service industry in regional GDP is small (The Economist, 2014). Per capita urban residential floorspace in the long term reaches lower boundaries in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2, respectively).

Rural Residential: Low income growth results in low housing demand in rural areas. Per capita rural residential floorspace in Heilongjiang has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Due to the growth in the early stage of China's development, per capita commercial floorspace in Heilongjiang today is higher than the national average. However, the economic turndown would lead to low demand for commercial buildings. Per capita commercial floorspace in the long term reaches lower boundaries in the low, medium, and high growth scenarios.

Hunan

Urban Residential: Per capita urban residential floorspace in Hunan is 31 m^2 in 2015, which exceeds the current level of floorspace in UK; it is expected to continue to grow due to economic growth. In the low growth scenario, per capita floorspace grows slowly toward the Japanese level. In the medium growth scenario, driven by the development of local economy and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches the Norwegian level. In the high growth scenario, per capita floorspace eventually reaches the Canadian level of around 60 m^2.

Rural Residential: Per capita rural residential floorspace in Hunan is high, on average around 42 m^2 in 2010. As income continues to grow, per capita floorspace in rural areas is expected to keep rising. In the low growth scenario, it reaches the Swedish level in the long term, whereas it reaches Danish and U.S. levels in the medium and high growth scenarios.

Commercial: The demand for commercial floorspace continues to grow, as Hunan is adjusting its industrial structure and encouraging the growth in the service sector. However, lacking major cities and businesses, the growth is limited in the long term. Per capita commercial floorspace in the long term reaches the Belgian, Japanese, and Finnish levels in the low, medium, and high growth scenarios, respectively.

Jilin

Urban Residential: Northeast China, as a base for heavy industry, suffered high unemployment and slow economic growth in the past two decades, which resulted in low demand for housing. The situation may persist as over-capacity in heavy industry is pervasive and the share of service industry in regional GDP is small (The Economist, 2014). Per capita urban residential floorspace in the long term reaches lower boundaries in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2, respectively).

Rural Residential: Low income growth results in low housing demand in rural areas. Per capita rural residential floorspace in Jilin has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Due to the growth in the early stage of China's development, per capita commercial floorspace in Jilin today is higher than half of provinces in China. However, the economic turndown would lead to low demand for commercial buildings. Per capita commercial floorspace in the long term reaches lower boundaries in the low, medium, and high growth scenarios.

Jiangsu

Urban Residential: Jiangsu has strong local economy and the income level is higher than most provinces. There are also several major cities in Jiangsu, further driving the demand for urban housing. In the low growth scenario, per capita floorspace follows the upper boundary of growth and reaches the Japanese level. In the medium growth scenario, driven by high income growth and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches the level of Denmark. In the high growth scenario, the income-driven growth in floorspace continues and eventually reaches the U.S. level of around 70 m^2,

Rural Residential: Per capita rural residential floorspace in Jiangsu is high, on average over 46 m^2 in 2010, and it grew to 55 m^2 in 2015. Jiangsu is one of the provinces with highest income levels. Driven by income growth, per capita floorspace is expected to grow fast. In the low, medium, and high growth scenarios, per capita rural residential floorspace in Jiangsu reaches per capita residential floorspace level in Canada, U.S., and Australia, respectively.

Commercial: Per capita GDP in Jiangsu is among Top 5 in China and the current per capita commercial floorspace is among the highest in Chinese provinces. Jiangsu also has strong growth potential, with its diversified industrial structure and high demand for service industry. Per capita commercial floorspace in Jiangsu grows to high levels in the long term, reaching the current level of Belgium, Sweden, and the United States.

Jiangxi

Urban Residential: The current per capita urban residential floorspace in Jiangxi is 40 m^2 and exceeds the current level of floorspace in UK, Belgium, France, Germany, and Japan. In the low growth scenario, per capita floorspace grows slowly toward the Swedish level. In the medium growth scenario, low income level in Jiangxi limits the demand for housing and per capita floorspace reaches the Norwegian level. In the high growth scenario, per capita floorspace eventually reaches the Canadian level of around 60 m^2.

Rural Residential: Per capita rural residential floorspace in Jiangxi in 2013 is 49 m^2, higher than the national average. However, per capita GDP in Jiangxi is lower than the national average, which may limit the growth in the long term. Per capita rural residential floorspace grows to 55, 60, and 70 m^2 in the low, medium, and high growth scenarios, respectively.

Commercial: Per capita GDP in Jiangxi is lower than the national average. Lacking major cities and businesses results in low demand for commercial floorspace, and per capita commercial floorspace reaches the lower boundaries in the long term in the low, medium, and high growth scenarios.

Liaoning

Urban Residential: Northeast China, as a base for heavy industry, suffered high unemployment and slow economic growth in the past two decades, which resulted in low demand for housing. The situation may persist as over-capacity in heavy industry is pervasive and the share of service industry in regional GDP is small (The Economist, 2014). Per capita urban residential floorspace in the long term reaches lower boundaries in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2, respectively), as the current per capita urban residential floorspace in Liaoning is over 30 m^2.

Rural Residential: Low income growth results in low housing demand in rural areas. Per capita rural residential floorspace in Liaoning has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Due to the growth in the early stage of China's development, per capita commercial floorspace in Liaoning today is among Top 10 in China. However, the economic turndown would decrease the demand for commercial buildings. In the low, medium, and high growth scenarios, the saturation level of per capita commercial floorspace reaches the Belgium, Japanese, and Finnish levels, respectively.

Inner Mongolia

Urban Residential: Inner Mongolia has abundant natural resources and is experiencing rapid economic growth. It also has large land areas for farming and grazing. Traditional lifestyle leads to slow growth in floorspace in Inner Mongolia despite its high income levels. Per capita urban residential floorspace in the long term reaches lower boundaries in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2, respectively), as the current per capita urban residential floorspace in Liaoning is over 30 m^2.

Rural Residential: Different from southern China, a large share of rural area in Inner Mongolia is grazing area and has slow growth in building floorspace. Per capita rural residential floorspace in the long term reaches lower boundaries in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2, respectively)

Commercial: Per capita commercial floorspace in Inner Mongolia today is higher than the national average, so is per capita GDP. However, lacking major cities and businesses may lead to low demand for commercial buildings in the future. Per capita commercial floorspace in the long term reaches the level of Belgium, Japan, and Finland in the low, medium, and high growth scenarios, respectively.

Ningxia

Urban Residential: Lacking major cities and low income level lead to slow increase in housing demand in Ningxia. Per capita urban residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively), given that the current per capita floorspace is 31 m^2.

Rural Residential: Low income level results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Per capita commercial floorspace in Ningxia today is higher than the national average. However, lacking major cities and businesses may lead to low demand for commercial buildings. Per capita commercial floorspace in the long term reaches the level of Belgium, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Qinghai

Urban Residential: Lacking major cities and low income level lead to slow increase in housing demand in Qinghai. Per capita urban residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively), given that the current per capita floorspace is 31 m^2.

Rural Residential: Low income level results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Per capita GDP in Qinghai is lower than the national average. Lacking major cities and businesses results in low demand for commercial floorspace and per capita commercial floorspace reaches the lower boundaries in the long term in the low, medium, and high growth scenarios.

Sichuan

Urban Residential: The current per capita urban residential floorspace in Sichuan is 31 m^2 and exceeds per capita residential floorspace in UK. However, low income level leads to low housing demand in Sichuan. Per capita urban residential floorspace has limited growth and reaches 35, 45, and 60 m^2 in the low, medium, and high growth scenarios, respectively.

Rural Residential: The current per capita rural residential floorspace in Sichuan is 36 m^2 and already exceeds per capita residential floorspace in UK and Belgium. However, low income level results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and reaches 40, 45, and 60 m^2 in the low, medium, and high growth scenarios, respectively.

Commercial: Per capita GDP in Sichuan is lower than the national average. Although the capital city in Sichuan, Chengdu, is one of the biggest cities in West China, the high vacancy rate of commercial buildings in Chengdu limits future development (Miner, 2015). In the low, medium, and high growth scenarios, the saturation level of per capita commercial floorspace is close to the current level in Belgium, UK, and Finland, respectively.

Shandong

Urban Residential: The current per capita urban residential floorspace in Shandong is 35 m^2, which exceeds per capita residential floorspace in UK and is close to the level of Belgium. Income growth and demand for higher quality of life lead to housing growth in Shandong. Per capita urban residential floorspace reaches 40 and 50 m^2 in the low and medium growth scenarios, respectively. However, the growth is not unlimited; in the high growth scenario per capita urban residential floorspace in Shandong reaches the Canadian level in the long term.

Rural Residential: The current per capita rural residential floorspace in Shandong is 36 m^2, which exceeds per capita residential floorspace in UK and Belgium. Income growth and demand for higher quality of life lead to housing growth in Shandong. Per capita rural residential floorspace reaches 40 and 50 m^2 in the low and medium growth scenarios, respectively. However, the growth is not unlimited; in the high growth scenario per capita rural residential floorspace in Shandong reaches the Canadian level in the long term.

Commercial: Shandong has high income level and consumption demand. It is also a coastal province, which facilitates trade and economic development. In the low, medium, and high growth scenarios, the saturation level of per capita commercial floorspace is close to the current level in Belgium, Sweden, and the United States, respectively.

Shanghai

Urban Residential: The current per capita urban residential floorspace in Shanghai is over 35 m^2 and exceeds that in Tokyo and Paris. Since the current per capita floorspace in Shanghai exceeds the selected saturation levels in the low growth scenario, we assume that it continues to growth reaches the level of Berlin in the low scenario and the level of Copenhagen in the medium growth scenario. In the high growth scenario, per capita urban residential floorspace eventually reaches the Sydney level of around 55 m^2.

Rural Residential: The current per capita rural residential floorspace in Shanghai is close to 60 m^2, which is higher than that of most countries except for the United States and Australia. In the low growth scenario, in the long term it reaches the current level of per capita residential floorspace in the United States, whereas the saturation level in the high growth scenario is close to the current level of per capita residential floorspace in Australia.

Commercial: Demand for commercial buildings in Shanghai grew rapidly in the past few years and is expected to continue to grow due to high growth in the service sector. The current per capita commercial floorspace in Shanghai is 15 m^2, exceeding that of London and Tokyo. In the low, medium, and high growth scenarios, per capita commercial floorspace in Shanghai reaches the Osaka, New York, and Sydney levels, respectively.

Shaanxi

Urban Residential: Slow income growth leads to slow increase in housing demand in Shaanxi. Per capita urban residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively), given that per capita floorspace is 31 m^2 in 2015.

Rural Residential: Per capita rural residential floorspace in Shaanxi grew rapidly in the past five years and reached 45 m^2 in 2016, higher than that in Japan and countries in West Europe. In the low growth scenario, the saturation floorspace is close to the Swedish level, and in the medium and high growth scenarios, it reaches the Danish and U.S. levels, respectively.

Commercial: Service industry grew fast in Shaanxi and the growth rate is higher than the national average. In the low, medium, and high growth scenario, the saturation level of per capita commercial floorspace is close to the current level in Belgium, Japan, and Denmark, respectively.

Shanxi

Urban Residential: Lacking major cities and low income level lead to slow increase in housing demand in Shanxi. Per capita urban residential floorspace has limited growth and in the long term reaches the lower boundaries of the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively), given that the current per capita urban residential floorspace in Shanxi is over 30 m^2.

Rural Residential: Low income level results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and in the long term reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively), given that the current per capita rural residential floorspace in Shanxi is over 30 m^2.

Commercial: Low income level and low level of household expenditure in Shanxi results in low growth in the service sector and demand for commercial buildings. Per capita commercial floorspace in the long term reaches the level of Australia, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Tianjin

Urban Residential: The current per capita urban residential floorspace in Tianjin is around 30 m^2 and shows an upward growth trend. In the low growth scenario, per capita floorspace grows slowly toward the level of Tokyo. In the medium growth scenario, driven by the development of local economy and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches 45 m^2. In the high growth scenario, per capita floorspace eventually reaches the Copenhagen level of around 50 m^2.

Rural Residential: Although Tianjin has high income level, per capital rural floorspace is low, less than 30 m^2 in 2010. This will continue to grow as people demand for higher quality of life. In the low, medium, and high growth scenarios, the saturation level of per capita rural residential floorspace reaches the level of Belgium, Sweden, and Canada, respectively.

Commercial: Demand for commercial buildings in Tianjin grew rapidly in the past few years and is expected to continue to grow due to high growth in the service sector. In the low growth scenario, it reaches the Tokyo level in the long term. However, Tianjin is close to Beijing geographically, some businesses may choose to expand in Beijing instead of Tianjin, which limits the high level growth of the commercial floorspace. In the medium and high growth scenarios, the saturation levels of per capita commercial floorspace in Tianjin are close to those in Osaka and Copenhagen, respectively.

Xinjiang

Urban Residential: Lacking major cities and slow income growth lead to slow increase in housing demand in Xinjiang. Per capita urban residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Rural Residential: Low income level results in low housing demand in rural areas. Per capita rural residential floorspace has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 30, 45, and 60 m^2 respectively).

Commercial: Per capita commercial floorspace in Xinjiang today is higher than the national average. However, lacking major cities and businesses may lead to low demand for commercial buildings. Per capita commercial floorspace in the long term reaches the level of Australia, UK, and Finland in the low, medium, and high growth scenarios, respectively.

Tibet

Urban Residential: Due to strong policies to improve people's quality of life, per capita floorspace in Tibet grew rapidly in the past decade and is expected to continue to grow (Yuan et al., 2017). Per capita urban residential floorspace in the long term reaches the Japanese, Norwegian, and Canadian levels in the low, medium, and high growth scenarios, respectively.

Rural Residential: Different from southern China, a large share of rural area in Tibet is grazing area and has slow growth in building floorspace. Meanwhile, there are strong policies to improve people's quality of life, including large living areas. As a result, per capita rural residential floorspace in the long term reaches the level of Belgium, Norway, and Canada in low, medium, and high growth scenarios, respectively.

Commercial: Per capita GDP in Tibet is lower than the national average. Lacking major cities and businesses results in low demand for commercial floorspace and per capita commercial floorspace reaches the lower boundaries in the long term in the low, medium, and high growth scenarios.

Yunnan

Urban Residential: Yunnan has low population density and large land areas; the current per capita residential floorspace in urban areas is high, exceeding that of UK and Belgium. The growth is expected to continue and in the long term per capita residential floorspace in urban areas reaches the Japanese, Norwegian, and Canadian levels in the low, medium, and high growth scenarios.

Rural Residential: Low income level results in low housing demand in rural areas. Per capita rural residential floorspace in Yunnan has limited growth and reaches the lower boundaries of saturation levels in the low, medium, and high growth scenarios (i.e. 35, 45, and 60 m^2 respectively), given that per capita rural floorspace in Yunnan is greater than 30 m^2 today.

Commercial: Per capita GDP in Yunnan is lower than the national average. Lacking major cities and businesses results in low demand for commercial floorspace and per capita commercial floorspace reaches the lower boundaries in the long term in the low, medium, and high growth scenarios.

Zhejiang

Urban Residential: Zhejiang has strong local economy and the income level is higher than most provinces. There are also several major cities and growing service industry in Zhejiang, further driving the demand for urban housing. In the low growth scenario, per capita floorspace follows the upper boundary of growth and reaches the Japanese level. In the medium growth scenario, driven by high income growth and demand for better quality of life, people continue to pursue larger homes and per capita floorspace reaches the Danish level of 55 m^2. In the high growth scenario, the income-driven growth in floorspace continues and eventually reaches the U.S. level of around 70 m^2,

Rural Residential: The current per capita rural residential floorspace in Zhejiang is over 60 m^2, which is higher than that of most countries except for the United States and Australia. In the low growth scenario, in the long term it reaches the current level of per capita residential floorspace in the United States, whereas the saturation level in the high growth scenario is close to the current level of per capita residential floorspace in Australia.

Commercial: Per capita GDP in Zhejiang is among Top 5 in China and the current per capita commercial floorspace is among the highest in Chinese provinces. Zhejiang also has strong growth potential, with its diversified industrial structure and high demand for service industry. Per capita commercial floorspace in Zhejiang grows to high levels in the long term, reaching the current level of Belgium, Sweden, and the United States in the low, medium, and high growth scenarios, respectively.

Appendix B. Supporting Information for Chapter 4

Table B1. Regions in GCAM-China

Code	Provincial Name	Subregion	Grid Region
AH	Anhui	East China	East China Grid
BJ	Beijing	North China	North China Grid
CQ	Chongqing	Southwest	Central China Grid
FJ	Fujian	East China	East China Grid
GD	Guangdong	South China	China Southern Power Grid
GS	Gansu	Northwest	Northwest China Grid
GX	Guangxi	South China	China Southern Power Grid
GZ	Guizhou	Southwest	China Southern Power Grid
HA	Henan	South China	Central China Grid
HB	Hubei	South China	Central China Grid
HE	Hebei	North China	North China Grid
HI	Hainan	South China	China Southern Power Grid
HL	Heilongjiang	Northeast	Northeast China Grid
HN	Hunan	South China	Central China Grid
JL	Jilin	Northeast	Northeast China Grid
JS	Jiangsu	East China	East China Grid
JX	Jiangxi	East China	Central China Grid
LN	Liaoning	Northeast	Northeast China Grid
NM	Inner Mongolia	North China	North China Grid
NX	Ningxia	Northwest	Northwest China Grid
QH	Qinghai	Northwest	Northwest China Grid
SC	Sichuan	Southwest	Central China Grid
SD	Shandong	East China	North China Grid
SH	Shanghai	East China	East China Grid
SN	Shaanxi	Northwest	Northwest China Grid
SX	Shanxi	North China	North China Grid
TJ	Tianjin	North China	North China Grid
XJ	Xinjiang	Northwest	Northwest China Grid
XZ	Tibet	Southwest	Northwest China Grid
YN	Yunnan	Southwest	China Southern Power Grid
ZJ	Zhejiang	East China	East China Grid
---	31 GCAM Global Regions; see http://jgcri.github.io/gcam-doc/		

Table B2. Top 10 provinces in building final energy use in 2050 by scenario

Rank	Consumption Boom (CB)	Sustainable Development (SD)	Concentrated Growth (CG)	Leader and Follower (LF)
1	Sichuan	Sichuan	Sichuan	Guangdong
2	Hebei	Hebei	Guangdong	Shandong
3	Guangdong	Guangdong	Hebei	Inner Mongolia
4	Inner Mongolia	Shandong	Shandong	Beijing
5	Shandong	Inner Mongolia	Inner Mongolia	Sichuan
6	Beijing	Beijing	Beijing	Hebei
7	Shanxi	Shanxi	Shanxi	Tianjin
8	Henan	Henan	Henan	Hubei
9	Xinjiang	Xinjiang	Guizhou	Jiangsu
10	Guizhou	Guizhou	Tianjin	Zhejiang

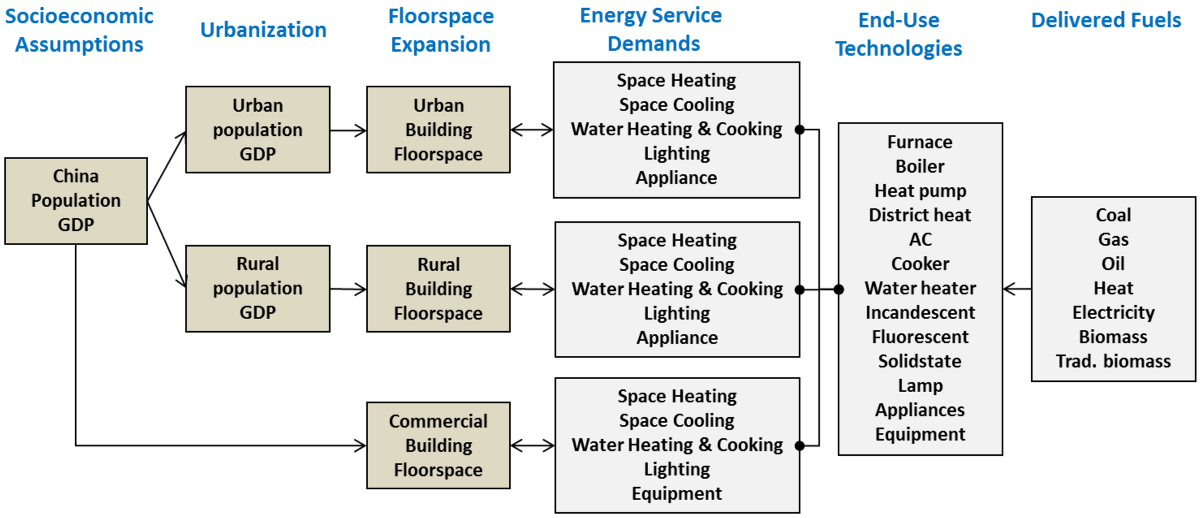

Figure B1. Structure of the building energy model in GCAM (Eom et al., 2012)

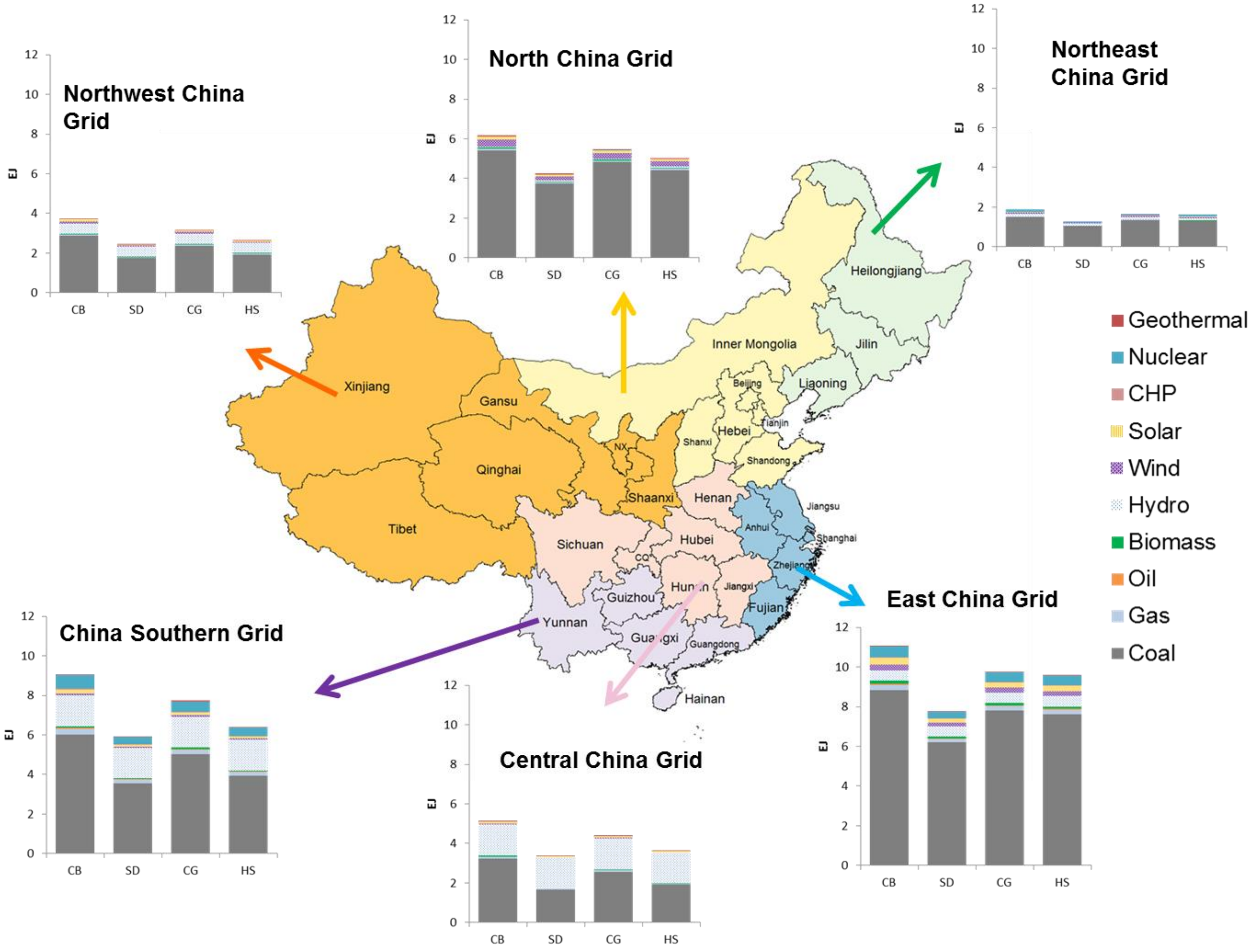

Figure B2. Electricity generation technology in 2050 by grid region

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