Cost-Effective Options for Transforming the Chinese Building Sector

Nan Zhou, Nina Khanna, Wei Feng, Lixuan Hong and David Fridley,
Lawrence Berkeley National Laboratory
Jon Creyts, Ellen Franconi, Roy Torbert and Yi Ke, Rocky Mountain Institute

ABSTRACT

As China's urbanization and economic growth continue, rising energy use in the building sector poses significant challenges to national energy and carbon goals. While China is ripe for efficiency savings as the government seeks to change incentives and boost energy productivity, many questions about energy efficiency potential and impacts remain unanswered.

This study is part of a collaborative project to quantify China's energy efficiency opportunity today and until 2050. The very few previous studies that have explored the subject lack credible baselines as well as transparency in data and methodology. For this specific study, we developed an updated bottom-up end-use model of China's building sector by accounting for differences in building type, climate zones, new versus existing buildings, and efficiency retrofits versus new efficient designs. This paper introduces the methodology and key assumptions for a baseline scenario of efficiency development in the building sector from 2010 to 2050. The baseline scenario assumes that policies in place by 2010 will continue to have impact with autonomous technological improvement over time, and can serve as a baseline for evaluating the potential of a more transformative and cost-effective pathway of development. We find that residential building energy consumption will continue to grow rapidly through 2050, with space heating, appliances, and cooking as the major energy consumers. Commercial energy consumption will slow after 2020, with office, hotel and retail as the largest building consumers and space heating, cooling and lighting as the three largest end-users.

Introduction

China is building roughly 2 billion m^2 of new buildings per year, due to rapid population growth, urbanization, and economic development. China is expected to add another 280 million people in urban area in the next 20 years, and that will drive additional urban residential building construction estimated to be nearly 1.5 billion m^2 per year through 2030. Chinese buildings use much less energy per square meter compared with many other developed countries (Diamond et al. 2013), but typical buildings are not necessarily efficient. Envelope thermal integrity and infiltration are key problems in existing Chinese buildings, and appliance and equipment efficiency also lag behind international levels.

China's current building energy efficiency standards are set based on typical buildings built in the 1980s that do not have insulation, and current Chinese appliance and equipment efficiency standards also lag behind international counterparts. Building energy performance can be improved significantly if better insulation, windows and roofs are used, and if more efficient equipment is adopted over average efficiency models. However, building owners and tenants in general focus on the initial investment over the long-term return from the life-cycle operation of the more efficient equipment and better envelope material. The Chinese government has adopted policy and incentives to promote the installation of certain renewable technologies in buildings such as ground source heat pumps and solar photovoltaic systems, but questions remain unanswered on the impact and potential of these clean technologies. The Rocky Mountain Institute study, "Reinventing Fire: US," shows that the use of conventional and rapidly emerging technologies, changes in how building occupants use building services, and integrated design can save up to 69% of the building sector's projected primary energy use in 2050 very cost-effectively. This paper is the first part of a collaborative study to replicate the "Reinventing Fire" methodology to develop a transformative pathway for China's building sector. It focuses on the development of an updated and comprehensive baseline scenario of Chinese building energy consumption to 2050. This baseline scenario is a business-as-usual pathway of development for the buildings sector in which only policies in place by 2010 continue to have impact and autonomous technological improvement occur. It is intended to serve as a baseline for evaluating the potential of a more transformative and cost-effective pathway of development.

Methodology

Modeling Future Building Energy Consumption

In order to evaluate the potential energy savings in the Chinese building sector, a baseline building energy consumption outlook is developed for 2010 through 2050. In this study, we use the LBNL China Energy End-Use Model to develop a likely baseline pathway of development for Chinese residential and commercial buildings. The China Energy End-Use model provides an accounting framework of China's energy and economic structure using the LEAP (Long-Range Energy Alternatives Planning) software platform developed by Stockholm Environmental Institute. LEAP is a medium to long-term integrated modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy as well as conduct long-range scenario analysis. Using LEAP, the China Energy End-Use Model captures diffusion of building end-use technologies and macroeconomic and sector-specific drivers of energy demand. Residential and commercial buildings are modeled separately, with further distinctions by climate zone, existing versus new buildings, and retrofit versus new building efficiency levels. Figure 1 shows the model structure for residential and commercial buildings.

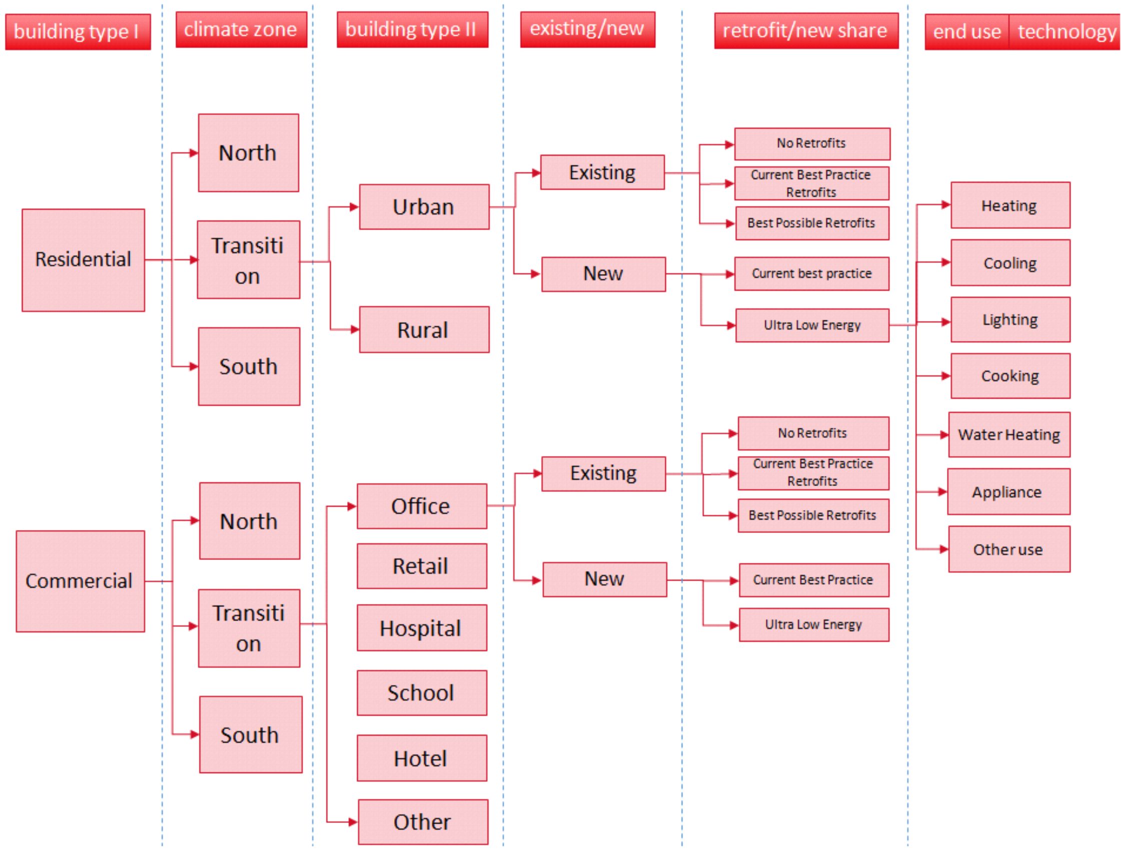

Figure 1. Residential and commercial building model structure.

Unlike our previous Chinese building model (Zhou et al. 2011), this model enables a more nuanced characterization and analysis of China's growing building sector by breaking out the building stock and end-uses by the three very different climate zones of North China's severe cold climate, Transition zone's hot summer and cold winter climate and South China's hot summer and warm winter climate. The different climates in these three regions have important implications for regional differences in heating and cooling demand. The buildings are also broken out by building type, vintage (i.e. existing versus new) and retrofit versus new design.

As a bottom-up accounting model, the China Energy End-Use Model calculates the future energy consumption of buildings (FECB) for each type of end-use in each building type using the following formula:

$$FECB = \sum_n \left\{ AB_n \times \sum_q \left[P_{q,n} \times \left(\sum_k Intensity_{q,n} \times Share_{k,q,n} / Efficiency_{k,q,n} \right) \right] \right\}$$

Where:

k	=	Energy/technology type
q	=	End use
n	=	Building type
AB_n	=	Floor area of building type n
$P_{q,n}$	=	Penetration of end use q of building type n
$Intensity_{q,n}$	=	Energy intensity of end use q of building type n

$Share_{k,q}$ = The share of the kth technology of end use q
$Efficiency_{k,q}$ = Efficiency of the kth technology of end use q

Residential Buildings

Residential energy demand is driven simultaneously by urbanization and growth in household incomes. Whereas urban households tend to consume more energy than rural households, particularly in non-biofuels, household income growth also affects the size of housing units and subsequent heating and cooling loads, and increase in ownership and use of energy-consuming equipment such as appliances, lighting and electronics. The key drivers of residential energy demand thus include continuing urbanization, household size changes, growing residential floor space per person, and ownership of key energy-consuming appliances. In terms of household size, international experience has shown that household size tends to decline with rising income and urbanization. This is especially true for China given its "One Child Policy," and both urban and rural average household sizes are expected to decrease in the future. As described in another 2014 ACEEE Summer Study paper (Hong et al. 2014), rapid urbanization, increasing from 53% of population in 2012 to 69% by 2030 and 77% by 2050, along with rising residential floor space per person from 7.2 m^2 in 2012 to 32.9 m^2 in 2050 in urban areas and from 9.4 m^2 in 2012 to 37.1 m^2 in 2050 in rural areas, will significantly increase residential building floor space. By 2050, total residential building floor space will reach 63.8 billion m^2, a 33% increase from the 2012 residential floor space of 47.7 billion m^2. This increase in the total stock of residential buildings means that more floor space will need to be heated and cooled, and that more energy will be consumed in heating and cooling residential buildings. Similarly, the decline in household size leads to an increase in the total number of households which, together with the increase in living area, will multiply the contribution of energy demand from households.

In terms of energy end-uses, we model space heating, air conditioning, appliances, cooking, water heating, lighting and a residual "Others" end-use category. These end-uses are further broken out by technologies and fuel types; and specific appliances modeled include air conditioners, refrigerators, clothes washers and televisions. For all end-uses, appropriate technology and fuel shares are assigned, with saturation (rates of penetration) and energy efficiencies based on historical statistical and survey data up to the base year (Tsinghua 2012) and future values based on analysis of government plans, trends, and comparisons to other countries. Heating and cooling loads are also differentiated for the three climate zones, while the other end-uses are assumed to be the same across climate zones.

As household incomes increase, growing demand for greater thermal comfort will increase heating and cooling saturation and loads across all climate zones. For example, space heating in China's Transition Zone with hot summer and cold winter climate was historically minimal and provided only by individual heating devices such as electric heaters. Over time, however, we expect space heating saturation to increase from 20% of urban and rural residential floor space in 2010 to 25% in 2050, and the energy intensity to increase by 10% in 2030 and 30% in 2050 from 2010 levels in this region. Similar increases are also expected for cooling, especially in the warmer regions in the Transition Zone and Southern China.

In terms of efficiency, we assume continuous efficiency improvement as a result of efficiency policies implemented by 2010, such as building energy codes and equipment efficiency standards, as well as autonomous technological change. By 2050, on average, China is expected to reach nearly half of the efficiency level of superefficient technologies today. Table 1 shows the change in efficiencies of selected key technologies in the residential sector.

Table 1. 2010 and 2050 efficiencies for key residential technologies

End-Use Category	Technology Name	Building Type	2010 Efficiency (%)	2050 Efficiency (%)
Heating	District Heating	Residential/Commercial	76	84
	Electric Heater	Residential/Commercial	90	93
	Coal Boiler	Residential/Commercial	62	76
	Gas Boiler	Residential/Commercial	78	86
	Air Source Heat Pump	Residential/Commercial	237	245
	Ground Source Heat Pump	Residential/Commercial	300	360
	Coal Stove	Residential	40	63
Cooling	Air Conditioner	Residential/Commercial	257	311
Cooking	Coal Cooker (Anthracite)	Residential	33	59
	Coal Gas Cooker	Residential	60	78
	Biomass Cooker	Residential	17	31
	Biogas Cooker	Residential	47	56
Water Heating	Natural Gas Water Heater	Residential/Commercial	60	70
	Electric Water Heater	Residential/Commercial	89	91
	Air Source Heat Pump	Residential	237	245
	Ground Source Heat Pump	Residential	360	390

Over time, we also expect heating technologies in the urban residential sector to shift towards cleaner fuels such as from coal district heating and distributed coal boilers to natural gas district heating, electric heaters and ground source heat pump. Biomass will continue to play an important role in rural residential heating. Figure 2 shows the heating technology shift in North urban residential buildings as an example.

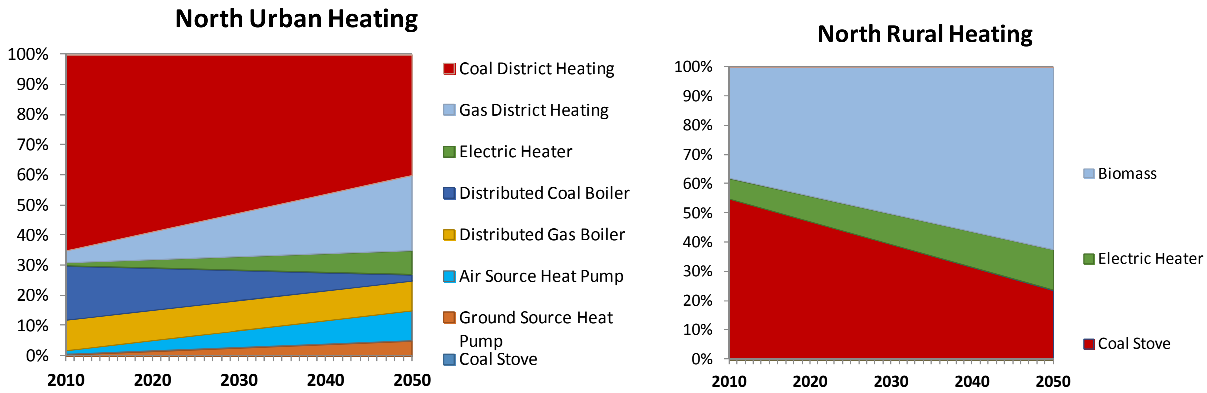

Figure 2. North residential heating technology shares, 2010-2050.

Table 2 shows final energy intensities for urban buildings by end-use and climate zone for 2010 and 2050 in our model, taking loads, efficiency and technology shares into consideration. By 2050, the final energy intensity of Chinese urban residential buildings in Northern China will consume about 20% less energy than U.S. urban residential buildings and 15% less energy than Japanese residential buildings (EIA 2014, ECCJ 2013). The increase in energy intensity over time is expected as demand for greater thermal comfort and energy services increase along with rising incomes, but levels will be lower than that of Japan and U.S. because of different comfort levels, operating hours, equipment type and usage.

Table 2. Final Energy Use Intensities for Urban Residential End-Uses in 2010 and 2050

	Total	**Heating**	**Cooling**	**Lighting**	**Cooking**	**Water Heating**	**Equipment**
2010 Energy Use Intensities (kWh/m2)							
North	105.3	68.8	1.8	5.1	21.3	3.3	5.0
Transition	39.5	2.0	2.9	5.1	21.3	3.3	5.0
South	41.1	0.0	6.5	5.1	21.3	3.3	5.0
2050 Energy Use Intensities (kWh/m2)							
North	125.6	68.8	5.4	10.2	21.3	9.9	10.1
Transition	105.0	45	8.7	10.2	21.3	9.9	10.1
South	75.8	5	19.4	10.2	21.3	9.9	10.1

Commercial Buildings

As China continues on its economic development path and the structural shift away from heavy industry towards service-oriented economy quickens, the commercial sector will become an increasingly important sector and a larger energy consumer than today. Commercial building energy demand is the product of two factors: building area (floor space) and end use intensity (MJ per m^2). Forecasting commercial building floor space requires an understanding of the drivers underlying the sector's recent growth and where these trends are likely to be heading. As described in detail in Hong et al. 2014, global commercial building floor area has been driven by the percentage of employment in service sector of the economy and growth in the average floor space per employee in this sector. Based on international experiences, we assume the average commercial floor space per employee to be a logistic function of per capita income. But because growth is not unlimited, we set a maximum floor space per employee at 40 m^2 per employee for 2050, a level equivalent to the current United Kingdom level. China's floor space per employee in the tertiary sector (i.e, service sector) is expected to grow from 32.6 m^2 per employee in 2010 to 40 m^2 per employee in 2050. The total commercial floor space is projected to nearly double from 10 billion m^2 in 2010 to reach 18.9 billion m^2 by 2050, with office buildings occupying more than one third of total commercial floor space.

Commercial building energy consumption varies by building type and its main functions, and commercial buildings are separated into the major building types of retail, office, school, hospital, hotel, and other buildings in our model. The key end-uses for each commercial subsector include space heating, space conditioning or cooling, water heating, lighting, and equipment. Heating and cooling loads are differentiated by building type and climate zone, while the other end-uses are assumed to be the same for a given building type across climate zones. As with residential buildings, we assume the cooling load across all commercial building types will increase by 30% from 2010 to 2050 due to lower temperature setpoints and/or longer period of operation resulting from demand for greater thermal comfort. Space heating loads are also assumed to increase by 30% from 2010 to 2050 in the Transition Zone for all commercial buildings, but are expected to decrease by 10% in Northern China. This decrease is only expected in Northern China because heating intensities are already relatively high compared to international (e.g., Japan) levels and energy efficiency retrofitting policies have been implemented to improve heating efficiency. Lighting and plug load equipment energy use intensities in China are currently relatively low and only a fraction of the current Japanese level so future growth is expected.

We assume commercial equipment efficiency improvements as seen in Table 2. In addition, the efficiency of commercial air conditioners are expected to improve from 257% in 2010 to 310% in 2050, centralized air conditioners by electricity from 284% to 347% and geothermal heat pump from 360% to 390%. As with residential buildings, we also assume technology shifting towards cleaner fuels and more efficient technologies. Figure 3 shows the switching that occurs in heating technologies for commercial buildings as an example.

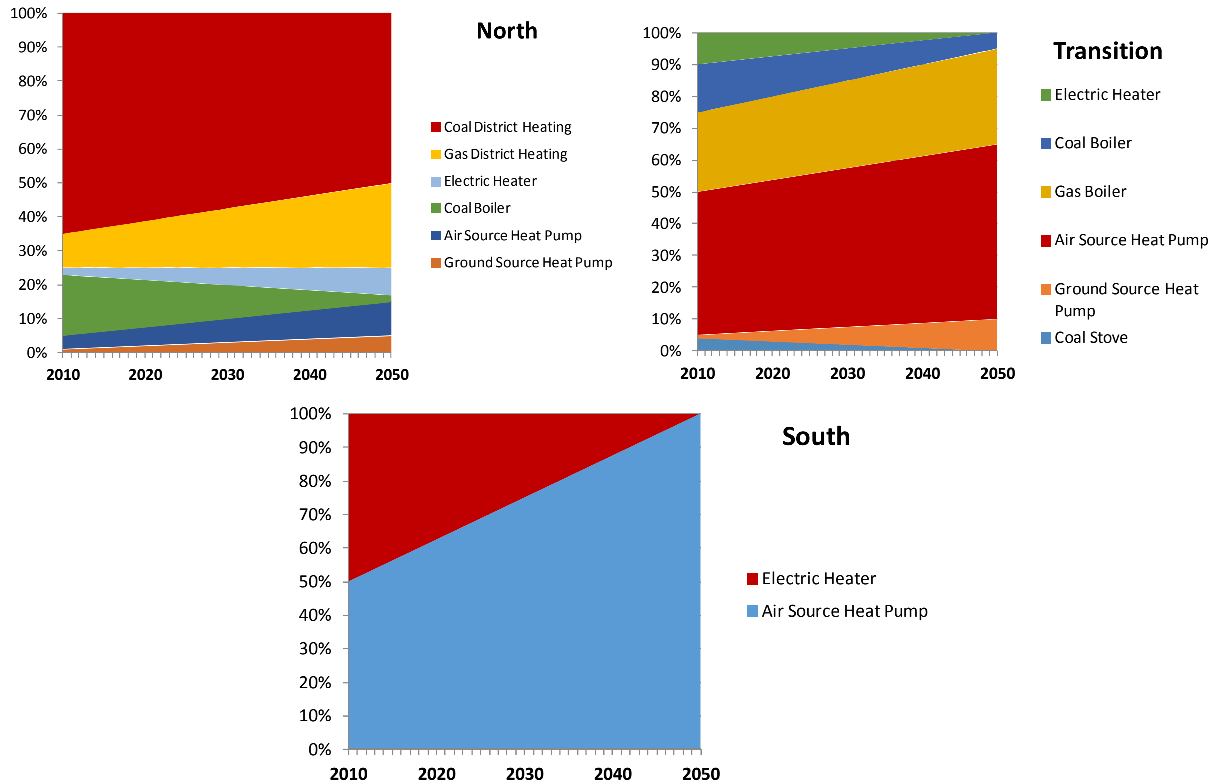

Figure 3. Commercial heating technology shares, 2010 – 2050.

After taking commercial loads, efficiencies and technology shifting into consideration, final energy intensities are developed for each building type, climate zone and end-use. The final energy intensities for new office buildings are shown as an example in Table 3. By 2050, the total final energy intensity of new Chinese office buildings in Northern and Transition zones will be about 20% lower than the average U.S. office buildings and 27% lower than the average Japanese office building (EIA 2014, ECCJ 2013).

Table 3. Final energy intensities for new office buildings by end-use in 2010 and 2050.

	Total	Heating	Cooling	Water Heating	Lighting	Equipment
2010 Energy Use Intensities (kWh/m2)						
North New	82.2	37.9	9.0	10.1	18.7	6.5
Transition New	67.5	19.3	12.9	10.1	18.7	6.5
South New	50.5	0.0	15.1	10.1	18.7	6.5
2050 Energy Use Intensities (kWh/m2)						
North New	151.8	37.9	18.0	20.3	56.0	19.6
Transition New	152.5	30.9	25.7	20.3	56.0	19.6
South New	126.1	0.0	30.2	20.3	56.0	19.6

Modeling Energy Results

Residential Buildings

The final energy consumption outlook for residential buildings by end-use under the baseline scenario is shown in Figure 4. As seen in Figure 4, residential space heating, appliances, and cooking are the major energy consumers, accounting for 62%, 11%, and 12% of total residential energy consumption in 2050, respectively. Energy consumption for residential cooling, although small in absolute numbers, will grow rapidly from 2010 to 2050.

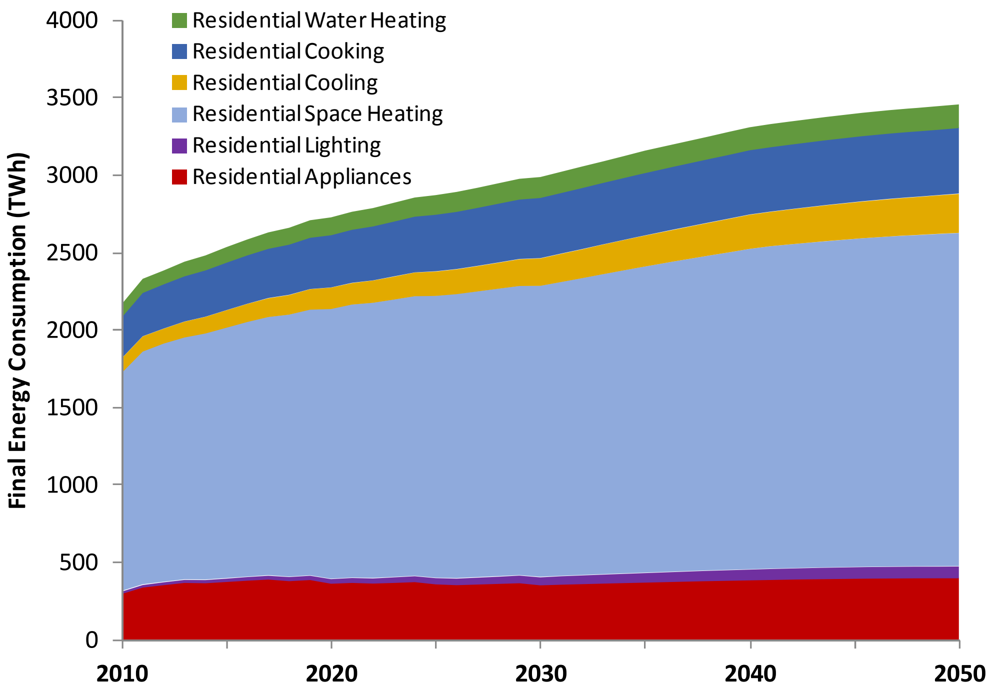

Figure 4. Baseline residential final energy consumption by end-use

Commercial Buildings

The final energy consumption by building type is shown in Figure 5 and by end-uses across all commercial building types in Figure 6. Office, hotel and retail are the three largest energy-consuming building types, accounting for 30%, 24% and 24% of total commercial building final energy consumption, respectively. In terms of end-use, space heating, cooling and lighting are the three largest energy-consuming end-uses, together accounting for 78% of total commercial energy consumption.

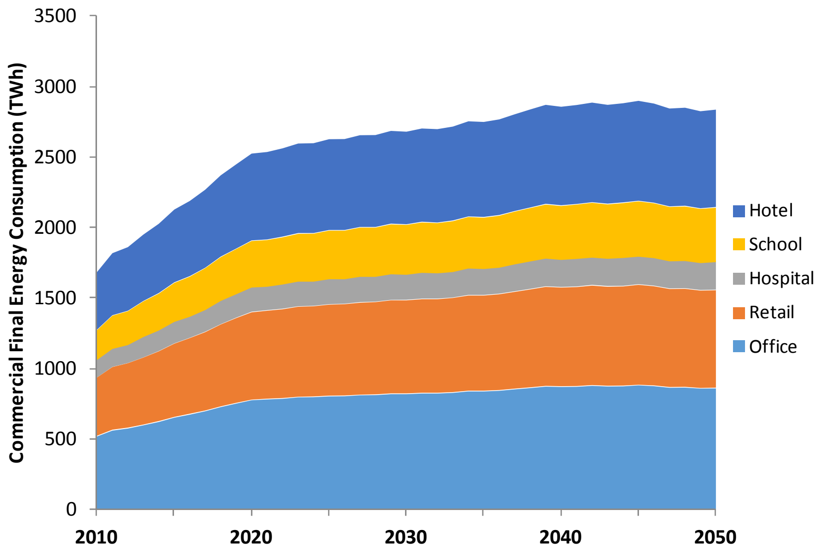

Figure 5. Baseline commercial final energy consumption by building type.

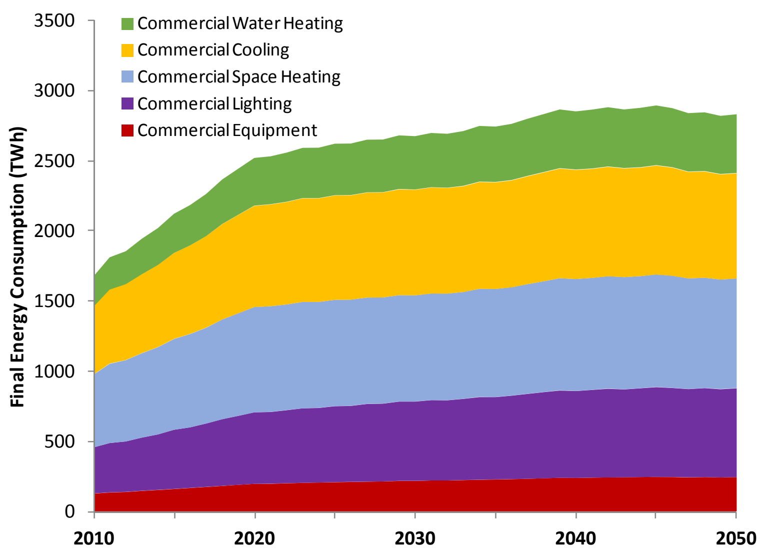

Figure 6. Baseline commercial final energy consumption by end-use.

Conclusions and Next Steps

This project combines a bottom-up energy end-use model of China's distinct residential and commercial building types with current efficiency and technology share data to develop a comprehensive baseline energy outlook for buildings to 2050. The baseline results show residential building energy consumption will continue to grow rapidly through 2050, with space heating, appliances, and cooking as the major energy consumers. Cooling energy consumption, while small, will also continue to increase. Commercial energy consumption will slow after 2020, with office, hotel and retail as the largest building consumers in the commercial sector. In terms of commercial end-use, space heating, cooling and lighting are the three largest end-users. The results of this analysis will serve as a baseline for helping identify and quantify the potential savings from a transformative and cost-effective pathway for China's building energy future in the next phase of this project. Specifically, a transformative scenario will be developed in which China can meet its energy needs while improving its energy security and environmental quality by using the maximum feasible share of cost-effective energy efficient and renewable supply through 2050. This will include full adoption of today's super-efficient technologies, integrative and passive design, renewable energy, demand response and prefabricated buildings, and more aggressive efficiency retrofits and longer building lifetimes. Cost-curve analysis and case studies will be integrated to illustrate the cost-effectiveness of the transformative pathway of buildings development.

Acknowledgments

We are grateful to the China Sustainable Energy Program of the Energy Foundation and Rocky Mountain Institute for funding this work. We thank our collaborators at the China Energy Research Institute for their contribution to this work and Chinese experts from the Ministry of Housing and Urban-Rural Development, Chinese Academy of Building Research, Tsinghua University, Energy Foundation, and Shenzhen Institute of Building Research for their feedback and input. This study was supported through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231

References

Energy Conservation Center of Japan (ECCJ). 2013. *Energy Data and Modelling Center of the Institute of Energy Economics, Japan Handbook of Energy and Economic Statistics 2013*. Tokyo: the Energy Conservation Center, Japan.

Diamond, R. C., Ye Q., Feng W., Yan T., Mao H., Li Y., Guo Y., and J. Wang. 2013. "Sustainable Building in China – A Green Leap Forward?" *Buildings* 3: 639-658.

Hong, L., Zhou N., Feng W., Khanna N. and D. Fridley. 2014. "Modeling China's Building Floor Area Growth and Its Implications for Building Material and Energy Demand." *2014 ACEEE Summer Study on Energy Efficiency in Buildings* (Accepted).

Tsinghua University Building Energy Research Center. 2012. *China Building Energy Efficiency Development and Research Annual Report 2012.* Beijing: China Construction Industry Press.

U.S. Energy Information Administration (EIA). 2014. "2003 Commercial Building Energy Consumption Survey (CBECS) Survey Data." http://www.eia.gov/consumption/commercial/data/2003/

Zhou, N., Fridley D., Khanna N., Ke J., McNeil M. and M. Levine. 2013. "China's energy and emissions outlook to 2050: Perspectives from bottom-up energy end-use model." *Energy Policy* 53: 51-62.