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Global Scenarios of Urban Density and Its Impacts on Building Energy Use Through 2050

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SPECIAL FEATURE

Global scenarios of urban density and its impacts on building energy use through 2050

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Although the scale of impending urbanization is well-acknowledged, we have a limited understanding of how urban forms will change and what their impact will be on building energy use. Using both top-down and bottom-up approaches and scenarios, we examine building energy use for heating and cooling. Globally, the energy use for heating and cooling by the middle of the century will be between 45 and 59 exajoules per year (corresponding to an increase of 7–40% since 2010). Most of this variability is due to the uncertainty in future urban densities of rapidly growing cities in Asia and particularly China. Dense urban development leads to less urban energy use overall. Waiting to retrofit the existing built environment until markets are ready in about 5 years to widely deploy the most advanced renovation technologies leads to more savings in building energy use. Potential for savings in energy use is greatest in China when coupled with efficiency gains. Advanced efficiency makes the least difference compared with the business-as-usual scenario in South Asia and Sub-Saharan Africa but significantly contributes to energy savings in North America and Europe. Systemic efforts that focus on both urban form, of which urban density is an indicator, and energy-efficient technologies, but that also account for potential co-benefits and trade-offs with human well-being can contribute to both local and global sustainability. Particularly in growing cities in the developing world, such efforts can improve the well-being of billions of urban residents and contribute to mitigating climate change by reducing energy use in urban areas.

urbanization | cities | urban form | climate change | mitigation

Urban areas account for 67–76% of global final energy consumption and 71–76% of fossil fuel-related CO_2 emissions (1). With the global urban population expected to increase by an additional 2.5 billion people between 2010 and 2050 (2) and concomitant expansion of urban areas (3), the urban shares in total energy use and greenhouse gas (GHG) emissions are also expected to increase. It is not, however, just the rate or scale of urbanization that matters for urban energy use. An important, and often underexamined, factor is the future spatial patterns of urban development.

The most recent Intergovernmental Panel on Climate Change (IPCC) assessment report identifies urban form, the 2D and 3D relationships between the physical elements, spaces, and activities that constitute urban settlements, as a key determinant of urban energy use (4). Urban form significantly affects both direct (operational) and indirect (embodied) energy (5). Beyond energy use, urban form also affects two other dimensions of sustainability: human well-being and economic productivity. Urban form that enables nonvehicular transport, characterized by smaller city blocks, higher street connectivity, mixed land use, and higher population and built-up densities, has been shown to be beneficial for health by promoting more physical activity, such as walking and bicycling (6, 7). Higher levels of population density, one key feature of urban form, are associated with economic co-benefits (8), higher productivity (9), and vibrant street life (10). Overall, more compact urban forms are important levers for targeting transportation energy use reductions (11). However, there are trade-offs because higher urban densities are also associated with disproportionately larger embodied energy in buildings and other infrastructure (5), higher exposure to air pollutants (12), and traffic congestion (13).

However, we have little understanding of how future urban growth in different parts of the world will manifest in terms of spatial development and what its implications will be for human well-being and the environment. Our primary goals in this study are to develop possible scenarios of future urbanization, using urban population density as the metric, and to estimate the energy implications of these different urban futures. We aim to answer the following questions: What are likely future trajectories in urban densities, and what is the potential for cities worldwide to alter their densities significantly? Globally, what are the relative energy savings from increasing building energy efficiencies versus increasing urban densities? Where might concerted efforts to alter urban densities yield the greatest benefits in terms of energy savings?

Our analysis is a global-scale study that provides scenarios of the spatial dimension of urbanization and associated energy use in the built environment. Of the three major forms of urban energy—embodied, operational, and transport (5), the scope of our paper is limited to operational building energy use. We use two global energy/climate models: One is a top-down regionally

SUSTAINABILITY SCIENCE

Significance

Urban density significantly impacts urban energy use and the quality of life of urban residents. Here, we provide a global-scale analysis of future urban densities and associated energy use in the built environment under different urbanization scenarios. The relative importance of urban density and energy-efficient technologies varies geographically. In developing regions, urban density tends to be the more critical factor in building energy use. Large-scale retrofitting of building stock later rather than sooner results in more energy savings by the middle of the century. Reducing building energy use, improving the local environment, and mitigating climate change can be achieved through systemic efforts that take potential co-benefits and trade-offs of both higher urban density and building energy efficiency into account.

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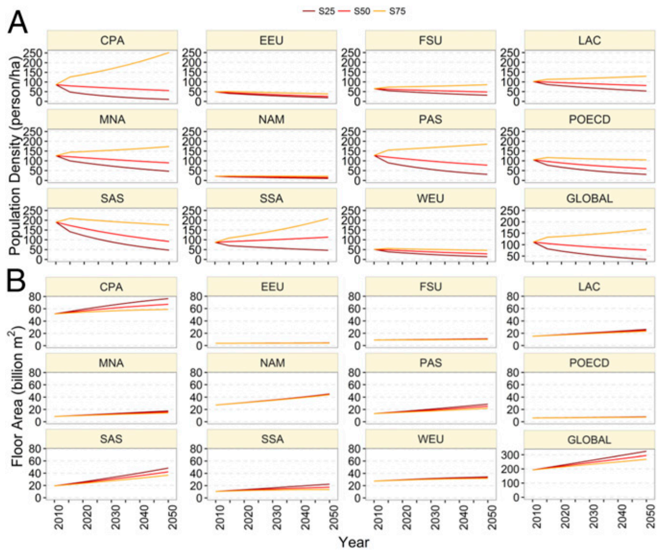

Fig. 1. Urban population density (*A*) and respective floor area (*B*) forecasts by region through 2050 under three urban density scenarios used in the top-down analysis. The 11 International Energy Agency regions used in the analysis are Centrally Planned Asia and China (CPA), Central and Eastern Europe (EEU), newly independent states of the former Soviet Union (FSU), Latin America and the Caribbean (LAC), the Middle East and North Africa (MNA), North America (NAM), Other Pacific Asia (PAS), Pacific countries that are members of the Organization for Economic Cooperation and Development (POECD), South Asia (SAS), Sub-Saharan Africa (SSA), and Western Europe (WEU). Results are also provided in tabular format in Dataset S1.

aggregated integrated assessment model, and the other is a detail-rich bottom-up approach that starts with individual buildings (*Methods*). In presentation of our findings, we adopt the regional representation of the International Energy Agency (Fig. 1 and *SI Appendix*, Table S1).

We use scenarios as a set of plausible stories to explore the long-range outlook for urban areas and building energy use from 2010 to 2050 (Table 1). For the top-down analysis, one set of scenarios represents three different pathways of urban (population) density, an imperfect but common proxy for urban form (11). We use a single projection of the urban population for every region across all scenarios. Therefore, the scenarios of urban density representing low, medium, and high levels of urban population densities characterize a range of urban forms from dispersed to compact. We also calculate the regional floor area projections corresponding to each of the three urban density scenarios. The scenarios for building energy use, however, involve different rates of energy efficiency improvements. There are two scenarios of energy efficiency: a business-as-usual scenario that keeps efficiency improvements at their current rates and an advanced scenario that assumes faster energy efficiency improvement for all regions.

The bottom-up analysis focuses on different levels, timing, and depth of retrofitting the existing built environment as a constituent of future urban form. In this analysis, based on regional urban density estimates already built into the model, the regional variations serve as a substitute for the scenarios of urban density used in the top-down analysis. In addition, we developed three scenarios of building energy use in the bottom-up analysis. The frozen efficiency scenario keeps the energy efficiency of new and retrofitted buildings unchanged from their 2010 efficiency levels. The moderate efficiency scenario assumes improvements in the energy efficiency levels of new and retrofitted buildings; however, these levels reflect current policy trends and are far from the levels permitted by current state-of-the-art architecture and retrofit technology in the respective regions. The deep efficiency scenario assumes that the energy efficiency levels permitted by current state-of-the-art architecture and retrofit technology become the "standard" after a transitional period of market adjustment, i.e., in about 5 years.

Results

Urban Population Densities Are Likely to Continue to Decline Through 2050. For the past three decades, urban population densities have been declining across all countries, income levels, and geographies (1). Our analysis shows across the three future urban density scenarios that urban population densities are likely to continue to decline for nearly all geographic regions through the first half of this century (Fig. 1*A*). The range across the three scenarios tends to be very large in all developing regions, exhibiting evidence of their ongoing urbanization dynamics, with their cities exhibiting a wide variety of expansion patterns from more compact to more dispersed. This range is particularly large in Centrally Planned Asia and China (henceforth, China, in short, to refer to the whole region), whose urban population density was about 90 persons per hectare in 2010. Its urban population density in 2050 is forecasted to range from 10 to 250 persons per hectare, primarily due to the rapid increase of urban population density in the most compact urban form (S75) scenario. Of all of the developing regions, only South Asia is forecasted to exhibit more dispersed urban forms in all three scenarios. Both North America and the two European regions exhibit trajectories toward more dispersed urban forms, but with little difference between the three scenarios. The population densities in these regions remain below 50 persons per hectare through 2050 in all three scenarios (Fig. 1*B*).

Despite the relatively wide ranges across the urban density scenarios, the ranges of the corresponding floor area projections are remarkably narrow (Fig. 1*B*). There are, however, significant differences in both the scale and pace of projected change in floor area from one region to another. The most rapid projected increases in floor area are expected in South Asia, increasing by 80–150% from 2010 to 2050. China has the most floor area throughout our study period. The rate of increase in its floor area tends to slow down over time. Nonetheless, starting with slightly over 50 billion m^2 in 2010, projected floor areas will range from 58 to 78 billion m^2 in 2050 across the three urban density scenarios.

With the exception of the Middle East and North Africa, almost all developing regions exhibit wider ranges than developed regions in their projected floor areas. This finding suggests the emergence of widely different urban forms in cities of developing regions during our study period (Fig. 1*B*). In particular, the difference between the most compact and most dispersed scenarios is

Table 1. Scenarios used in the top-down and bottom-up analyses in the study

Analysis	Scenario	Urban density	Energy efficiency*
Top-down	S25BAU	Low	Current initiatives
	S50BAU	Medium	Current initiatives
	S75BAU	High	Current initiatives
	S25ADV	Low	Advanced
	S50ADV	Medium	Advanced
	S75ADV	High	Advanced
Bottom-up	Frozen V1	Medium	At year 2010 levels
	Moderate V1	Medium	Current initiatives with slow deployment
	Deep V1	Medium	State of the art with fast deployment
	Moderate V2	Medium	Current initiatives with fast deployment
	Deep V2	Medium	State of the art with slow deployment

*Note that although energy efficiency refers to the efficiency in energy used for heating and cooling of unit floor area in the top-down analysis, it refers to the efficiency in building retrofit in the bottom-up analysis. The details of each scenario are provided in *SI Appendix*.

the largest for China, with about 20 billion m^2. In contrast, the range of forecasted floor area in 2050 will be modest at 2–3 billion m^2 for regions that are already highly urbanized: the Americas, Europe, the former Soviet Union, and the Pacific countries that are members of the Organization for Economic Cooperation and Development. In North America, the increase in projected floor area across all three scenarios is comparable to those floor areas projected for the developing regions. It is notable, however, that the range of the projections across the three urban density scenarios is narrow for North America. These projections suggest that even though it is a highly urbanized region, North America will continue adding built-up space at similar rates to developing regions.

Urban Density Influences Future Energy Use as Much as Energy Efficiency. Globally, our top-down analysis shows that urban density is about as effective as efficiency improvements for energy savings in building heating and cooling. Across all urban density scenarios, advanced efficiency technologies result in about 7 exajoules per year ($EJ \cdot y^{-1}$) less energy use for heating and cooling in 2050 (Fig. 2*A*). In comparison, the difference between the high and low urban density scenarios (corresponding to the most compact and least compact urban form futures) is about 8 $EJ \cdot y^{-1}$ (in the case of advanced efficiency) to 9 $EJ \cdot y^{-1}$ (in the case of business-as-usual efficiency) in 2050. Across all scenarios, the annual global energy use for heating and cooling may increase 7–40% from 2010 levels by 2050 (Fig. 2*A*). For the high urban density and advanced efficiency scenario combination, the annual building energy use for heating and cooling first plateaus around 2030 and then decreases after 2040, settling just below 45 $EJ \cdot y^{-1}$ in 2050. Thus, the global annual energy use in 2050 is forecasted in our top-down analysis to range from 45 to 59 $EJ \cdot y^{-1}$ and falls well within the range of the forecasts for heating and cooling reported in the IPCC Fifth Assessment Report (4).

Regionally, the largest proportional increases in building energy use are projected for South Asia (Fig. 2*A*). Nonetheless, by 2050, China's building stock will consume about fivefold more than South Asia. In addition, China's energy use for heating and cooling will exceed the energy use of North America across all of the scenarios, except in the high urban density scenario (S75). In contrast, the largest proportional decreases are expected for the former Soviet Union and Eastern Europe.

Cumulatively, our top-down analysis projects that urban density becomes slightly more effective in moderating increases in building energy use than efficiency improvements (Fig. 2*B*). From 2010 to 2050, the difference in cumulative building energy use between the low and high urban density scenarios ranges from 150 to 200 EJ, respectively, under the business-as-usual and advanced efficiency scenarios. The difference between the two efficiency scenarios ranges from 125 to 150 EJ across the three urban density scenarios. Overall, the largest possible cumulative savings in building energy use would be about 300 EJ. Savings at such levels could be attained if all of the regions around the world adopted a compact urban development trajectory while simultaneously investing in advanced efficiency (S75ADV scenario in Fig. 2*B*).

Collectively, China, Europe, and North America account for the bulk of the future cumulative energy use for heating and cooling through 2050 (Fig. 2*B*). However, of these three regions with the largest forecasted building energy consumption, China has the largest potential for savings. Moreover, two-thirds of this potential can be realized through encouraging higher urban densities (i.e., more compact urban forms), not only in China but also in South Asia, Sub-Saharan Africa, and the Middle East and North Africa. In North America and Europe, efficiency improvement is more influential than urban density, whereas in Latin America and the Caribbean and the former Soviet Union, both urban density and efficiency improvement are equally influential. Advanced efficiency makes the least difference in building energy use in South Asia and Sub-Saharan Africa but the largest difference in North America and Europe.

Retrofitting Sooner Does Not Necessarily Lead to Less Building Energy Use in the Future. The state of the building stock plays a crucial role in urban energy demand. Across all of the retrofit

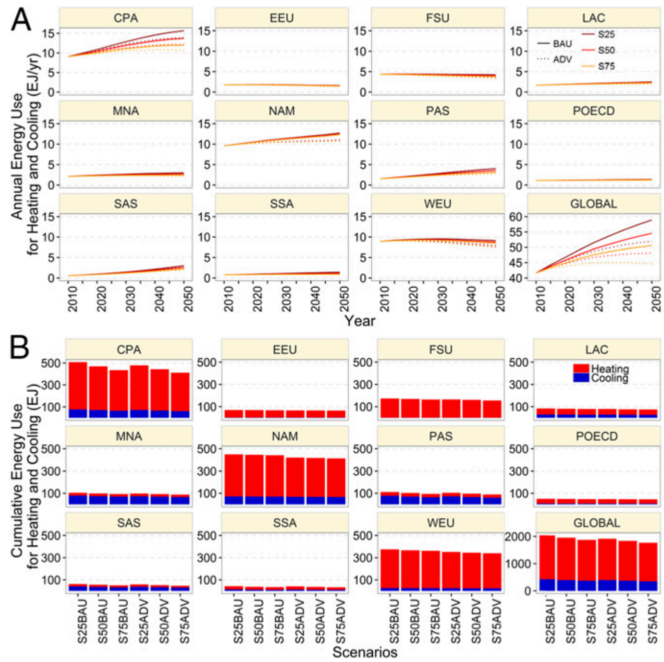

Fig. 2. Regional and global energy use for heating and cooling under the six combined scenarios in the top-down analysis: less compact (S25), baseline (S50), and more compact (S75) population density scenarios; and advanced efficiency scenario (ADV) and business-as-usual (BAU) efficiency scenario annually (*A*) and cumulatively (*B*) from 2010 to 2050. The regional breakdown is provided in Fig. 1. Results are also provided in tabular format in Dataset S2.

scenarios in our bottom-up analysis, new construction will dominate building energy use for heating and cooling in 2050 in developing regions. However, in developed regions, retrofitting of the existing building stocks will be especially important (Fig. 3). In North America and Europe, the majority of the existing building stock will either be replaced or renovated by 2050 (Fig. 3). Overall, both new buildings and efficiency retrofits present a tremendous opportunity to decrease energy use worldwide. In each world region, the frozen and moderate scenarios result in significantly larger building energy demand for heating and cooling than the deep scenario. Among the developing regions, retrofitting makes the largest difference in the case of more densely populated South Asia; this region is followed by less densely populated Latin America and the Caribbean, which, nevertheless, is at a relatively more advanced stage of urbanization. Thus, the latter region starts with a larger share of energy use by the existing building stock with standard technology. The forecasted energy use in South Asia is larger in the bottom-up analysis compared with the top-down analysis because of the differences between the two with regard to heating energy demand, particularly in India.

Our bottom-up analysis suggests that increasing the retrofit adoption rate before markets sufficiently mature to accommodate deep retrofits may lead to a failure to achieve the largest possible reductions in building energy demand. For instance, in the moderate scenario, a retrofit adoption rate of 5% per year (S2 variant) achieves about the same amount of reduction in building energy demand by 2050 as does an adoption rate of 1.4–3% per year (S1 variant) (Fig. 3). Similarly, assuming a retrofit adoption rate of 5% per year instead of 3% per year turns out to be counterproductive in the deep scenario: The faster adoption rate stabilizes global building energy demand at a higher level than the slower adoption rate (Fig. 3). This observation is the most evident for North America, where ambitious energy performance standards can achieve much larger energy demand reductions than increasing the retrofit adoption rates prematurely. Thus, waiting to retrofit buildings until the current most-energy saving technologies are widely available will yield the most savings in long-term building energy use.

Discussion

Our analysis suggests that the potential for cities to alter urban densities varies significantly across the world. For some regions undergoing high rates of urban population growth (i.e., China, South Asia, Pacific Asia, the Middle East and North Africa, and Sub-Saharan Africa), the wide range of possible urban density trajectories is indicative of the substantial leverage that urban policies can have. Steering cities in these regions toward more energy-efficient urban densities is an ambitious but attainable goal, particularly for the regions in Asia that collectively exhibit similar ranges of economic development and income levels. However, even in our most compact urbanization scenario, the urban population densities are projected to continue decreasing through 2050 in South Asia, Europe, and North America. These trends suggest that the dispersed urban forms in these regions will continue to dominate urban expansion patterns well into the first half of the 21st century. Furthermore, the urban density futures of North America, Latin America and the Caribbean, and Europe suggest a lock-in within an established trajectory of the spatial arrangement of their respective urban structures. Recently, scholars have identified urban form as a type of carbon lock-in that shapes energy demand for long periods (14). Once in place, the physical structure of urban areas cannot be easily changed, and creates long-lasting interdependencies across land use, transport, and buildings that lock in the energy demand in these sectors.

Our results from our top-down analysis show that urban density will be a key factor in determining building energy use through the first half of the century. Overall, our findings indicate that the savings in energy use from compact development can grow to substantial amounts by 2050. In particular, we find that energy savings in China across the three urban density scenarios will be twice the energy savings between the two energy-efficiency scenarios (i.e., business-as-usual, advanced). The energy savings to be gained through compact urban development in Europe are comparable to and even larger than the energy savings in many of the developing regions. Europe exhibits the most divergent urban density futures throughout the developed world, primarily due to the fact that there is significant heterogeneity among its cities. Coupled with Europe's large base energy use, the energy savings through higher urban densities can still account for a significant drop in total building energy use for heating and cooling in the region.

Our scenario analyses show that there is a risk of significant lock-in associated with low urban densities if energy efficiencies do not improve or trends of declining urban densities persist. For highly urbanized regions faced with limited ranges in their projected urban densities, committed emissions from urban infrastructure may continue to grow (15) unless cities invest in energy efficiency improvements, including retrofitting their existing built-up areas. For example, our bottom-up analysis shows that retrofitting the existing urban built environment will still be an important part of the solution, particularly for the developed world, where significant energy waste occurs due to the inefficient building stock. This situation, however, is also the case for rapidly urbanizing China, where most of the existing urban built environment is vastly energy-inefficient. In short, efficiency gains matter relatively more in those regions that are already highly urban. However, how cities will physically grow and how efficient their built environment is will matter for countries that are still undergoing significant urbanization.

Most developed country governments have recently put policies in place that accelerate energy-efficient retrofits. Our bottom-up scenarios indicate that these well-intentioned policies may prematurely lock in the existing built environments for a long time to subpar retrofit options. These retrofit options typically result in savings of 20–40% of the building energy use, whereas savings that range between 70% and 90% could be achieved with state-of-the-art (i.e., deep) retrofit options. Therefore, from a long-term sustainability perspective, it would be more effective to promote deep retrofits first to reach technological and price maturity, and thus a wide market penetration, before introducing policies that accelerate the widespread implementation.

Energy demand for heating and cooling depends on several factors. These factors range from behavioral factors, to building

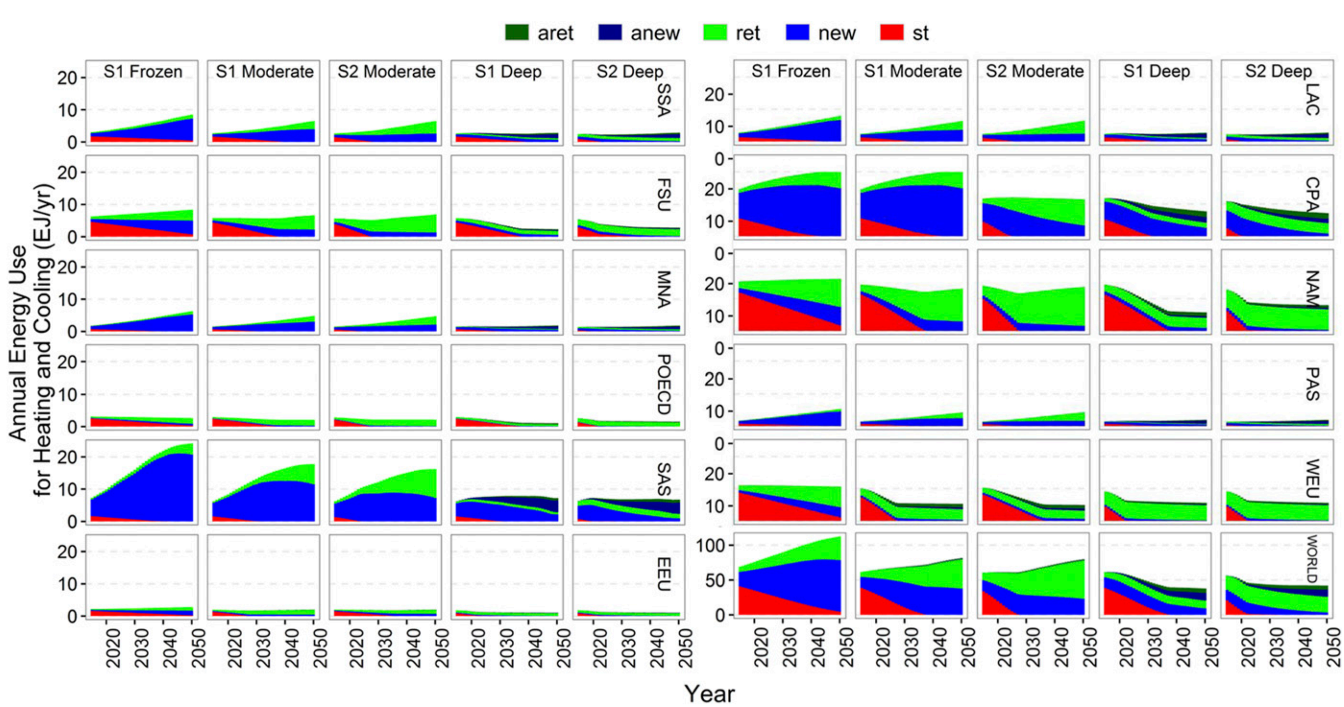

Fig. 3. Regional and global heating and cooling energy use scenarios from the bottom-up analysis. The difference between S1 and S2 variants is that the latter assumes faster adoption of the respective retrofit technology under each scenario. Colors show the energy use divided into different vintages: st (existing stock with standard technology in 2010), new (new buildings with standard technology as of 2010), ret (existing stock with standard retrofit technology as of 2010), aret (existing stock with advanced retrofit technology), and anew (new buildings with advanced technology). The regional breakdown is provided in Fig. 1. Results are also provided in tabular format in Dataset S3.

design, to climate. In our study, we considered two of these factors: urban density and energy efficiency. Although the effect of energy efficiency on energy demand is relatively straightforward, the effect of urban density is less clear due to confounding factors (5). There is, however, evidence for an indirect, but potentially important, link between density and energy use for heating and cooling. Studies show that as urban population density increases, the dwelling size [i.e., floor area per capita (FAC)] tends to decrease. This decrease in dwelling size results in a lower per capita energy use and, for a fixed total population, a lower total energy use for heating and cooling. The reasons for the inverse relation between urban density and FAC primarily lie in the price of land and housing, which tends to be higher in high-density areas due to demand (16, 17). Likewise, in our analysis, urban population density is found to be inversely related to FAC (*SI Appendix*, Tables S1 and S2), and thus to total building floor area across the three urban density scenarios (Fig. 1 *A* and *B*). Lower total building floor area, assuming all other potentially influential factors are kept constant across the scenarios, means lower heating and cooling energy use in cities.

There are other reasons, not captured in our analysis, for expecting higher urban densities to reduce energy demand, at least for heating in cities. In higher density urban environments, heat loss in buildings is typically smaller due to smaller surface-to-volume ratios and more shared walls (18). In addition, more efficient heating technologies, such as district heating, can be deployed in sufficiently dense urban environments. Similar arguments hold for energy demand for cooling as well, especially considering new advances in district cooling (19).

Although density has generally been regarded as a desirable property of urban environments for sustainability, it is only one constituent of urban form. The spatial forms of urban areas are also characterized by such factors as the configurations of buildings, land use mix, and connectivity. Consequently, an overdue emphasis on density causes confusion between urban stakeholders and scholars on how to achieve urban environments that nurture sustainability (20). For example, one common source of confusion is conflating high densities with high-rise buildings, whereas the same level of density can be achieved through different building configurations (21, 22). Thus, medium-rise buildings may have a higher built-up density than high-rise buildings with a small building footprint. Built-up density is higher in traditional European urban forms composed of medium-rise buildings (five to seven floors) with large building footprints (around 65% of the total plot area) compared with contemporary high-rise buildings (over 30 floors) with very small building footprints (less than 15% of the total plot area) (23).

An analysis of trade-offs and co-benefits with human well-being of different trajectories of urban density futures is beyond the scope of this study. However, we discuss several of these trade-offs and co-benefits to place our findings in a broader context, especially when other constituents of urban form are considered (24, 25). For example, high densities, if achieved by high-rise buildings, tend to decrease solar exposure and natural ventilation, and increase obstruction of buildings on each other (26). These factors increase the need for mechanical means of air conditioning and artificial lighting, thus increasing energy consumption. There are also trade-offs between heating energy demand and cooling energy demand that depend on both urban density and local climatic conditions, among other factors (27). For example, low urban densities with expansive urban forms may be favorable for cooling purposes in cities in hot climates but at the expense of transportation costs. In contrast, high urban densities with compact urban forms often offer savings in heating energy use in cool climates; especially with multifamily dwellings, these savings would synergize with walkability and savings in transport costs.

The spatial form of new urban developments can be shaped by both zoning policies that manage the development and strategically planned infrastructure investments. Containing the expansion of urban areas is a well-established planning approach to encourage compact, public transport-oriented urban forms that can save not only energy but also nonurban areas, such as agricultural lands and habitats, from conversion to urban land (28). In our study, where we assume fixed regional population projections across the scenarios, higher urban density futures are, in effect, representative of this kind of development, where, as a co-benefit, land is saved for agriculture and nature. Moreover, zoning regulations also determine the residential and commercial land use within cities that can significantly affect travel patterns (11). In particular, higher land use mix and connectivity, together with colocated higher residential and employment densities, enables the use of alternative forms of transportation such as mass transit, cycling, and walking (29), that would not only cut down energy use for transportation but also bring health benefits (30).

There are sound economic reasons for encouraging more compact urban development with higher population densities and increased energy efficiencies. Both high density and increased energy efficiency have substantial positive effects on economic development in cities. Increasing density of urban development is associated with higher wages and productivity due to agglomeration economies, primarily knowledge spill-overs (9, 31). Controlling for other factors, density explains a large portion of the variation in output per worker in the United States (32); on average, doubling the density increases productivity by 2–4% (9). There is also a clear link between energy efficiency and economic development that extends to building energy use through cost savings for households and in the production process (33, 34). Particularly for low-income households, energy-efficient urban forms and technologies increase the after-energy disposable income (35, 36). Other co-benefits of energy-efficient technologies, such as deep retrofits, include comfort and air quality improvements (37–39). In addition, among the most important co-benefits of well-retrofitted commercial buildings are productivity gains due to a reduced incidence of transmittable respiratory diseases, such as flu and cold (40).

Conclusion

Urban density, along with other determinants of urban form, strongly shapes local environmental conditions such as air quality, walkability, and access to green space, all of which have a bearing on the well-being of urban residents. Moreover, developing effective strategies to adapt to and mitigate climate change in urban areas requires looking beyond aggregate statistics on population, physical extent, and resource use. In our study, the large range of potential future patterns of urban development in most of the developing world indicates that these regions can gain a lot in energy savings by encouraging higher urban densities. With growing urban extents and urban populations, how urban areas are configured spatially will matter for the reduction of energy use and associated GHG emissions, with significant implications for the global sustainability.

Methods

Projecting Residential and Commercial FAC to 2050. We use urban population density and follow a Monte-Carlo approach to cover potential trajectories of change in urban population density by 2050. We first build two separate multiple linear regression models with residential FAC and commercial FAC as dependent variables and natural logarithm-transformed urban population density and gross domestic product per capita (GDPC) estimates for years 1990 and 2000 as independent variables. We then estimate the probability density functions (PDFs) of the urban population density change rate for each region based on its historical trends (1970–2000) using estimates reported by Angel et al. (41) and Seto et al. (42). From these PDFs, we select three levels (low, 25%; medium, 50%; and high, 75%) of urban population density change rate and generate the corresponding projections for urban population density for each region in 5-y intervals to the year 2050 using 2000 as the base year. We also generate the regional projections for GDPC based on projection of population growth, aggregated from country-level United Nations projections (43), and GDP growth (44). Finally, using the panel regression region-specific estimated coefficients, and the projected GDPC, we generate forecasts of residential FAC and commercial FAC by 2050 for the three scenarios of future urban population density. The projected commercial and residential FAC values are used in the top-down analysis to project building energy use by 2050. More details are provided in *SI Appendix, Supporting Materials and Methods*.

Modeling. Our study is one of the few studies to use both a top-down approach and a bottom-up approach, drawing on the complementary strengths of each. Whereas our top-down analysis highlights the synergistic impacts of urban density and energy-efficient technologies on energy use in the built environment across world regions with varying levels of urbanization and technological capabilities, our bottom-up analysis uses a detailed representation of the built environment to study the implications of a large-scale retrofitting program for building energy use.

We use the top-down Global Change Assessment Model (GCAM) to quantify the likely influence of urban density on the commercial and residential building energy use of heating and cooling. The GCAM is an integrated assessment model with 32 energy-economy regions; it captures the interactions between economic, energy, land use, water, and climate systems through the end of the century in 5-y intervals (44–46). We use the top-down model to explore the role of future urban densities in different world regions in determining building energy use from 2010 to 2050.

We use the bottom-up Center for Climate Change and Sustainable Energy Policy High-Efficiency Buildings (3CSEP HEB) model to quantify the energy savings from various retrofitting options for the same time period. The 3CSEP HEB model is a global, engineering-economic model with a rich characterization of the world's building stock based on building and climate typology, urbanization, vintage, and other characteristics (47). As a first approximation to the potential impact of different urban density futures on building energy use, we assume most of the building stock in any region is concentrated in urban areas. Thus, using these two models, we analyze how building energy use will change by 2050 under different urban density, retrofit, and energy-efficiency futures. More details are provided in *SI Appendix, Supporting Materials and Methods*.

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