Transformative pathway for Chinese buildings by 2050

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Keywords

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Abstract

As China's urbanization and economic growth continue, rising energy use in the building sector – which already accounts for over 20 % of national energy use – poses significant challenges to national energy and carbon goals. While various policies have been introduced over the years to improve building efficiency, total final building energy use (space heating, cooling, lighting, domestic hot water, etc. …) is still expected to more than double through 2050 and contribute to a larger share of national energy and emissions.

This study aims to quantify China's maximum technically feasible and cost-effective energy efficiency opportunity through 2050. We use a bottom-up model with building stock turnover to identify and evaluate the savings potential of a transformative yet cost-effective vision for Chinese residential and commercial buildings. This transformative pathway of development considers the individual and combined energy savings potential of high efficiency and passive buildings, integrated design, super-efficient appliances, smart controls, prefabricated buildings, and building-integrated renewables, microgrids and demand response. On the basis of a comprehensive baseline scenario, we developed a transformative scenario that encompasses the latest building technologies and best practice case studies of high performing buildings, and potential for adoption in China. The results show that the transformative and cost-effective pathway can significantly reduce China's baseline building energy consumption by nearly 50 % by 2050 to levels comparable with current total building energy use. The largest savings potential lies in passive building measures on heating and cooling energy use and building equipment efficiency improvements. With renewable energy incorporated, a reasonable share of Net Zero Energy Buildings can also be achieved. The results also reveal that although the current policy focus is targeted mostly on new construction, existing building retrofits will become very important. The results of this study have significant policy implications such as the need for establishing a regular codes update roadmap, tighter building codes, and data transparency and disclosure for Chinese policymakers, and offers important insights and perspectives on China's rapidly evolving building sector.

Introduction

Buildings use more energy than any other sector in the world and account for nearly 40 % of global greenhouse gas emissions (GHGs). China's buildings are a major contributor. China is already building an average of two billion square meters (m^2) of new buildings every year, driven by national population growth, urbanization, and unprecedented rapid economic development. In the next 20 years, China is expected to add another 280 million people in urban areas as its urbanization rate increases from 50 % in 2010 to 68 % in 2030, with the addition of nearly 1.5 billion m^2 of new urban residential building construction per year for the next two decades. Residential energy demand in China 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 but m^2 per capita tends to increase with rising income and urbanization. This is especially true for China given its "One Child Policy" – both urban and rural average household sizes are expected to decrease in the future but the total urban residential building stock is expected to significantly increase. 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 also 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). Global commercial building floor area has been driven by the percentage of employment in the service sector of the economy and growth in the average floor space per employee in this sector. In China, this value is also expected to continue rising from the relatively low 30 m^2 per service sector employee to 45 m^2 per service sector employee – a level consistent with current international levels – by 2050, leading to a larger commercial building stock.

Currently, Chinese buildings use much less energy per square meter compared with many other developed countries due to different usage patterns and temperature set-point preferences (Diamond et al. 2013). Buildings, especially the HVAC system, are operated in partial time and partial space instead of conditioning space continuously, and thus exhibit low energy consumption. But typical buildings are not necessarily efficient based on the Chinese building codes and standard requirements (Feng et al. 2014). Envelope thermal integrity and infiltration are key problems in existing Chinese buildings, and appliance and equipment efficiency also lag behind international levels. This is partly because China's current building energy efficiency standards are set based on typical buildings built in the 1980s that do not have insulation, and many of the existing 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 current market average efficiency models. However, building owners and tenants in general focus on the initial upfront investment over the long-term return of energy savings accrued by more efficient equipment and better envelope material. The Chinese government has adopted policies and incentives to promote the installation of certain renewable technologies in buildings such as ground source heat pumps and solar photovoltaic systems, but the specific impact and potential of these clean technologies are not quantified or evaluated. The Rocky Mountain Institute's "Reinventing Fire: Bold Business Solutions for the New Energy Era" study for the U.S. shows that the use of conventional and rapidly emerging technologies, changes in how building occupants use building services, and applying integrated design can save up to 70 % of the U.S. building sector's projected primary energy use in 2050 very cost-effectively (Lovins and RMI 2011).

This paper is part of a collaborative study to replicate the "Reinventing Fire" methodology used for the U.S. study to develop a transformative pathway for China's building sector. It focuses on the development of a comprehensive and very detailed residential and commercial building energy end-use model capable of distinguishing between three major climate zones, existing and new buildings, and five different building efficiency vintages. It also centers around the development of two distinct scenarios for evaluating potential energy and emissions reductions in the Chinese buildings sector from 2010 through 2050. An updated 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 serve as the baseline scenario, while a more transformative and cost-effective pathway of development reflect the potential of accelerated and full adoption of passive and integrative designs, superefficient equipment, smart controls and renewable and clean energy sources.

Modeling methodology

BOTTOM-UP BUILDINGS MODEL

The bottom-up building energy end-use model used in this study is part of a larger national energy end-use model developed by researchers at Lawrence Berkeley National Laboratory (LBNL). This Demand Resource Energy Analysis Model (DREAM) includes residential and commercial building modules on the demand-side, and power generation and other energy transformation modules on the supply-side. This 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. This model was developed as part of an ongoing collaborative project called "Reinventing Fire: China" between two U.S. research institutions, LBNL and the Rocky Mountain Institute, and China's Energy Research Institute, the leading energy-related government think-tank that advises China's key policymaking body, the National Development and Reform Commission. This project adopts the "Reinventing Fire: U.S." methodology to develop a transformative pathway for China's building sector using updated and comprehensive baseline and transformative scenarios of Chinese building energy consumption to 2050.

Using LEAP, the DREAM model captures the 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 two existing building and three new building efficiency vintages. Figure 1 shows the model structure for residential and commercial buildings.

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

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

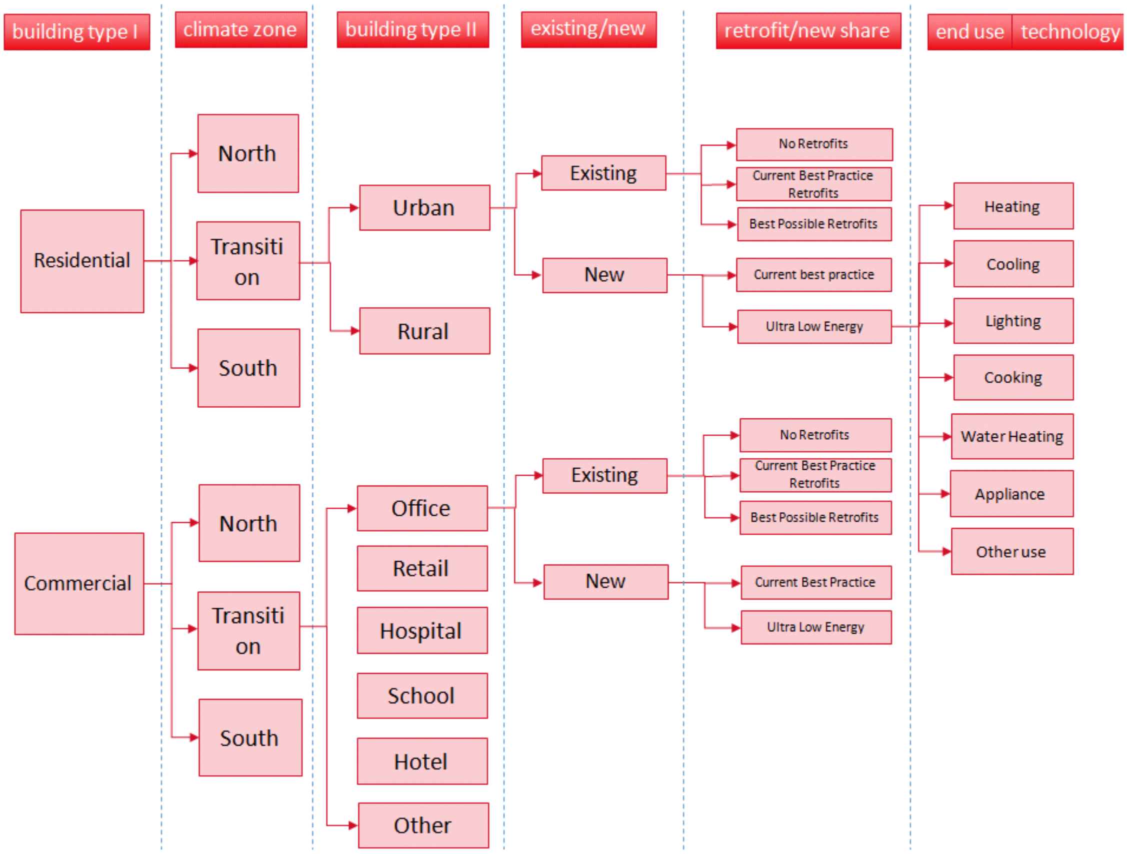

Figure 1. Residential and Commercial Building Model Structure.

Where:

k	Energy/technology type
q	End use
n	Building type
FAB_n	Floor space 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 k^{th} technology of end use q
$Efficiency_{k,q}$	Efficiency of the k^{th} technology of end use q

Unlike previous Chinese building models, 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, the 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 levels of efficiency.

Floorspace Stock Turnover Model

Another important feature of this buildings model is that it incorporates a sophisticated building stock turnover model to predict annual residential and commercial new construction, taking into account varying building lifetimes, retirement distributions, and retrofit rates. The use of a stock turnover model, rather than a simple projection or forecast of future new construction, has multiple benefits. It allows us to model new construction and existing buildings separately, which may have very different efficiency measures and energy savings potentials. It also enables the tracking of different building vintages and the diffusion of high efficiency new building designs. For existing buildings, we have three levels of building efficiency for retrofits including existing buildings with no retrofits, existing buildings with current best practice retrofits, and existing buildings with best possible (i.e. deep) retrofits that incorporate elements of integrative and/or passive design. For new buildings, we have two levels including new buildings with current best practice design and ultra-low energy buildings that incorporate passive and/or integrative design associated with different climate zones and building types. These different vintages have different heating, cooling and lighting loads and energy-use intensities (EUIs) per m² associated with them, reflecting the impact that deep retrofits and improved design have on improving thermal insulation, passive cooling and daylighting.

The building stock turnover model to calculate annual existing, new, retrofit, and retired residential and commercial buildings is based on the following equation:

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

where $S_{i,t}^{B}$ is the residential/commercial building stock in region i in year t, $N_{i,t}^{B}$ is the newly built residential/commercial building in region i in year t, and $D_{i,t}^{B}$ is the demolished residential/commercial building in region i in year t.

Table 1. Key opportunity areas for transforming Chinese buildings in the Transformative Scenario.

	Integrative Design	Passive Buildings: Heating, Cooling and Lighting Impacts	Renewables, Fuel Switching and Net Zero Energy Buildings	Super-efficient appliances and space conditioning systems	Microgrids and Demand Response	Pre-fabricated buildings
Opportunity Description	Bundled and optimized measures. Maximum whole building system energy efficiency in a cost-effective way.	Passive House for residential buildings. Natural ventilation and shading for Southern buildings. Day/natural lighting.	Onsite generation PV, solar thermal, geothermal. Fuel switching from coal to natural gas and electricity.	Superefficient heating and cooling systems. Superefficient AC, refrigerator, clothes washer, LED, and other equipment.	Microgrids with distributed generation. Storage such as battery, EV, fuel cells. Demand response Smart control.	Longer building lifetime due to higher finished quality and more durable precast material. Speedy and high quality construction.
Modeling Parameters	Building vintage adoption rates for best possible retrofits and ultra low energy buildings with lowered loads for all end-uses due to integrative design savings.	Building vintage adoption rates; lowered EUIs (70 % reduction in all heating and cooling loads, 30 % reduction in residential lighting EUI and 20 % reduction in commercial lighting EUI).	Fuel switching through different technology shares (e.g., coal vs. natural gas boilers) for all key end-uses. See Tables 3 and 4 for specific values.	Accelerated market adoption of superefficient equipment (e.g., OLED TVs, current TopTen clothes washer).	Lowered EUIs (20 % reduction in all heating and cooling loads, 10 % reduction in commercial lighting EUI) as a result of smart control.	Building lifetime changes. See Tables 3 and 4 for specific values.

A cumulative normal distribution is used to reflect the probability of building stock being demolished after a certain number of years and serves as a representative building stock retirement function. In terms of building lifetime, there is insufficient data and statistics but past research has found that the average lifetime of Chinese buildings in urban areas is 30 to 40 years (Song 2005) and 15 years or less in rural areas (Huang 2006). For our study, we assume that the average lifetime of buildings will increase over time as a result of more effective retrofits and improved building material quality. Under the Reference scenario, for instance, construction from 1980 to 1999 is assumed to have an average lifetime of 30 years, with longer average lifetimes of 40 years and 50 years assumed for construction from 2000 to 2019 and 2020 to 2050, respectively. More detailed description of the building stock turnover model can be found in Hong et al. 2014.

Model Scenarios

In this study, we developed two distinct scenarios to evaluate the potential energy savings from a transformative pathway of development for Chinese buildings. The Reference scenario serves as the baseline scenario, and assumes that all policies in place by 2010 will continue to have impact on building energy demand with no additional policies after 2010, but autonomous technological improvement is expected to occur through 2050.

The Transformative scenario, in contrast, represents a vision for transforming China's building sector to be self-sustaining and resilient with increased comfort levels by using maximum technically feasible and cost-effective shares of efficiency and renewable supply through 2050. By deploying technologies and using design approaches available today, efficiency opportunities can yield attractive paybacks and produce better buildings with improved comfort, health, and productivity for occupants under the Transformative scenario. The energy-reducing opportunities represented in the Transformative scenario can be broadly categorized into six categories as shown in Table 1[1]. These opportunity areas are then implemented in our model through different assumptions for key modeling parameters that affect building energy demand for the Transformative scenario, including the market shares of different vintages of building design and retrofit, EUIs for specific end-uses, the market share of superefficient equipment, fuel shares for specific end-uses, and building lifetime assumptions.

Table 2 summarizes the key modeling parameters for the building stock turnover model in the base year of 2010 and under the two different scenarios.

Figure 2 shows the different distribution of residential and commercial building stock by vintage between the two scenarios. From 2010 to 2050, total residential floorspace is expected to grow from 40.8 billion m^2 to 63 billion m^2 while total commercial floorspace is expected to grow from 12 billion m^2 to 23 billion m^2. Under the Reference scenario, most of the urban residential and commercial floorspace will be new construction after 2030. Under the Transformative scenario, however, the longer lifetime for construction after 2,000 results in a sig-

1. Renewables, Fuel Switching and Net Zero Energy Buildings: Off-site renewables are included in the power generation sector and not included in the building model. The building model only considers distributed renewables within the boundary of buildings.

Table 2. Summary of Key Building Stock Turnover Model Parameters.

	2010	Reference Scenario 2050	Transformative Scenario 2050
Building Stock Turnover Model Parameters			
Building Lifetime		1980–1999 construction: 30 years 2000–2019 construction: 40 years 2020–2050 construction: 50 years	1980–1999 construction: 30 years 2000–2010 construction: 40 years 2010–2019 construction: 50 years 2020–2050 construction: 70 years
Urban Residential Retrofit Rate	2 % retrofitted	5.1 % retrofitted	100 % retrofitted
Residential: New building share of total floorspace	0 % in 2010	Share of new buildings increase to 80 % in 2050	Share of new buildings increase to 67 % in all regions (lower than Reference due to longer lifetime)
Commercial Retrofit Rate	0.4 % retrofitted	0.4 % of retrofitted	20 % of retrofitted
Commercial: New building share of total floorspace	0 % in 2010	Share of new buildings increase to 77 % in 2050	Share of new buildings increase to 60 % in 2050 (lower than Reference due to longer lifetime)

Note: existing buildings are defined in the stock turnover model as buildings built before 2010. New buildings are defined as buildings built after 2010.

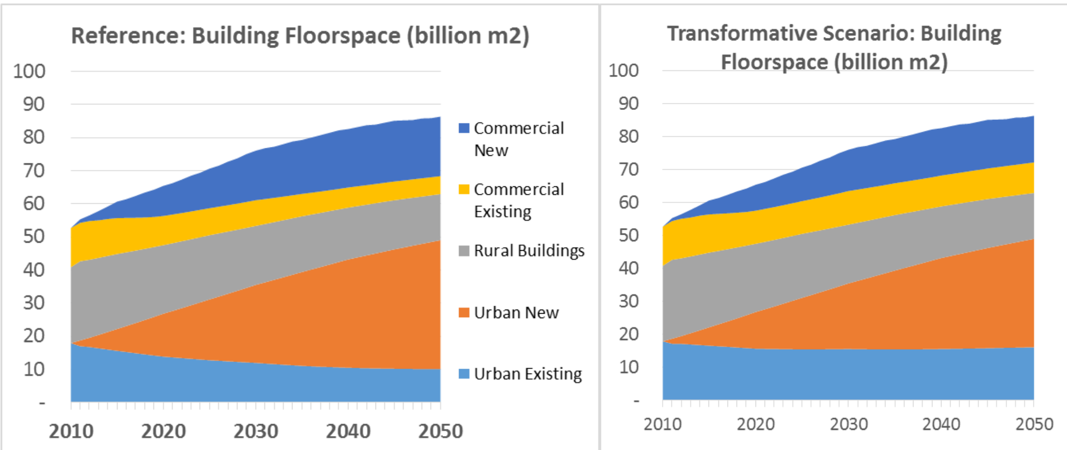

Figure 2. Total Building Floorspace by Building Sector and Vintage, Reference (left) and Transformative Scenario (right). Note: existing buildings are defined in the stock turnover model as buildings built before 2010.

nificantly larger share of existing buildings (i.e., buildings built before 2010) instead of new buildings (i.e. buildings built after 2010) for urban residential and commercial buildings.

Tables 3 and 4 summarize the key energy-related modelling parameters for the residential and commercial buildings, respectively, for both scenarios.

Modeling Results and Discussion

The final energy demand outlook for residential and commercial buildings in China for both scenarios is shown in Figure 3. Under the Reference scenario, both residential and commercial energy consumption will grow rapidly from 2010 levels of 321 million tonnes of coal equivalent (Mtce)[2] and 151 Mtce, respectively, to 2050 levels of 763 Mtce and 578 Mtce, respectively. This is more than doubling of the final energy consumption. As seen in the Transformative Scenario of Figure 3, if all of the opportunities are successfully implemented, this scenario holds a significant energy savings potential that exceeds 50 % from the baseline, or in other words, it can avoid increases in final energy demand by 100 %. By 2050,the annual residential and commercial energy consumption only totals 372 Mtce and 223 Mtce, respectively, representing a small increase from the base year level in 2010.

In terms of total building final energy demand by fuel source, the important benefits of efficiency improvement and fuel switching under the Transformative scenario are shown in Figure 4. Compared to the Reference scenario (shown on the left), significant efficiency improvements under the Transformative scenario (shown on the right) reduced total electricity demand by 348 Mtce per year in 2050 compared with the

2. Million tons of coal equivalent (Mtce) is the standard unit for energy in China. 1 Mtce = 29.27 million GJ.

Table 3. Summary of Key Energy Modelling Parameters for Residential Buildings.

	2010	Reference Scenario 2050	Transformative Scenario 2050
Residential Buildings			
Building vintage changes	0 % current best practice retrofits, 0 % current best practice new design and 0 % ultra low energy.	Current best practice retrofits shares grow to 13.9 % in existing buildings by 2050; remaining is no retrofit. New buildings grow to 100 % current best practice by 2050.	Existing buildings grow to 100 % best possible retrofit by 2050. New buildings grow to 100 % ultra-low energy buildings by 2050.
Building Load Changes: Space Heating		Heating loads increase from 2010 to 2050 in North, Transition and South (urban only) China due to demand for greater thermal comfort.	Heating loads in North China decrease by 10 % and remain constant in Transition and South due to new metering and improved design/insulation/retrofit for best possible retrofit and ultra low energy residential buildings.
Building Load Changes: Cooling		Cooling loads increase significantly from 2010 to 2050 in all climate zones (particularly Transition and South) due to demand for greater thermal comfort.	Same trends as Reference, but cooling loads are lower for best possible retrofits and ultra-low energy buildings due to passive and integrative design.
Appliance and Equipment Efficiency Improvements	100 % existing technology in 2010.	Linear shift to 60 % existing technology and 40 % superefficient technology by 2050.	Linear shift to 100 % superefficient technology by 2050.
Fuel Switching: Heating		Urban: shift away from coal towards cleaner natural gas for district heating in North China and distributed boilers, increase shares of air source and ground source heat pumps. Rural: decreased shares of coal stoves, replaced by growing shares of gas furnaces and electric heaters and slight decline in biomass.	Urban: Complete phase-out of coal district heating and coal boilers, replaced by gas district heating and ground source heat pump. Rural: complete phase-out of coal stoves and biomass, replaced by ground source heat pump, air source heat pump and gas furnaces and some electric heaters.
Fuel Switching: Cooling	Ground source heat pump: 0.5 % in urban, 0 % in rural.	Ground source heat pump for cooling share grows to 5 % in 2050 in urban only, replacing room air conditioners.	Ground source heat pump for cooling share grows to 7 % in 2050 in urban and to 30 % in rural, replacing room air conditioners.
Fuel Switching: Cooking		Urban: complete phase-out of coal gas stoves and declining shares of LPG cooker, replaced by modern and cleaner natural gas cookers and electric cookers. Rural: biomass shares reduced by half from 2010 to 2050 and complete phase-out of coal stoves, replaced by electric, natural gas and biogas cookers.	Same as Reference, with much faster phase-out of rural LPG cookers and greater increase in biogas cookers.
Fuel Switching: Urban Water Heating		Complete phase-out of coal gas and LPG water heaters by 2050 with decreasing shares of natural gas water heaters, replaced by 30 % share of solar water heaters by 2050 and more electric water heaters.	Complete phase-out of coal gas and LPG water heaters by 2050 with decreasing shares of natural gas water heaters, replaced by 50 % share of solar waters by 2050 and more electric water heaters.

Table 4. Summary of Key Energy Modelling Parameters for Commercial Buildings.

	2010	Reference Scenario 2050	Transformative Scenario 2050
Commercial Buildings			
Building vintage changes	0 % current best practice retrofits, 0 % current best practice new design and 0 % ultra low energy.	Existing buildings: Current best practice retrofits shares grow to 13.9 % by 2050; remaining is no retrofit. New buildings: Grow to 100 % current best practice by 2050.	Existing buildings: Grow to 100 % best possible retrofit by 2050. New buildings: Grow to 100 % ultra-low energy buildings by 2050.
Building Load Changes: Space Heating		Heating loads in North and Transition zones increase significantly because current levels very low compared to international levels.	Minimal or no increase in heating loads for best possible retrofits and ultra-low energy buildings due to superior design and thermal insulation.
Building Load Changes: Cooling		Cooling loads increase significantly across all climate zones due to greater demand for cooling and improved thermal comfort.	Cooling loads increase but at slower pace for best possible retrofits and ultra-low energy buildings in all climate zones.
Equipment efficiency improvements	100 % existing technology.	Shift to 60 % existing technology and 40 % superefficient technology by 2050.	Shift to 100 % superefficient technology by 2050.
Fuel Switching: Heating		North: lower shares for coal boilers replaced by more gas boilers, ground source and air source heat pumps, electric heaters and natural gas district heating. Transition: lower shares for coal boilers, replaced by air source and ground source heat pumps and gas boilers. South: shift away from electric heaters to 100 % air source heat pumps by 2050.	North: phase-out of coal boilers towards coal district heating, with more ground and air source heat pumps. Transition: phase-out of electric heaters, coal stoves and coal boilers by 2050 with growing shares of air source and ground source heat pumps, gas boilers. South: shift away from electric heaters to air source and some ground source heat pumps by 2050.
Fuel Switching: Cooling	Geothermal heat pump: 3 % in 2010.	Geothermal heat pump share increases to 6 % in 2050, with declining shares of room AC.	Geothermal heat pump share increases to 25 % in 2050, with faster decline in room AC and centralized AC.
Fuel Switching: Water Heating		Complete phase-out of coal and oil boilers and declining shares of electric water heaters and gas boilers. Solar water heater and heat pump shares each increase from 2 % in 2010 to 10 % in 2050, and small cogen share increases from 1 % in 2010 to 14 % in 2050.	Complete phase-out of coal and oil boilers and faster declining shares of electric water heaters and gas boilers. Solar water heater and heat pump shares each increase from 2 % in 2010 to 20 % in 2050, and small cogen share increases from 1 % in 2010 to 14 % in 2050.

counterfactual baseline despite increased rural electrification. These efficiency improvements – both on the equipment side as well as in improved retrofit or new building designs that significantly reduce heating loads – also slowed the growth of natural gas use despite its increased share in residential and commercial heating and residential cooking. Fuel switching away from dirty coal towards cleaner, modern energy sources is also readily apparent with the complete phase-out of direct coal consumption in the buildings sector under the Transformative scenario. The reduction in fossil fuel use, including 238 Mtce of coal and 105 Mtce of natural gas *annually* by 2050 under the Transformative scenario, can also be attributed to the increased adoption of renewable technologies such as geothermal heat pumps and solar water heaters.

In terms of end-use, heating and cooking dominate residential energy use and heating and cooling dominate commercial energy use in both the Reference and Transformative scenarios as seen in Figure 5. Increased thermal comfort in residential

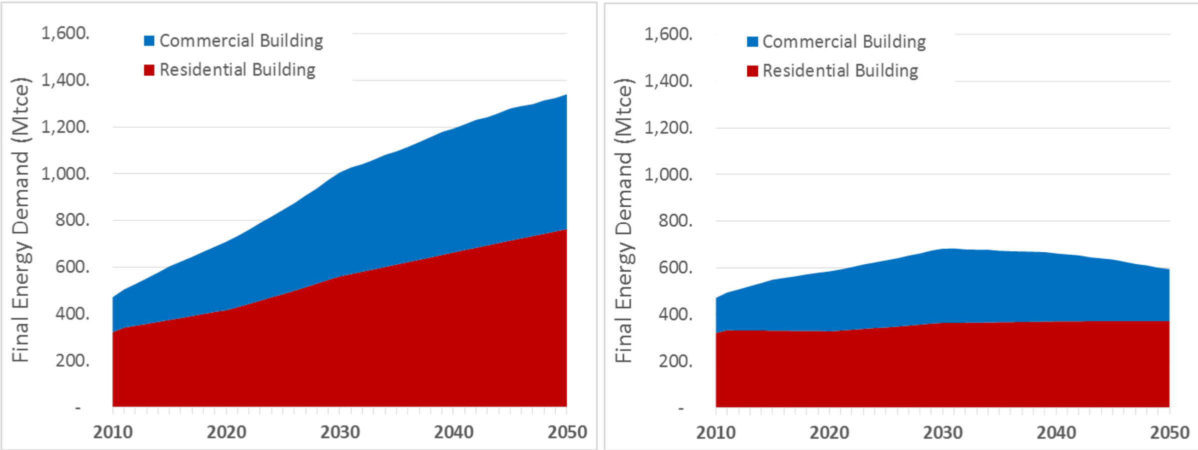

Figure 3. Final Energy Demand Outlook for Residential and Commercial Buildings, Reference (left) and Transformative Scenario (right.)

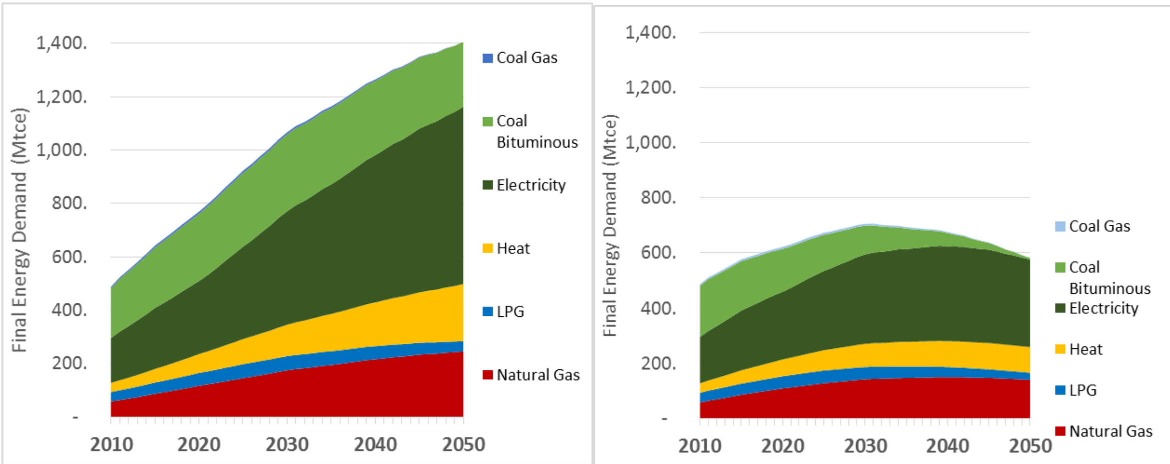

Figure 4. Total Building Final Energy Demand by Fuel Type, Reference (left) and Transformative (right) Scenarios.

buildings in the future increases heating and cooling energy use by two and nine-folds, respectively, under the Reference scenario, but improved comfort with much lower energy consumption for heating and cooling is achieved under the Transformative scenario. From 2010 to 2050, the annual residential heating energy consumption actually decreases while annual cooling energy consumption only increases three-fold. The faster modernization of rural residential cooking and water heating in the Transformative scenario also increases the use of commercial (purchased) fuel by offsetting biomass use, resulting in small reductions in the energy use for these two end-uses. In commercial buildings, increased cooling loads result in large energy use increase for heating, but the Transformative scenario is also able to achieve increased comfort with nominal increase in cooling energy use. The faster penetration of superefficient equipment also significantly reduce commercial equipment loads, with a 30 % reduction in annual energy use from 82 Mtce under Reference to only 59 Mtce under Transformative in 2050.

Figure 6 shows the energy savings potential by major opportunity areas under the Transformative scenario. As seen in Figure 6, most of the additional energy use and emissions from buildings, between now and 2050, can be avoided with a minimal increase in total building energy consumption from 2010 to 2050 under the Transformative scenario.

The largest savings potential – 33 % of the total energy savings potential under Transformative scenario with 514 Mtce saved annually by 2050 – lies in the increased adoption of passive and integrative design for new buildings, both commercial and residential buildings. Both passive and integrative design incorporates whole-systems thinking and technologies such as envelope insulation, high-performance windows, infiltration control, natural ventilation and daylighting that can help minimize building loads for heating, cooling, and lighting.

The second largest area of energy savings potential is the accelerated adoption of superefficient equipment, particularly for major appliances in the residential sector, which also has a 33 % savings potential with slightly lower 506 Mtce saved annually by 2050. The energy savings from applying of high-efficiency products available today to meet China's future building service needs for appliances, cooling, heating and water heating equipment highlights the important role of energy efficiency for future Chinese buildings.

Demand response and microgrids can also reduce total building energy use by 19 % through improved scheduling and operation of both local supply and demand, and has the added benefit of increasing the ability to decrease building loads in response to energy price signals.

Prefabricated buildings have the smallest energy savings potential in the buildings sector, but it also holds important energy savings for the industrial sector that is not apparent in Figure 6 since less demand for building materials translates into lower industrial activity and related energy consumption.

In terms of CO_2 emissions, the impact is even more pronounced as increased adoption of building-integrated renewables, fuel switching for building end-uses, and a heavily decarbonized power sector all contribute to additional emissions reductions as seen in Figure 7. By 2050, the annual total CO_2 emissions of 783 $MtCO_2$ is 60 % lower than the 2010 base level of 1,937 $MtCO_2$. Compared to the counterfactual 2050 annual total emissions under the Reference scenario, the Transformative 2050 annual total CO_2 emissions are 80 % lower. As with primary energy savings, passive and integrative design and superefficient appliance and equipment have the two largest CO_2 emissions reduction opportunities, each with 30 % reduction potential. This is followed by microgrids and demand response, which can reduce buildings CO_2 emissions by another 17 %. Renewable adoption and fuel switching would contribute to another 10 % reduction in the total building CO_2 emissions by 2050.

Conclusions and Policy Implications

This paper focuses on evaluating and quantifying the impact of key drivers for growth of energy use and emissions in China's building sector as well as on alternative future pathways. The economic analysis and specific policy instruments for the achievement of the strategies laid out here are not included here, but the key conclusions and their implications on policies in general are summarised below.

China's residential and commercial building sectors will undergo significant expansion in the coming 35 years, driven by urbanization, rising incomes, and demand for commercial services. Given that Chinese buildings are currently relatively

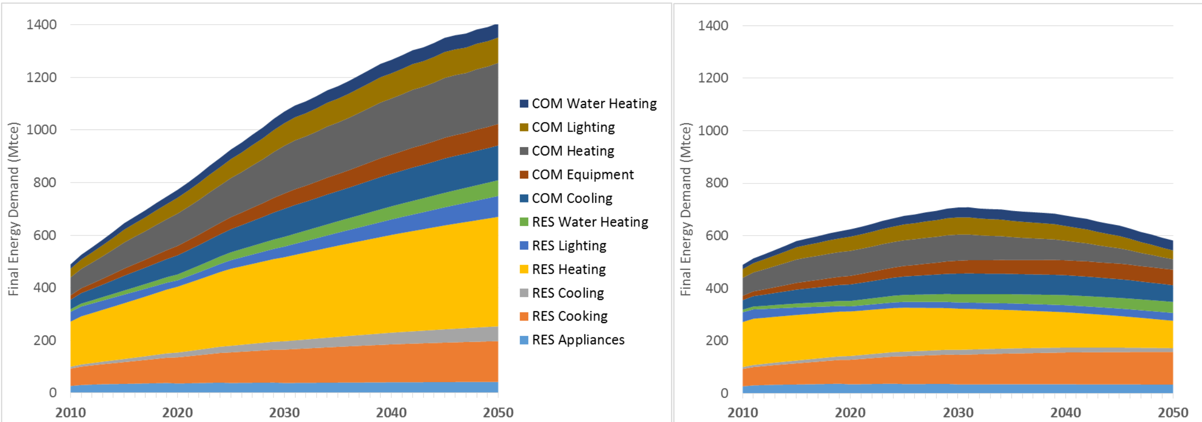

Figure 5. Residential and Commercial Building Final Energy Demand by End-Use for Reference (left) and Transformative (right) Scenarios.

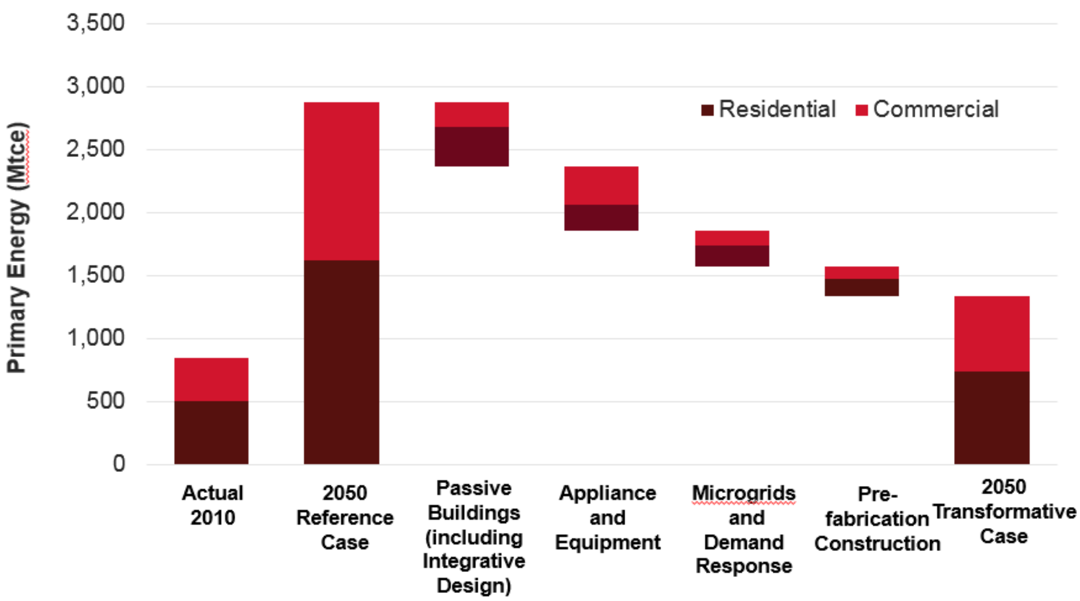

Figure 6. China Buildings Sector Energy Savings Potential Waterfall Chart.

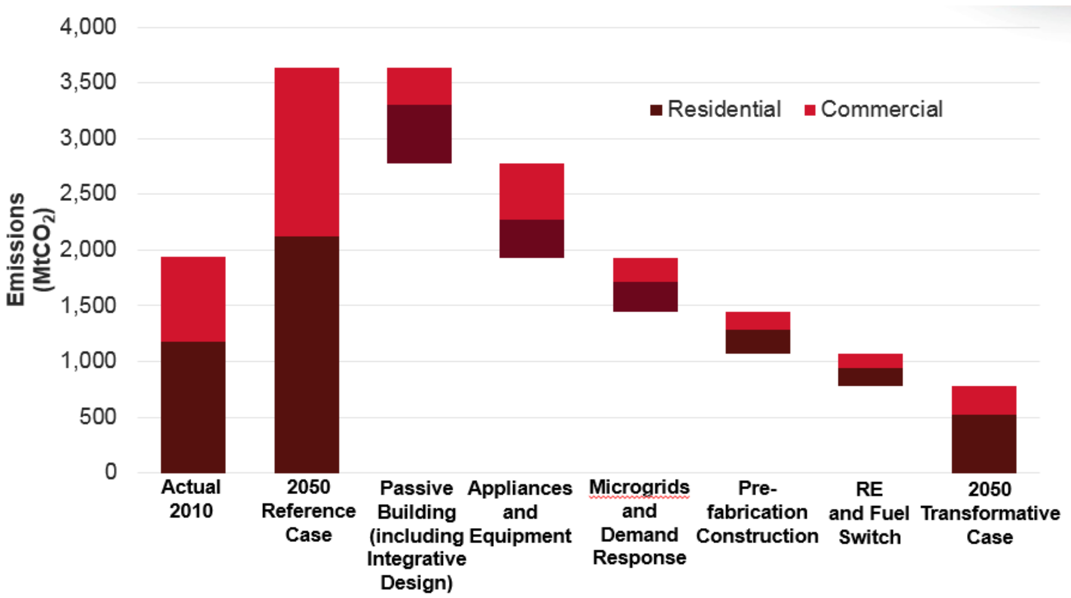

Figure 7. China Buildings Sector CO_2 Emissions Reduction Potential Waterfall Chart.

inefficient compared to international levels, the total energy consumed by buildings is expected to continue rising. Our bottom-up energy end-use model showed that under a business-as-usual, Reference scenario of development, total residential and commercial energy use could increase three-fold between 2010 and 2050. Much of this increased energy demand for buildings can be attributed to growing heating and cooling loads resulting from demand for increased thermal comfort as Chinese economic development progresses. However, our study reveals significant energy savings potential if China were to follow a transformative pathway of development for its buildings where passive and integrative design are adopted for retrofitting existing buildings and new buildings, superefficient equipment and renewables are fully deployed by 2050, and smart controls, microgrids, demand response, and prefabricated buildings are all actively integrated into the buildings sector. These cost-effective opportunities for improvement can reduce total building energy consumption by more than 50 %. In terms of energy-related CO_2 emissions, the transformative scenario can reduce total annual building emissions by 80 % compared to the reference scenario by 2050, or a level that is 60 % lower than the 2010 base level. The biggest potential for both energy savings and CO_2 emissions reduction potential lies in passive design and integrative design, followed by superefficient equipment, microgrids and demand response, and prefabricated buildings. Although prefabricated buildings have the smallest savings potential in the buildings sector, it can also contribute to lower energy demand in the industrial sector from avoided production of building materials. However, fully achieving this enormous savings potential requires addressing many key barriers that exist in the buildings sector in China today. These barriers and required solutions for each of the Key Opportunity areas are included in Table 5.

In general, a key barrier is the lack of *available* energy efficiency products and services and the relatively higher cost of such products. Many products such as advanced window technologies and high performance equipment are not widely available in China, nor can all owners afford to renovate their homes with leading technologies. Second, the designers, construction workforce, and building operators are not widely familiar with how to design, build, and operate energy efficient buildings. Third, building owners' and tenants' behavior is often not supportive of energy efficient buildings. Owners have established practices and habits for developing, purchasing, operating, leasing, renovating, and selling buildings that can make introducing energy efficiency into their process an uncertain value proposition and present new risk. Incentives need to be created to change these behaviors. Lastly, *structural* issues in the system do not promote energy efficient buildings. The lack of strong building code standards and enforcement, energy pricing distortions (the customer is not always properly compensated by the utility or landlord for saving energy), and split-incentives (which often result from the structure of many residential and commercial leases) impede positive behavior.

In order to fully realize the cost-effective energy savings that exist in this transformative pathway of development, the policy solutions needed can be summarized in the following four categories:

1. Greater information and data disclosure and transparency to better inform decision-making through:
   - promoting labelling of green buildings and energy-consuming products,
   - sharing building performance data through disclosure programs.
2. Establish and effectively enforce performance standards, mandatory energy reduction requirements, and codes through:
   - establishing legal basis for regular update and improvement of energy codes,
   - developing and implementing more stringent energy codes,

- making codes more effective through standardized compliance tools and a focus on actual building performance,
- expanding code inspections beyond just the largest cities,
- providing adequate resources for effective enforcement.

3. Support the reform of the power sector and energy prices to help correct wrong pricing signals and promote innovation that can bring greater efficiencies and significant cost savings through:
   - decoupling utilities' sales from their profits,
   - pricing reform to ensure electricity rates represent the true cost-to-serve,
   - introducing metered heat and cooling to link customer behaviors directly to costs.
4. Increase access to private capital through greater financing and investment opportunities to help stimulate behavioral change and stakeholder demand for efficiency, through:
   - developing workforce competence,
   - supporting broader knowledge of the co-benefits of building energy efficiency, such as comfort, health and productivity,
   - supporting private sector investment through innovative financing mechanisms,
   - establishing subsidies and rebate programs,
   - setting minimum targets for ensuring a percentage of newly constructed affordable housing meets energy efficiency standards.

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Table 5. Summary of Barriers and Solutions.

Focus Areas	Barriers	Solutions	Metrics
Prefabrication/ Longer Life Buildings	• Development emphasis on scale and quantity ("sprawl") • Replacing old with new "landmark" buildings	• National and local coordinated construction planning • Promote the industrialization of buildings ("prefab")	• Rate of new construction and demolition
Passive Building & Integrative Design	• Owners/developers are unaware • Non-supportive codes and enforcement • Designers and builders are unfamiliar • Upfront cost	• Codes based on whole-building energy use • Legal basis for regular energy code improvement • Workforce training to reduce cost and risk • Building energy use transparency	• Residential and commercial building energy use intensity
Efficient Appliance and Equipment	• Low efficiency standards • Lack of information on and consumer trust of energy label • Upfront cost	• World-class appliance labeling • Energy efficiency project financing	• Super-efficient equipment percent market share
Microgrid and Demand Response	• Historic use of inexpensive labor • Lack of skills to install and use	• Train operators for pro-active maintenance • Create market for demand response	• Percent share of buildings with load flexibility
Renewable and Fuel Switch	• Upfront cost • Non-supportive markets	• Fuel switching project financing • Energy pricing and tariff structure reform • Subsidies and incentives	• Share of biomass in rural residential, solar water heating in urban residential, solar PV and heat pumps all buildings

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