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As China's rapid urbanization continues and urban dwellers become more affluent, energy use in buildings is expected to grow. To understand how this growth can be slowed, we explore four scenarios for Chinese buildings, ranging from a high-energy-demand scenario with no new energy policies to lowest energy demand under a techno-economic-potential scenario that assumes full deployment of cost-effective efficient and renewable technologies by 2050. We show that, in the high energy demand scenario, building energy demand has an average annual growth rate of about 2.8%, with slower growth rates in the other three scenarios. In all scenarios, CO_2 emissions grow slower than energy, with building CO_2 peaking around 2045 in the high energy demand scenario, and as early as 2030 in the techno-economic-potential scenario. We show that although various technological solutions, systems and practices can be very effective in minimizing building energy use, rigorous policies are needed to overcome multiple implementation barriers.

Rapid and continuing growth in the buildings sector could imperil the Chinese government's commitment for CO_2 emissions to peak around 2030[1–3]. Failure to achieve these goals could result in inordinate stress on the energy supply system in China. From an international perspective, energy use in buildings in China (already 5% of total energy-related CO_2 emissions for the globe) has the potential to form a significantly increasing portion of total global emissions by 2050 in the absence of strong and effective policies to reduce these emissions.

Chinese buildings could become a large source of global emissions. Building energy use presently accounts for 20% of total energy use in China (measured as primary energy, including conversion and transport or transmission losses)[4], compared with 40% for developed countries. Since 2010, new building construction in China has comprised close to half of the world's growth in new construction, but per capita building area is still much lower in China than in other major developed countries. As shown in Supplementary Fig. 1, residential floorspace per capita (in square metre, m^2) is 92 for the United States[5], 67 for Germany[6] and 50 for Japan[7], but is just 36 m^2 in China[8]. Driven by continuing rapid urban growth, the expansion of building stock and area will continue for years to come.

The buildings currently being constructed in China have lower levels of thermal integrity than those in developed countries. The comfort conditions are also much lower than in developed countries, including those in Asia[9–11]. This lower thermal integrity combined with the almost certain increase in these conditions as Chinese society becomes wealthier will increase energy use in buildings[12,13]. Additionally, vast amounts of biomass are used in rural areas for heating and cooking. Over time, as China develops, most of this traditional use of biomass will be replaced by modern fuels and electricity, thus driving building energy use to higher levels[14,15].

On the other hand, there are reasons to believe that energy use in buildings may not grow substantially starting from the middle or late in the period 2010–2050. Indeed, most of the trends identified above will saturate in the first two or three decades and then level off or decline. This will include saturation for household appliances and other energy-using equipment; saturation for commercial building areas for all types of buildings as China's per capita commercial space approaches international levels; slowing down and ultimately the end of mass migration to urban areas; reduction of residential construction as living space per capita reaches international levels; low population growth (Supplementary Fig. 2 and Supplementary Table 1).

This study evaluates trajectories for China's building sectors to 2050 and the potential impact of policies on fully deploying today's maximum techno-economically feasible efficiency and renewables measures for Chinese buildings using four scenarios. It builds on existing long-term scenario studies that mostly focus on the entire energy system of a country or groups of countries[13,16–18]. This study looks at just one sector, which is typically difficult to analyse due to a lack of data and because of the complex interactions between energy use and human behaviour. It differs from other recent, bottom-up, 2050 Chinese building modelling and scenario analysis studies by considering specific policy scenarios rather than only cost optimization[19], by going beyond only modelling end-uses to treat a variety of technologies and systems[20], and by explicitly modelling technology packages rather than general policies with assumed rates of energy efficiency improvement[21]. We find, in all four scenarios, in the face of a 580% growth in gross domestic product (GDP) and 60% increase in building area between 2010 and 2050, that primary energy demand growth ranges from 210% in the highest case to 40% in the lowest case over the 40-year period. Two intermediate cases, judged most likely, exhibit energy increases of 170% (business-as-usual with continuation of policy development and implementation) and 90% (aggressive policy) between 2010 and 2050. In all cases, CO_2 emissions peak before 2050, with business-as-usual peaking around 2040 and aggressive policy around 2030. Comparing the two extreme high and low cases, we find that space conditioning and building envelope measures together account

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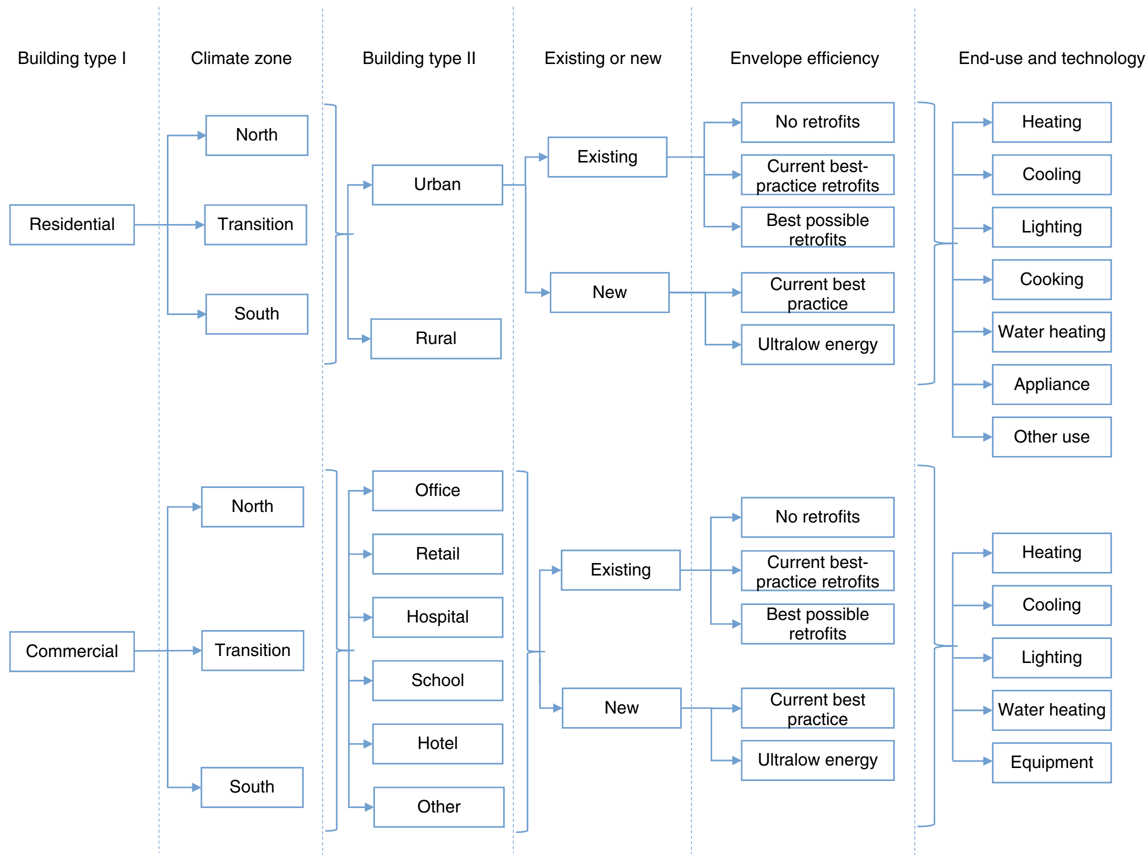

Fig. 1 | Residential and commercial building model structure. The high energy demand (HI) and techno-economic potential (TEP) scenarios serve as two benchmark high and low bounds of the analysis, reflecting two extremes of no new energy efficiency or renewable energy policies being adopted after 2010 under HI and full adoption of the highest cost-effective energy-saving and renewable technologies in TEP. Two additional scenarios are developed to represent the impact of continuing policy adoption at its current pace (business-as-usual, or BAU) and a more aggressive policy (AP) implementation resulting in overall 60% policy impact (penetration of 75% of the market and achieving 80% of desired energy savings with shortfall made up by poor installation, increased thermal comfort or rebound, and so on, in 2050). Supplementary Tables 2 and 3 provide illustrative data inputs for building energy use to contrast the different assumptions and drivers behind these four scenarios.

for nearly half of the energy-savings potential in 2050, followed by efficient equipment and existing building retrofits as the next two largest sources of potential savings.

Scenarios of future energy use in buildings

We developed four scenarios to represent two extreme scenarios of no policies to improve energy efficiency of Chinese buildings after 2010 and full adoption of cost-effective, highest efficiency measures by 2050, and two policy-driven scenarios of continuing the current pace of efficiency policy implementation and more aggressive policy implementation resulting in a majority of, but not all, potential energy savings. Figure 1 shows the multiple layers of building types, end-uses and technologies that were varied to define the scenarios.

Aggregate energy demand

Figure 2a,b provides a summary of the results of the analysis, both for energy (Fig. 2a) and for energy-related CO_2 emissions (Fig. 2b).

Figure 2a shows that primary energy use in Chinese buildings will continue to grow up to 2030, even under the techno-economic potential (TEP) scenario, due to multiple factors that contribute to increasing energy demand. These include continued rapid urbanization and population growth in the near term, and floorspace growth and growing demand for energy services with rising income. Without aggressive policies to counter this increase in energy service demand, the annual average growth rate (AAGR) of building energy demand for the time period 2010–2050 will reach 2.9% under the high energy demand (HI) scenario and 2.5% under BAU, significantly more than 2010 levels but still considerably lower than economic growth. This lower growth of energy is due to saturation of appliances and equipment ownership and gradual slowdown of new construction. With a stronger policy push and full implementation under the AP and TEP scenarios, respectively, building energy demand will either grow very slowly (AP) or plateau (TEP) after 2030 and decrease thereafter. The AAGR of building energy demand from 2010 to 2050 drops to 1.6% under AP and to 0.8% under TEP.

The results in Fig. 2b for CO_2 emissions show peaking of these emissions around 2030 for AP and TEP, 2040 for BAU and 2045 for HI. The peak of CO_2 emissions occurs sooner and at a relatively lower level than for energy as a result of the decarbonization of electricity. Solar thermal and solar electricity—both as part of the grid and on roofs and exterior walls—play an important role in producing additional CO_2 emissions reductions in the AP and TEP scenarios.

The results of the analysis of building energy use for the HI and TEP scenarios (showing the full techno-economic potential) for the whole building sector and major end-uses are shown in Fig. 3. The savings result from the multiplicity of end-uses depicted in this figure.

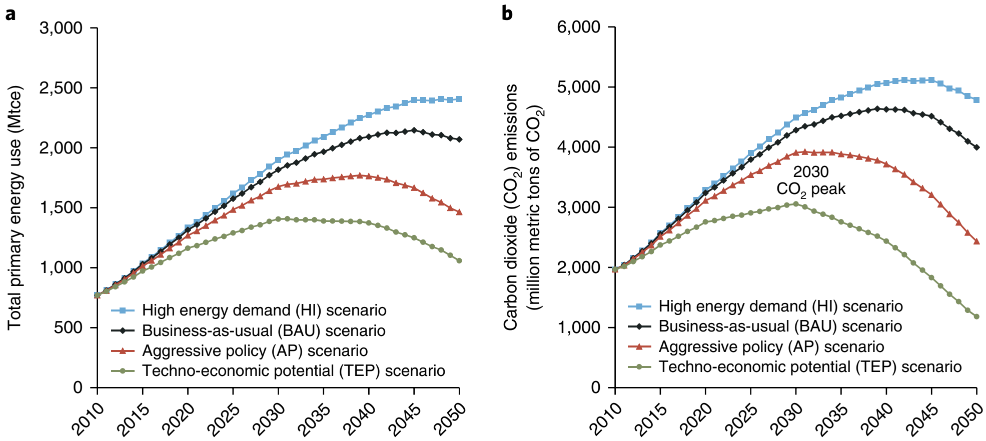

Fig. 2 | Energy use and emissions results by scenario over time. a, Projected building primary energy use for 2010–2050 by scenario. In calculating primary energy use, primary electricity is converted using the direct equivalent method consistent with the Intergovernmental Panel on Climate Change[60]. Mtce denotes million metric tons of coal equivalent, equal to 29.27 million GJ for China-specific coal energy content. **b**, Projected CO_2 emissions from energy use in Chinese buildings for 2010–2050 by scenario.

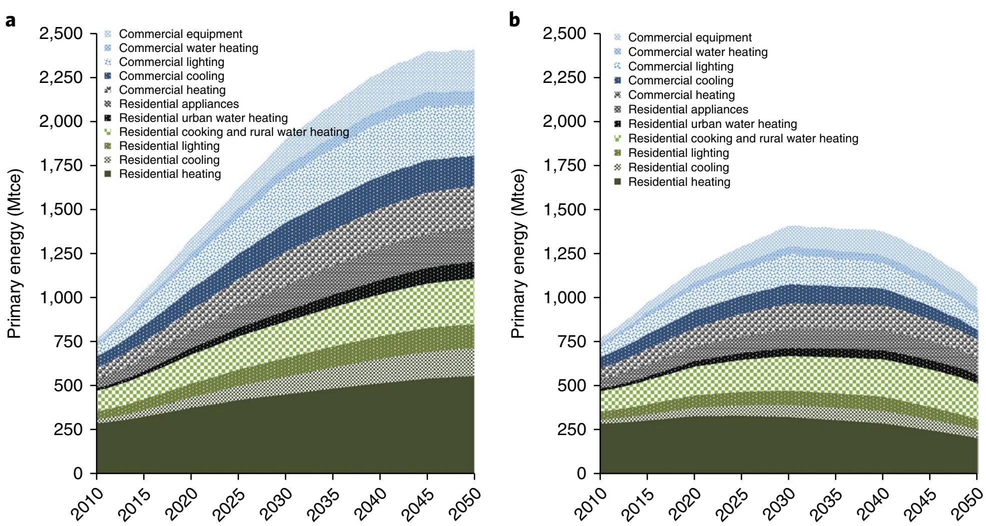

Fig. 3 | Projected building primary energy use by building type and end-use and by scenario. a, HI scenario. **b**, TEP scenario. In calculating primary energy use, primary electricity is converted using the direct equivalent method consistent with the Intergovernmental Panel on Climate Change[60]. Mtce denotes million metric tons of coal equivalent, equal to 29.27 million GJ for China-specific coal energy content.

Sources of energy savings

For this discussion we use the two extreme scenarios, HI and TEP, as these two scenarios illustrate the technical potential of energy-saving-absent policy considerations. Any energy reductions (compared to the HI scenario) require contributions from greater efficiency or reduced usage for all major end-uses. Specific reductions associated with each of the eight technology packages evaluated for the TEP scenario in 2050 are derived from independent scenario runs for the HI and TEP scenarios, with results developed to reflect each technology package as shown in Fig. 4.

Figure 4 shows potential sources of building energy saving. Space conditioning and building envelope measures represent 48% of the energy-saving differences between the HI and TEP scenarios. The next four largest contributors (lighting, efficient residential appliances and commercial equipment/plug loads, and existing building retrofits) contribute 33% to energy savings. Fuel switching for urban and rural buildings, especially from fossil fuels for electricity generation to renewables, and reduction of energy intensity of purchased electricity due to the decarbonized power sector represent the remaining 19% of energy savings. By building type, urban residential buildings contribute 49% of energy-saving potential, and urban commercial buildings 45%; rural buildings represent just 6% of potential energy savings, mainly due to the reduction in stock as a result of urbanization.

Similar to Fig. 4, the CO_2 emissions reductions chart in Supplementary Fig. 3 is virtually identical in shape to the energy-savings chart except that renewable electricity produces a much larger CO_2 emissions reduction. As such, CO_2 emissions in 2050 in the TEP scenario are 77% below the HI scenario, as discussed further in Supplementary Note 1.

The technology packages shown in Fig. 4 are considered for a commercial office building in China, taking into consideration the main climate zones in China. A similar analysis could be made for other commercial or residential building types with an appropriate technology mix and use pattern. The largest energy loads are space heating and cooling (columns 3 and 4 in Fig. 4). Space heating in an office building can be reduced to near zero by the use of insulation with very high K (or R) values, implementing heat recovery

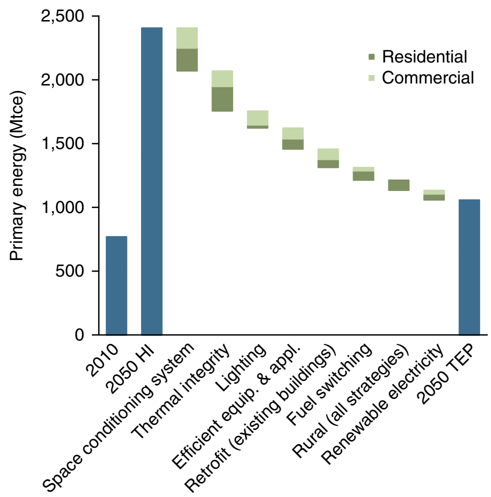

Fig. 4 | Potential 2050 primary energy savings by technology package for the Chinese buildings sector in the TEP scenario. Dark blue bars show total annual primary energy use for 2010 and 2050 under HI and TEP scenarios. Green bars show 2050 annual primary energy-saving potential by specific technology package, with the darker shade representing savings in residential buildings and the lighter shade representing savings in commercial buildings. Mtce denotes million metric tons of coal equivalent, equal to 29.27 million GJ for China-specific coal energy content.

Table 1 | Cooling systems energy-saving strategies for office buildings

Energy-saving technologies	Typical office building energy-saving potential
System commissioning[47–49]	10–15%
Improving duct sealing[50,51]	5–10% (depending on magnitude of leaks)
Fault detection and diagnostics[52,53]	5–15%
Economizers[54,55]	5–10%
Natural ventilation and night ventilation[56–59]	10–50% cooling loads

from naturally ventilated air, plugging leaks in the walls to keep air infiltration at low levels, and using window systems with insulating glazing and framing with low heat flow[22–25]. Many buildings in climates similar to Chinese climate zones already have space heating that is less than 20% that of a typical building (assumed in the HI scenario)[26–28].

Reducing energy use for space cooling is much more difficult than for space heating. A tight envelope is less effective because a large portion of the internal heat in a building is generated within the building (heat gain from lights, equipment and people). Table 1 illustrates a very important point: the energy savings are not from individual pieces of equipment but rather the entire energy system of which the equipment (chiller) is a part. The efficiency of a chiller in a commercial building might increase by 10–20% for the TEP scenario in 2050, but is limited by physical laws governing chiller performance and the size and weight limitations for the heat exchangers[29]. Considering the building loads and space cooling together as systems offers additional ways of conserving energy[2,30] (specific savings are listed in Table 1). Thus, energy savings from proper building and system design, operation and maintenance are much greater than savings from chiller efficiency improvements alone.

Many of the buildings that employ the measures in Table 1 are one-off demonstrations, and their low-energy systems may not be cost-effective. However, as more experience is gained (especially with design that integrates space conditioning systems with the building design, and vice versa), the number of buildings that have very low space conditioning and are cost-effective will increase over time until they are common enough to be aggressively promoted by policies.

The energy use of the lighting system stems not only from the efficacy of the lamp but also from other physical components (for example, the fixture), and most importantly from the myriad of factors that can lower usage: the use of task lighting, the installation of occupancy sensors to turn lights off when a space is unoccupied, and the use of monitoring and control to keep the system in calibration and provide finer control than occupancy sensors. In addition, daylighting involving the use of sensors and controls to measure outside light and dim artificial light has been shown to save 30–60% of lighting energy in the perimeter zones of buildings[31,32]. Where feasible, a building design can ensure that a large portion of the overall building comprises perimeter zones. Some of these system elements for providing suitable light require education of the building manager and for the occupant to be provided with more knowledge, and continuous monitoring of the lighting system performance is needed as such systems often need to be realigned or adjusted. Advances in performance and reductions in the cost of sensors and controls are critical enablers in all scenarios except HI. Indeed, research and development is needed to improve sensors and to reduce costs. It is reasonable to assume that lighting energy use could be 50–70% lower in 2050 in TEP than in HI, given the many ways in which lighting can be used and controlled by the occupant.

A reduction of energy intensity of 3% per year for the remaining energy-saving technology packages in Fig. 4—appliances and equipment, retrofits of existing buildings, fuel switching to natural gas and electricity, and retrofitting of rural buildings (generally residential buildings)—corresponds to an energy saving of 70% from HI to meet the potential shown in Fig. 4. Consideration of each of the packages suggests that such a magnitude of energy savings is possible.

The HI scenario, like the others, considers small incremental efficiency improvements on the order of 1% per year due to autonomous technological change, consistent with estimated rates of technology improvement of between 0.5 and 1% per year from analysis of a cross-section of countries[33]. Under the TEP scenario, it is assumed that 100% of new products sold by 2050 will be at the level of today's highest yet cost-effective efficiency. We note that an analysis of countries with efficiency standards and labelling programmes found average efficiency increases of 3–4% per year over a long period[33]. In Korea, for instance, efficiency improved 59% across all products covered by the national standards and labelling programme in only 14 years (1996–2010)[34].

Retrofitting existing buildings will yield significant energy savings. The existing building stock in China built before 2000 was subject to very few efficiency requirements. In this analysis, we assume that the existing stock that is not retired in the years leading to 2050 will be retrofitted to energy-efficient levels. Studies have shown that retrofitting existing Chinese buildings can save more than 50% of buildings' heating energy use[35], although such deep retrofits are not yet common. Installation of heat metering and application of energy-use-based heating tariffs enable residents to adjust their indoor air temperature and provide 10–20% energy savings[36]. Retrofitting commercial buildings can not only save heating energy use, especially in the cold climate of North China, but can at the same time also yield lighting and cooling savings. This study assumes that 70% of existing stock, except those that are retired, will be retrofitted by 2050 under TEP.

Fuel switching involves replacing coal-fired technologies with technologies that use electricity or natural gas. Examples include decreasing the use of coal stoves and using heat pumps to substitute for district heating. Ground source heat pumps can provide primary energy efficiency ratios of 120–160%, compared to 80–97% for traditional boilers[37]. Heat pump water heaters can have system efficiencies of 200% or more, and, when combined with solar hot water, heat pump efficiency can reach 400–600%[38].

Our main conclusion is that systems included in the technology packages are available today to achieve the goals of the 2050 TEP scenario, with the exception of a need to improve sensors and controls. There exist buildings in China and the United States that already achieve the 2050 energy use objectives. Some of these buildings demonstrate the cost-effectiveness of the technology packages. In other words, neither technology nor economics need be a barrier to such buildings. However, the fact that few buildings such as this exist and few are fully successful suggests that there are significant barriers to their achievement. These barriers include institutional barriers such as distorted energy price and tariff structures, non-supportive building codes for design changes, as well as a lack of information and skilled work force for advanced design and retrofits.

Illustrative policies and measures proposed to overcome these barriers include more aggressive efficiency standards and codes for appliances, equipment and buildings; testing in the field of building performance; development and commercialization of low-cost high-performing sensors and control systems; creation of training programmes for practitioners of all aspects of energy saving in buildings (with special attention to whole building training that provides in-depth understanding of integrated design and construction); production of guide books for very energy-efficient building design and assurance of their use by design institutes and other building professionals; numerous aspects of lighting design that save energy and provide high-quality light as needed; licensing requirements for building professionals that include demonstrating a mastery of energy efficiency and low-carbon solutions for buildings; and significant incentive programmes for one to two decades. A total of 30 different policies matched specifically to the eight efficiency/low-carbon pathways are also presented in Supplementary Note 2. Ongoing work involves deeper research on the requirements for success in these pathways.

Conclusions

Based on our modelling results, energy demand for buildings in the long run is most likely to fall between the BAU and AP scenarios. BAU in 2050 shows energy use increasing by 170% and CO_2 emissions by 100% above 2010 levels. In AP, energy use increases by 90% and CO_2 emissions by 20% in 2050. Peak CO_2 emissions are achieved around 2040 in BAU and 2030 in AP.

It is important to focus on systems rather than technologies to achieve energy efficiency. In general, systems (for example, space cooling system versus chillers and the thermal performance of the entire building envelope versus insulation) can save many times more energy than technologies. It is this insight that makes possible scenarios such as the AP scenario, in which energy demand grows by an AAGR of 1.6% over the 40-year period (higher growth to 2030 when growth becomes negative) in spite of the AAGR of 4.6% for GDP and 1% for building area over this period.

The AP and TEP scenarios are achieved by following seven energy end-use pathways for urban buildings. These pathways consist of sets of systems, technologies and practices. They include the following: space conditioning equipment and systems, thermal integrity improvements, efficient lighting systems, super-efficient appliances and equipment, energy retrofits for existing buildings, fuel switching, and use of solar photovoltaic panels and solar thermal energy systems.

The reduction in CO_2 emissions requires steps to ensure the rapid growth of low-carbon electricity generation technologies for the grid—especially wind, nuclear power and photovoltaic. Also, in spite of the very low growth of building in rural areas, existing buildings will benefit from retrofits and the new ones from employing state-of-the-art energy efficiency technologies and systems.

We present specific policies for each of the pathways to achieve the AP scenario and assume that these policies achieve on average 60% of full success in terms of degree of implementation, effectiveness of policies and (implicitly) losses due to rebound for the entire country by 2050. Altogether, some 30 policy initiatives—many already under way in China—need to have significant impacts during or before the 2020–2030 period for the 2050 AP scenario to be realized.

The concern about building energy use growing without limit is allayed by the results of this work. Because of saturation effects and building and equipment turnover, energy for buildings peaks before 2050 for all cases except the high case. It is highly unlikely that China will abandon its energy efficiency programmes and thus the high case is also highly unlikely.

This work points to the possibility that China can, through the development and implementation of energy efficiency and renewable energy policies in the AP scenario, achieve CO_2 emissions from energy use in buildings that are just 20% above 2010 levels in 2050 and likely to decline rapidly thereafter. To achieve these long-term results, policy actions must take place in the short term because buildings constructed now will be consuming energy for many decades. The payoff from these policies, in terms of reduced CO_2 emissions in the long term, is significant.

Future work is needed to model and assess the specific impacts of individual policy initiatives based on actual experience in different countries, with additional consideration for human and occupant behaviour. Additional co-benefits of reducing fossil fuel consumption, including corresponding reductions in air pollutants and particularly PM2.5 (particulate matter with a diameter of less than 2.5 μm) emissions, also need to be further evaluated.

Methods

Modelling methodology and macroeconomic drivers. The analysis of energy use in urban and rural residential and commercial sector buildings for the period 2010–2050 uses the Berkeley Lab's China 2050 Demand Resource Energy Analysis Model (DREAM)[39]. This model is an application of the LEAP (Long-Range Energy Alternatives Planning) software platform developed by Stockholm Environmental Institute. The suitability of the chosen model and modelling applications to the problem of long-term scenarios for China has been evaluated by others[40,41].

Figure 1 shows the model structure for residential and commercial buildings. In theory, data for this model structure require estimates of unit energy consumption for each year of the period. In practice, only for the first, last and one or more of the intermediate years need be specified as inputs. Data for other years are interpolated. This application is data-rich, containing thousands of data entries to characterize energy use for the first year of the period (2010) and last year of the analysis (2050). The model accounts for building stock turnover due to demolition and construction. Building equipment and appliances also turn over at the end of their natural lifetimes.

In addition to three to ten efficiency levels for technologies, buildings data characterize the following: residential and commercial buildings in each of three climate zones; for existing buildings, three levels of retrofits (including none); for new construction, two levels of energy-efficient construction practice; urban and rural buildings for residential buildings; six building types for commercial buildings; seven appliance and space conditioning end-uses, each with a least three efficiency levels.

The model structure to accommodate these configurations is shown in Fig. 1. There are more than 100 different combinations of building types: residential (urban/rural), commercial (office, retail, hospital, school, hotel and other), region (north, transition and south), vintage (new/existing) and building envelope efficiency level (three for existing, two for new).

For each of these building configurations, there are seven end-uses and up to five other factors that need to be taken into consideration for most or many technologies/end-uses: (1) penetration of the energy-efficient technology, (2) incremental cost of increased efficiency, (3) usage (for space conditioning end-uses), (4) saturation and/or number per household (for example, television sets) and (5) energy and technology type.

The China 2050 DREAM model calculates the future energy consumption of buildings (FECB) using the following general formula:

$$\mathrm{FECB} = \sum_n \left(\mathrm{AB}_n \times \sum_q \left(P_{q,n} \times \left(\sum_k \left(\frac{\mathrm{Intensity}_{q,n} \times \mathrm{Share}_{k,q,n}}{\mathrm{Efficiency}_{k,q,n}} \right) \right) \right) \right)$$

where k denotes the energy/technology type, q denotes end-use, n denotes building type, AB_n is the floorspace of building type n, $P_{q,n}$ is the penetration of end-use q of building type n, $\mathrm{Intensity}_{q,n}$ is the energy intensity of end-use q of building type n, $\mathrm{Share}_{k,q,n}$ is the share of the kth energy/technology of end-use q of building type n, and $\mathrm{Efficiency}_{k,q,n}$ is the efficiency of the kth energy/technology of end-use q of building type n.

A normalization for the year 2010 is carried out by adjusting inputs so that the overall building energy use in the model is equal to the aggregate estimate of building energy demand obtained from various sources in China. Specifically, utility data on electricity use in buildings can be aggregated in different weather regions. Also, data on energy supply, adjusted for net exports and changes in stock, can provide useful information about aggregate energy use in buildings.

For this work, the normalization process represented a change in overall energy demand of <10%. This suggests that the many assumptions needed to build up aggregate demand from the 'bottom up' are, in the aggregate, reasonable, even if individual data entries are necessarily approximate.

Supplementary Table 1 presents the detailed assumptions about three macroeconomic parameters. These values are based on Chinese government projections[42]. The average annual GDP growth rate consistent with these values is 6.5% (2010–2030) and 3.4% (2030–2050), resulting in 4.9% average annual growth rate over the entire 40-year period.

Population is essentially flat over the period, increasing 6% between 2010 and 2020 and declining 4% between 2020 and 2050. This may understate the population growth somewhat because of the recent revocation of the one-child policy.

Urbanization rates are assumed to grow from 50% in 2000 to 68% in 2030 and 78% in 2050[43]. This compares with a current urbanization rate in the United States of 81%.

Scenarios. Four scenarios are defined for the study. In the HI scenario China enacts no new energy efficiency or renewable energy policies after 2010—a highly unlikely circumstance. This case is counterfactual from 2010 to the present as the Chinese government has continued to develop and implement new policies and strengthened implementation of existing policies for energy saving in buildings. This approach is similar to the assumptions made by the Energy Information Administration in its forecasts of US energy demand, and is intended to serve as baseline for understanding any additional policy impacts after 2010.

The BAU scenario is the best estimate of what will happen assuming policy development and implementation continue to receive the emphasis they have now.

A more optimistic AP scenario reflects the effects of China being able to achieve 80% policy effectiveness (including any take-back of heating and cooling energy savings by improving comfort conditions) and 75% market penetration, resulting in overall 60% impact of policies in 2050.

In the highly unlikely TEP scenario the highest efficiency and renewable measures that are cost-effective or near cost-effective today are fully adopted in all buildings by 2050. This represents the maximum techno-economic energy-saving potential that exists in Chinese buildings based on today's commercially available technologies.

As the buildings sector is also a major electricity end-user, we also considered the impact of a significantly decarbonized power sector on reducing building CO_2 emissions in the AP and TEP scenarios. Previous studies[44] have analysed the impact of power sector policies on power sector CO_2 emissions, so it is not discussed in detail here.

Building construction rate assumptions. Driven by rapid urbanization and unprecedented economic development, China has seen rapid construction of buildings over the past decades. From 2003 to 2014, construction revenue experienced a 30.1% annual growth, increasing from ¥750 billion (US$109 billion) to approximately ¥17,700 billion (US$2,570 billion)[45]. In 2010, more than 2 billion m^2 of new buildings were constructed in China. This annual rate is expected to continue through 2020.

In 2010, China's residential buildings contained 44 billion m^2 of floorspace. Supplementary Fig. 1 compares per capita residential (Supplementary Fig. 1a) and commercial (Supplementary Fig. 1b) building area in China with that of key countries in the EU, the United States and Japan. Driven by continuing rapid urban growth—equivalent to increasing population in urban areas by the total population of the United States in a little over two decades—this rapid expansion of the building stock will continue for years to come.

Based on the assumed construction rate and the lower occupancy (and thus greater number) of buildings, residential building floorspace will be 64 billion m^2 in 2050, a 45% increase from 2010. By 2050, rural residential floorspace will account for 22% of total residential floorspace, down from the 56% share of total residential floorspace in 2010.

Global commercial building floorspace has been driven by the employment-in-service sector of the economy and growth in the average floorspace per employee, as described in a previous study[46]. For this study, a maximum floorspace per employee of 45 m^2 per employee for 2050 was set (up from 32.6 m^2 in 2010), equivalent to the current UK level. The total commercial floorspace is projected to nearly double from 12 billion m^2 in 2010 to reach 23 billion m^2 by 2050, with office buildings occupying one-third of total commercial floorspace.

An average construction of 1.47 billion m^2 per year for the period 2021–2050 is projected in urban China, with urban residential construction dominating, as shown in Supplementary Fig. 2. While rural building stock is captured in the analysis, rural new construction is negligible because of the continuous exodus of 300 to 400 million rural residents to urban areas[46]. The total projected residential and commercial floorspace does not vary between scenarios. However, the mix of building envelope efficiency levels for existing and new buildings does vary by scenario, as discussed in the Scenarios section.

Building energy data and assumption. This study uses office buildings as a significant portion of the commercial building sector to explain key input parameters in Supplementary Table 2. Supplementary Table 2 shows the weighted-average energy used for heating and cooling office buildings (heating and cooling load) and average heating and cooling system efficiency across the entire office building sector, weighted by the three building envelope efficiency levels for existing buildings (that is, no retrofits, current best practice retrofits and best possible retrofits) and two building envelope efficiency levels for new buildings (that is, current best practice and ultralow-energy new buildings). The relative shares of the different building envelope efficiency levels for existing and new buildings vary by scenario, and reflect the impact of technology adoption (for example, under HI and TEP) and policy adoption on changing building technology-specific and building systems' heating and cooling loads and efficiencies. For example, the best possible retrofits' share of existing buildings range from a low of 0% under the HI scenario to a high of 75% under the TEP scenario, with intermediary shares of 34% and 59% for the BAU and AP scenarios, expected to result from differing degrees of policy implementation. The weighted-average primary energy intensity for heating and cooling is calculated accordingly and shown in this table for base year 2010 and for 2050 for the four scenarios. Data are compiled for three typical climate regions in China as shown in Supplementary Table 2.

The illustrative final energy use per square metre intensities of the other energy services in urban and rural residential and commercial buildings for 2010 and 2050 for the four different scenarios are shown in Supplementary Table 3. For these end-uses, there is no additional differentiation by climate zone. The differences in these final energy end-use intensities result primarily from the differing paces of penetration of today's super-efficient equipment, ranging from only 40% adoption by 2050 under HI and 46% adoption by 2050 under BAU to 90% and 100% adoption by 2050 under AP and TEP, respectively.

A description of the selected inputs for building types and end-use technologies and efficiencies by scenario is provided in Supplementary Note 2 (previously introduced in ref. [39]).

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Author contributions
N.Z. led the design of the research, modelling and manuscript preparation. N.K. and W.F. assembled input data. N.K. implemented the model and analysed output data and results. W.F. developed additional waterfall scenarios that were implemented in the model by J.K. M.L. validated modelling results, and prepared the main paper with input from N.Z., N.K., W.F. and J.K. All authors discussed the results and implications and commented on the manuscript at all stages.