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

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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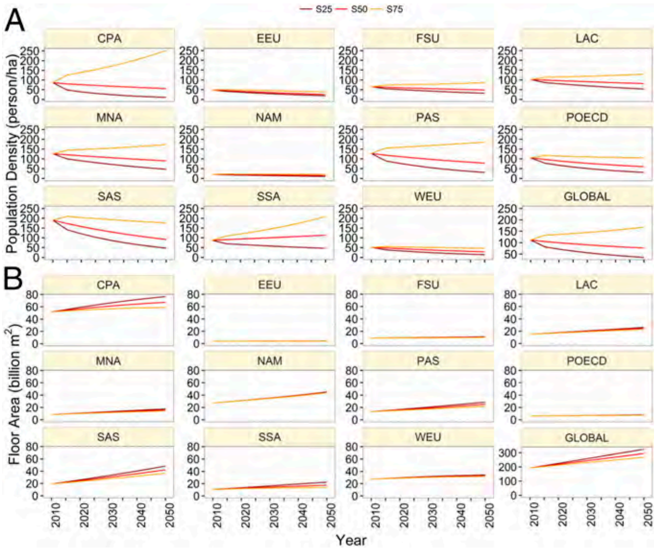

Fig. 1. Urban population density (*A*) and respective floor area (*B*) forecasts by region through 2050 under three urban density scenarios used in the top-down analysis. The 11 International Energy Agency regions used in the analysis are Centrally Planned Asia and China (CPA), Central and Eastern Europe (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 transitionary 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 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.

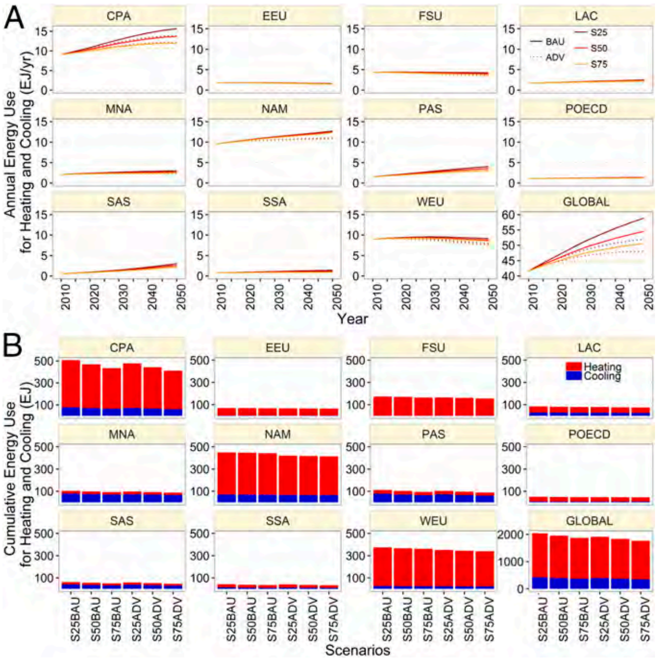

Fig. 2. Regional and global energy use for heating and cooling under the six combined scenarios in the top-down analysis: less compact (S25), baseline (S50), and more compact (S75) population density scenarios; and advanced efficiency scenario (ADV) and business-as-usual (BAU) efficiency scenario annually (*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.

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

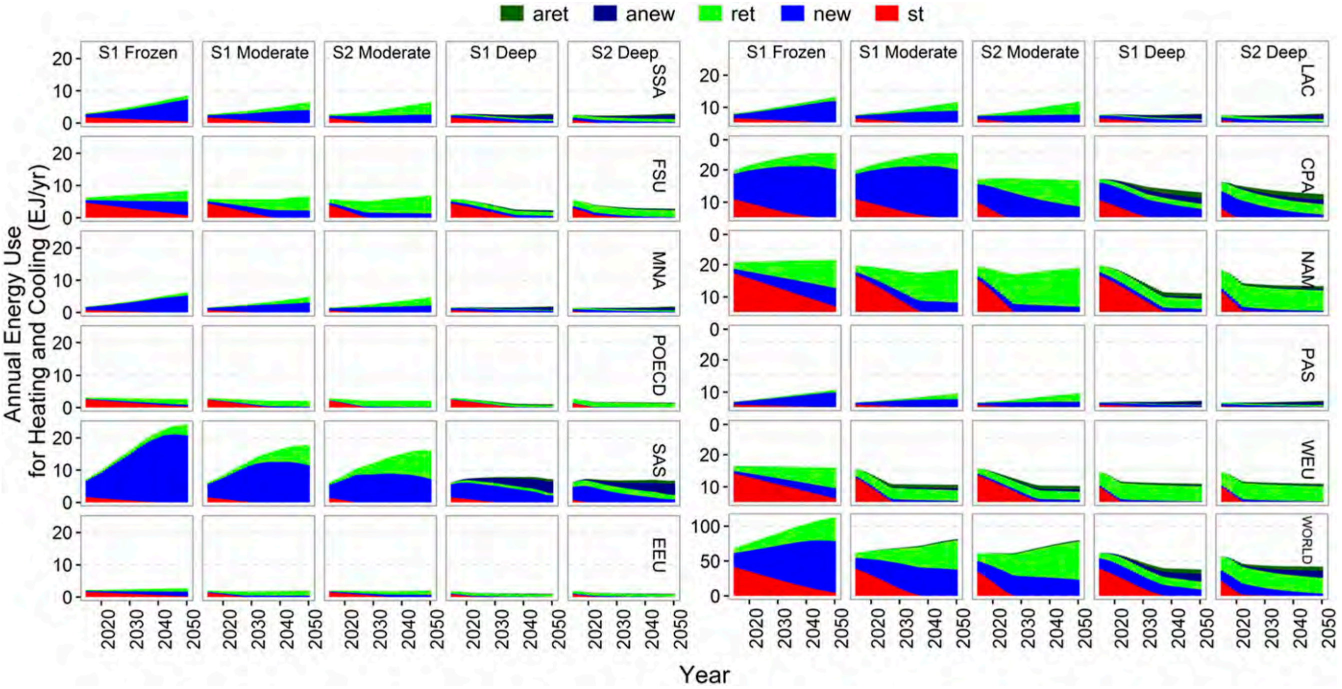

Fig. 3. Regional and global heating and cooling energy use scenarios from the bottom-up analysis. The difference between S1 and S2 variants is that the latter assumes faster adoption of the respective retrofit technology under each scenario. Colors show the energy use divided into different vintages: 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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Supporting Information

Table S1. Composition of the eleven regions used in the study.

Region	Countries in the region
CPA = Centrally planned Asia and China	Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam
EEU = Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia
FSU = Newly independent states of the former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
LAC = Latin America and the Caribbean	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyansa, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
MNA = Middle East and North Africa	Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen
NAM = North America	Canada, Guam, Puerto Rico, United States of America, Virgin Islands
PAS = Other Pacific Asia	American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa
POECD = Pacific OECD	Australia, Japan, New Zealand
SAS = South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
SSA = Sub-Saharan Africa	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe
WEU = Western Europe	Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom

Supporting Materials and Methods

Residential and commercial floor area per capita (FAC) projections to 2050: We build empirical multiple linear regression models to predict residential and commercial FAC, respectively using a panel dataset for 32 energy-economic regions in 1990 and 2000 (Tables S1-S2). Our explanatory variables are GDP per capita (GDPC) and urban population density as well as regional dummies. The scatter plots between the independent variables and the dependent variable indicate a log linear relationship between urban population density (UPD) and FAC, therefore we log transform UPD (Figure S1). However, it is not clear whether the relationship between FAC and GDPC is linear. We compare models with log transformed GDPC and models without transformed GDPC, and find the linear relationship better fit the relationship between FAC and GDPC (R^2: 72% for linear form and 68% for log-linear form for residential FAC, and 69% for linear form and 66% for log-linear model for commercial FAC; all without the regional dummy variables). To keep the regional variation of the effects of GDPC and UPD on FAC, we perform linear regression analysis with region fixed effects, separately, for residential FAC and commercial FAC (Eqns. S1-S2).

$$residentialFAC_{it} = \alpha_0 + \alpha_1 \ln(UPD_{it}) + \alpha_2 GDPC_{it} + \sum_{j=2}^{N} \gamma_j D_{ij} + \varepsilon_{it} \qquad i=1\ldots N,\ t=1990,\ 2000 \qquad \text{(S1)}$$

$$commercialFAC_{it} = \beta_0 + \beta_1 \ln(UPD_{it}) + \beta_2 GDPC_{it} + \sum_{j=2}^{N} \delta_j D_{ij} + \zeta_{it} \qquad i=1\ldots N,\ t=1990,\ 2000 \qquad \text{(S2)}$$

where α_0, β_0 are constants, $\alpha_1, \alpha_2, \beta_1, \beta_2$ are the coefficients of main explanatory variables to be estimated, γ_j, δ_j are the coefficients of the regional dummies D_{ij}, and ε_{it}, ζ_{it} are error terms. N = 29 since 3 of the 32 regions (Eastern Europe, European Free Trade Association, and Taiwan) are not included in the regression analysis because of lack of data. We run two versions of the above models: the first, employing regular panel regression utilizing dummy variables and the second adjusting the estimation process for the use of robust standard errors.

Diagnostics of the regression models: Four principal assumptions (i.e., linearity and additivity, statistical independence, homoscedasticity of errors, and normality of error distribution) justify the use of linear regression models for our purposes of inference or prediction. The diagnostics of our regression models are listed below.

Testing for linearity and additivity: We plot the residuals against the fitted values to check for the linearity and additivity (Figures S2-S3). Nonlinearities may be present when there is a systematic relationship between the two: low residuals with low fitted values and high residuals with high fitted values. The red lines that pass through the scatterplots show that there is not such a relationship for either the residential or the commercial model. The residuals of the residential model scatter around zero with constant variance indicating the assumption is satisfied (Figure S2). For the commercial model, the residuals scatter around zero but with a pronounced increase in variance: this “megaphone” pattern in the residual vs fitted plot shows a problem of heteroscedasticity, which we correct as detailed below (Figure S3).

Testing for independence of errors: The problem of serial correlation of errors is present in long time-series regression analysis (a problem of correlation of errors across time periods or seasonal correlations). In our case, we employ a pooled regression analysis for the cross-sectional observations with only two time periods; thus, we expect this problem to be minimized for the time dimension. Autocorrelation may also be present in space (spatial autocorrelation). We visually inspect residuals of the residential and commercial model against our regressors (Figure S4) and do not identify any systematic behavior of the residuals. We thus do not find evidence for challenging the assumption of zero covariance in the error term.

Testing for normality of errors: We examine the assumption for the normality of errors by examining the residuals and generating a Q-Q plot which plots order statistics of residuals against the quantiles of a standard normal distribution N(0,1). We find that the Q-Q plots for our two models is reasonably straight (Figures S2-S3). We interpret this as evidence that the normality assumption holds; thus, regression statistics such as the *t* and *F* tests should not be affected.

Testing for heteroskedasticity: Normality is not the only assumption that can affect our hypothesis tests. Plotting the regression residuals against our main explanatory variables (log population density and GDP per capita) provides a first visual test for heteroskedasticity; the plots reveal a potential problem with the classical homoscedasticity assumption as the dispersion around the residual mean of zero is affected by whether the values of our explanatory variables are high or low (Figure S4). GDPC appears to be the main culprit for the non-constant variance problem. We also verify that heteroskedasticity is an issue by examining the plots of residuals vs fitted values (Figure S3). The problem seems more pronounced in the commercial FAC model. Heteroskedasticity affects the statistical significance of our regression coefficients and needs to be accounted for in our models. We describe the process of correction of this problem below.

Testing for no multicollinearity: In regression analysis, perfect multicollinearity between variables is a serious problem and we typically desire little to no multicollinearity. Using simple correlation measures, we find that the correlation coefficient between the log urban population density and GDPC is significant, but the magnitude is low (Pearson correlation = -0.34). Furthermore, we calculated Variance Inflation Factor (VIF) –without the regional dummies– for the two independent variables, which are 3.72 and 3.29 for residential FAC and commercial FAC, respectively. We interpret these low values as showcasing no multicollinearity. We do not calculate VIF with the regional dummies because research shows that the VIF with dummies is not a reliable indicator of collinearity (1).

Correction for heteroskedasticity: We correct our heteroskedasticity issues (and the resulting high standard errors in the original regressions) by using covariance matrix estimators that consistently estimate the covariance of the model parameters – the so-called 'sandwich' estimator (Tables S3-S4). The panel regressions with robust standard errors produce coefficients for population density that are statistically significant at the 1% level or below (Tables S3-S4). But in the commercial model, GDPC is now not statistically significant at any reasonable level. Note that the correction for heteroskedasticity only affects standard errors and the coefficients and their interpretation remains the same.

Interpretation of coefficients: Having run all the above tests, we can go ahead with the interpretation of our regression coefficients. Both urban population density and GDPC have a significant effect (in terms of magnitude) on residential FAC and commercial FAC. Furthermore, the majoring of our regional dummies have significant (statistically and in magnitude) effects on residential and commercial FAC. Increasing incomes will increase FAC ceteris paribus, assuming that living space is a normal good. Increases in urban population density will decrease FAC. In particular, our models show that a 10% increase in urban population density leads to a drop of the expected residential FAC by 0.158 units and a drop of the expected commercial FAC by 0.342 units. The panel regression models explain 97.6% and 98.8% of the variation of the residential FAC and commercial FAC, respectively (Tables S3-S4).

Residential and commercial FAC projections:

We build three scenarios of urban population density projection to 2050 based on urban population density in 2000 and the historical urban population density change rate from 1970 to 2000. We first calculate annual urban population density change rate for each decade at the city level using the datasets of Angel et al. (2012) (2) and Seto et al. (2011) (3). Then, aggregating our findings to each of the 32 regions, we fit a probability density function (PDF) of the distribution of the calculated annual urban population change rate assuming a generalized logistic distribution of urban population density change rate (Figure S5). From the PDF of each region, we draw the low (25%), medium (50%), and high (75%) annual urban population density change. Taking 2000 as the base year, we estimate urban population density for each region in five-year intervals into the future up to 2050 for the three scenarios of annual urban population density change rate. For regions with few or no cities sampled, we use PDF of the region with a similar socioeconomic background. Thus, the PDFs of USA, EU-12, EU-15, South Asia, Africa South, and Japan was applied to Australia and New Zealand, Eastern Europe, European Free Trade Association, Pakistan, South Africa, and Taiwan, respectively.

Using the fitted parameter values of the regression model, we generate three scenarios of how residential FAC and commercial FAC are expected to change by 2050 for each region following the low, medium, and high levels of urban population density change rate and GDPC from the forecasts of GDP growth (4) and population growth (5). We do not build a regression model for Eastern Europe, European Free Trade Association, and Taiwan because of the absence of relevant urban population data. Instead, we use the models of the regions with similar socioeconomic characteristics, i.e., EU-12, EU-15, and Japan, respectively.

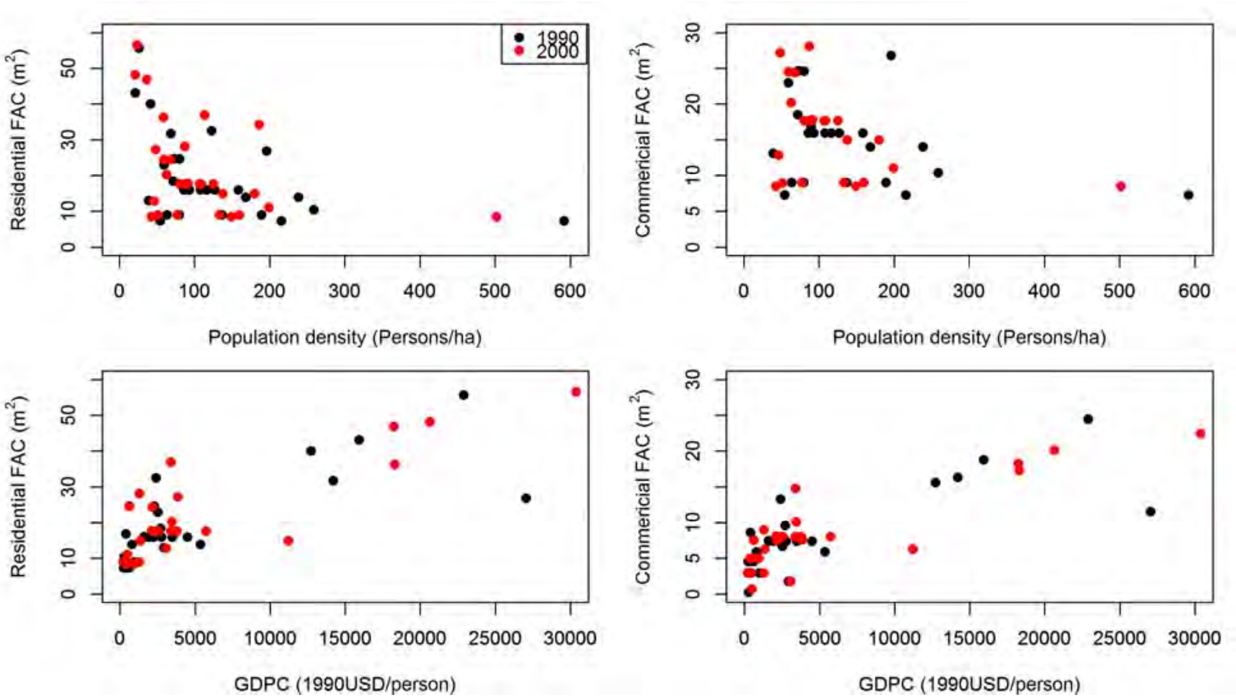


Figure S1. Scatter plot between FAC and urban population density and GDPC in 1990 and 2000.

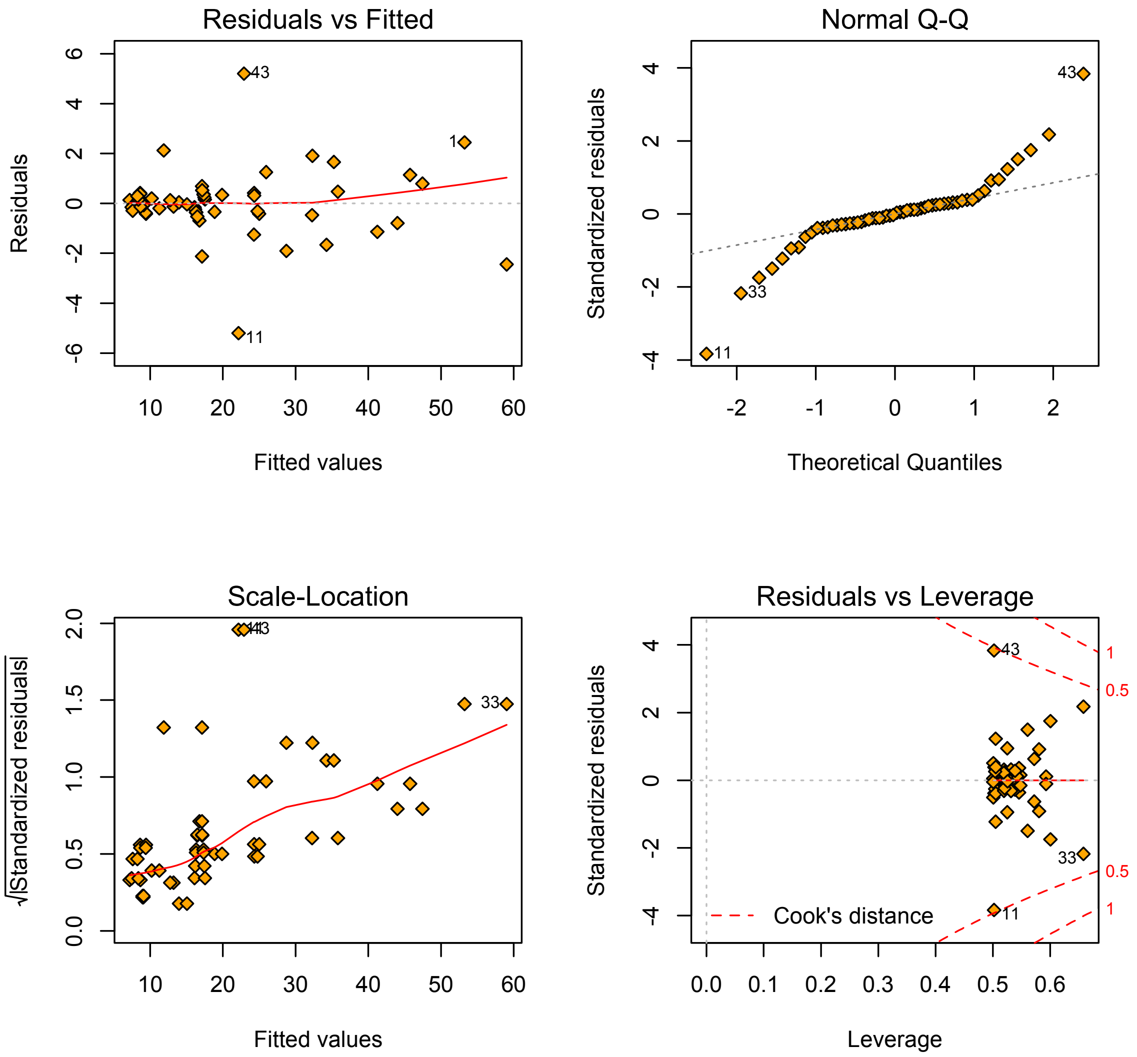


Figure S2. Regression diagnostics for residential FAC model (residuals vs. fitted values, Q-Q plot, scale-location and residuals vs leverage).

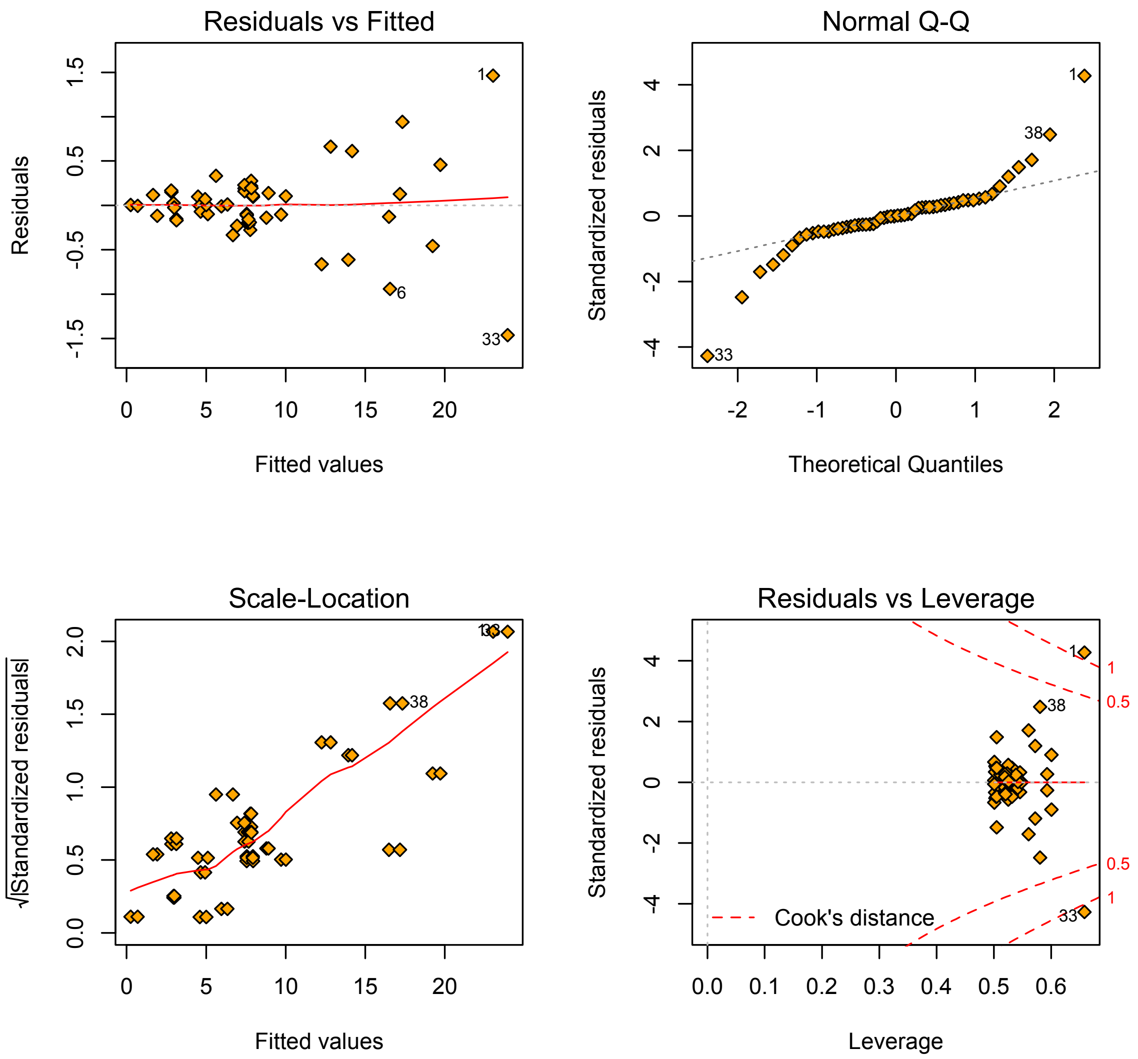


Figure S3. Regression diagnostics for commercial FAC model (residuals vs. fitted values, Q-Q plot, scale-location and residuals vs leverage).

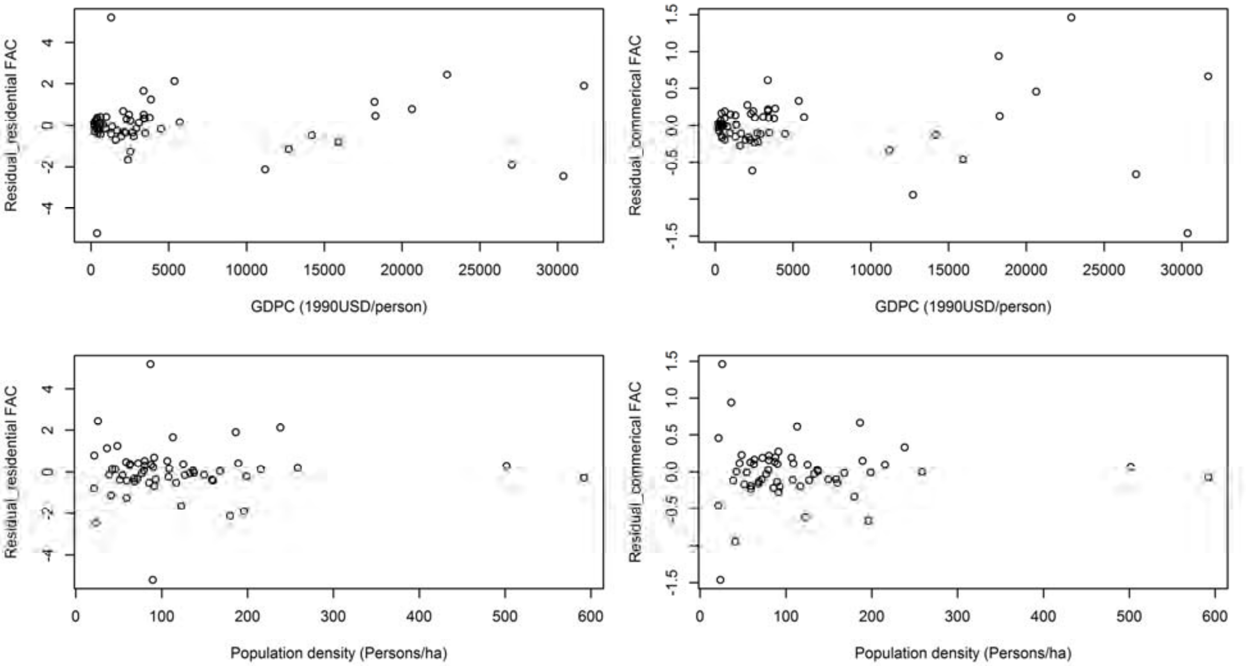
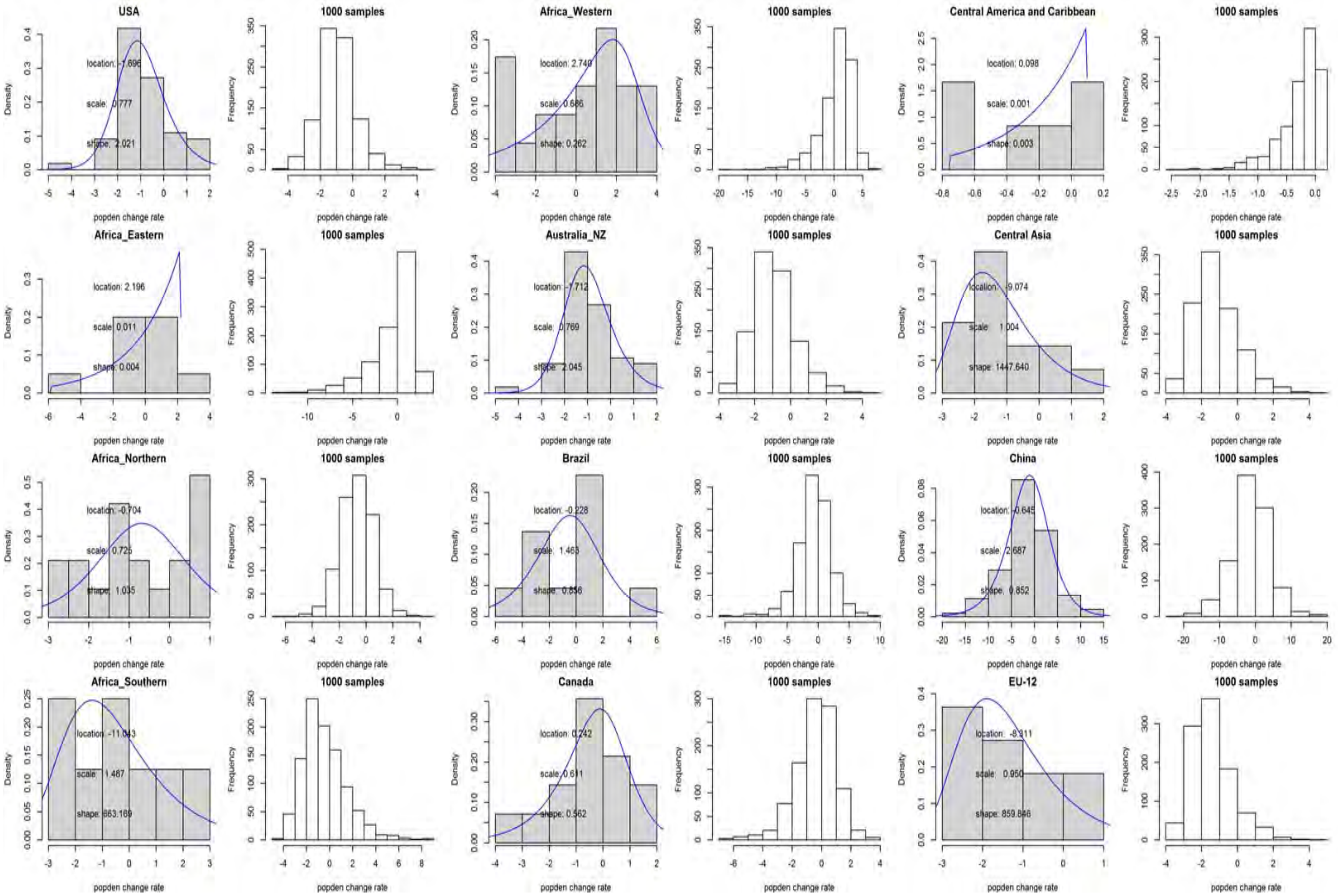
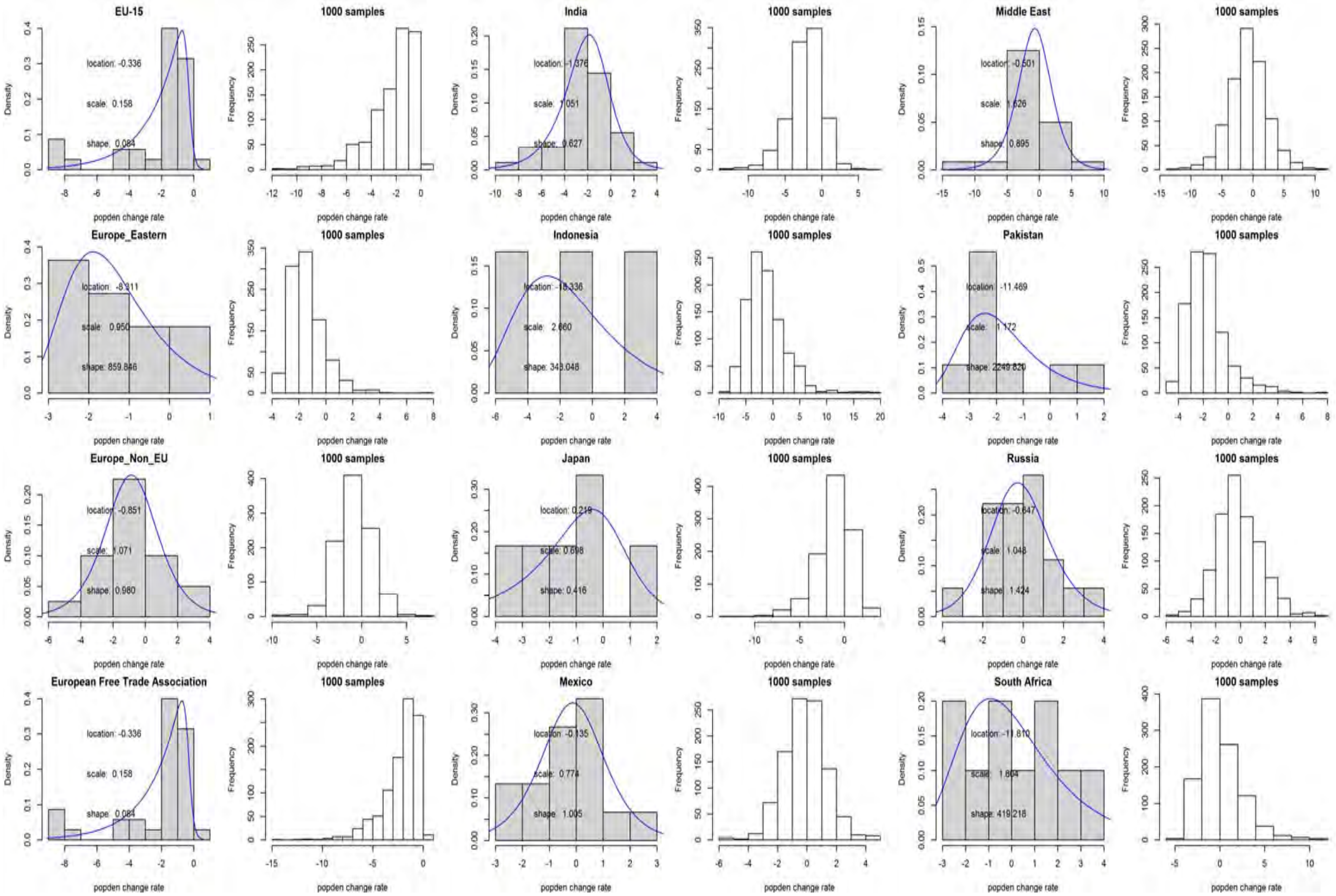


Figure S4. Regression diagnostics for the models to predict FAC (residuals vs. population density and GDPC).


USA
location: -1.696
scale: 0.777
shape: 2.021
1000 samples
Africa_Western
location: 2.740
scale: 0.686
shape: 0.262
1000 samples
Central America and Caribbean
location: 0.098
scale: 0.001
shape: 0.003
1000 samples
Africa_Eastern
location: 2.196
scale: 0.011
shape: 0.004
1000 samples
Australia_NZ
location: -1.712
scale: 0.769
shape: 2.045
1000 samples
Central Asia
location: -9.074
scale: 1.004
shape: 1447.640
1000 samples
Africa_Northern
location: -0.704
scale: 0.725
shape: 1.035
1000 samples
Brazil
location: -0.228
scale: 1.463
shape: 0.856
1000 samples
China
location: -0.645
scale: 2.687
shape: 0.852
1000 samples
Africa_Southern
location: -11.043
scale: 1.487
shape: 663.169
1000 samples
Canada
location: 0.242
scale: 0.611
shape: 0.562
1000 samples
EU-12
location: -8.311
scale: 0.950
shape: 859.846
1000 samples
Density
Frequency
popden change rate


EU-15
Density
location: -0.336
scale: 0.158
shape: 0.084
popden change rate
1000 samples
Frequency
popden change rate
India
Density
location: -1.376
scale: 1.051
shape: 0.627
popden change rate
1000 samples
Frequency
popden change rate
Middle East
Density
location: -0.501
scale: 1.626
shape: 0.895
popden change rate
1000 samples
Frequency
popden change rate
Europe_Eastern
Density
location: -8.311
scale: 0.950
shape: 859.846
popden change rate
1000 samples
Frequency
popden change rate
Indonesia
Density
location: -18.336
scale: 2.660
shape: 343.048
popden change rate
1000 samples
Frequency
popden change rate
Pakistan
Density
location: -11.469
scale: 1.172
shape: 2249.820
popden change rate
1000 samples
Frequency
popden change rate
Europe_Non_EU
Density
location: -0.851
scale: 1.071
shape: 0.980
popden change rate
1000 samples
Frequency
popden change rate
Japan
Density
location: 0.219
scale: 0.698
shape: 0.416
popden change rate
1000 samples
Frequency
popden change rate
Russia
Density
location: -0.647
scale: 1.048
shape: 1.424
popden change rate
1000 samples
Frequency
popden change rate
European Free Trade Association
Density
location: -0.336
scale: 0.158
shape: 0.084
popden change rate
1000 samples
Frequency
popden change rate
Mexico
Density
location: -0.135
scale: 0.774
shape: 1.005
popden change rate
1000 samples
Frequency
popden change rate
South Africa
Density
location: -11.810
scale: 1.804
shape: 419.218
popden change rate
1000 samples
Frequency
popden change rate

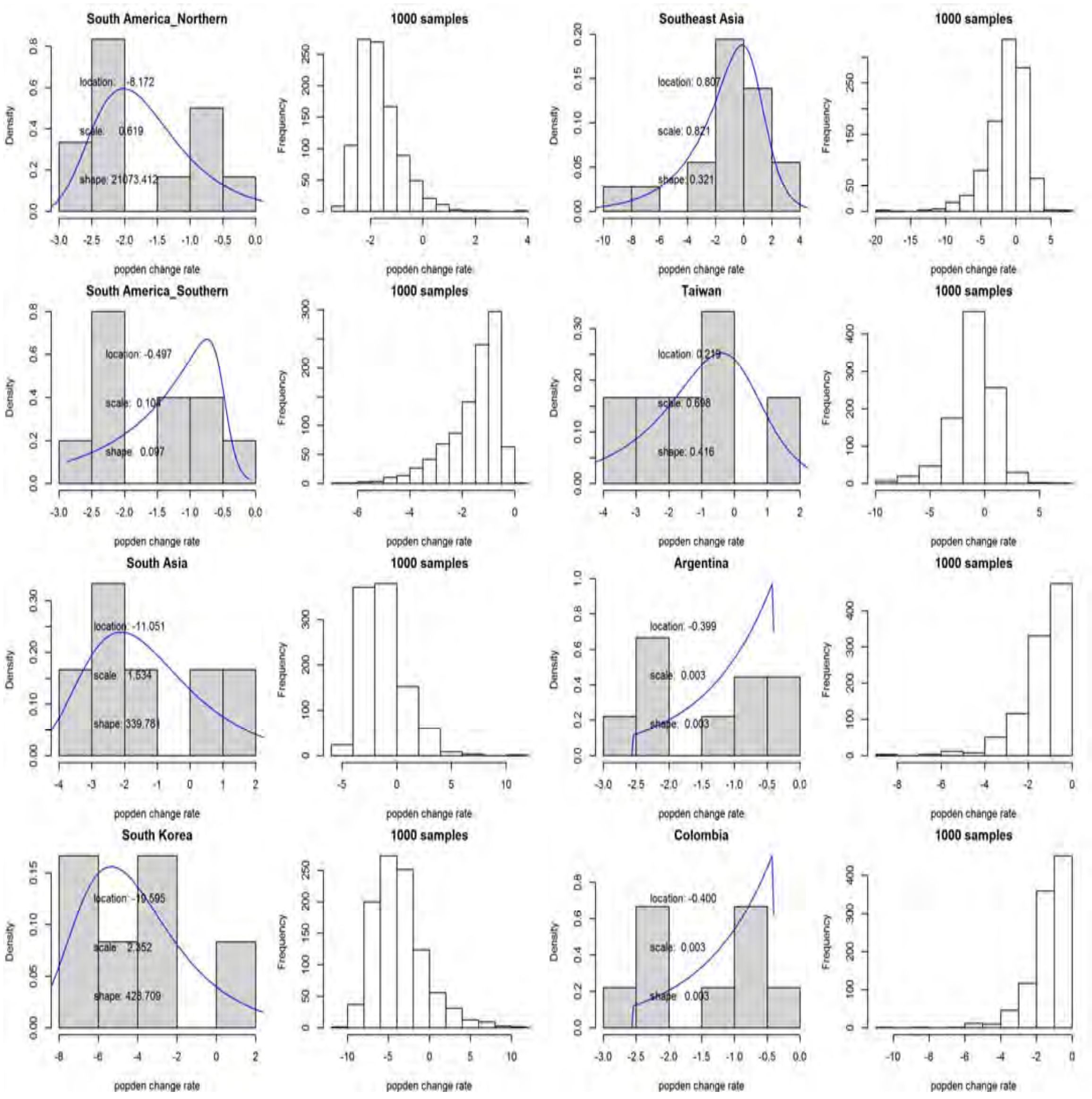


Figure S5. Probability density functions of regional urban population density change rates.

Table S2. Statistical summary of the data used to building the regression model.

	Min	**Mean**	**Max**	**SD**
1990				
Residential FAC (m^2/person)	7.30	19.29	55.69	11.81
Commercial FAC (m^2/person)	0.26	8.00	24.49	5.37
GDPC1990 (1990USD/person)	193.60	5191.00	27059.90	7586.64
Population density (persons/ha)	21.15	126.24	591.80	109.45
2000				
Residential FAC (m^2/person)	8.54	21.49	56.59	13.10
Commercial FAC(m^2/person)	0.69	8.51	22.48	5.51
GDPC2005 (1990USD/person)	223.60	6895.30	31687.40	9579.23
Population density (persons/ha)	21.34	107.94	501.61	90.02

Table S3. Results of panel regression for residential FAC.

	Before correcting for heteroskedasticity				After correcting for heteroskedasticity			
	coefficients	Std Error	t value	P	coefficients	Std Error	t value	P
(Intercept)	25.65	16.15	1.59	0.12	25.65	5.43	4.72	<0.01
Ln(population density)	-3.42	3.28	-1.04	0.31	-3.42	1.10	-3.10	<0.01
GDPC	0.00074	0.00022	3.40	<0.00	0.00074	0.00019	3.70	<0.01
Africa_Eastern	(baseline)							
Africa_Northern	0.19	2.14	0.09	0.93	0.19	0.49	0.38	0.70
Africa_Southern	-3.10	3.40	-0.91	0.37	-3.10	0.97	-3.18	<0.01
Africa_Western	-1.99	2.62	-0.76	0.45	-1.99	0.60	-3.35	<0.01
Argentina	4.52	2.26	2.00	0.06	4.52	0.59	7.64	<0.01
Australia_NZ	18.95	4.50	4.21	<0.01	18.95	2.92	6.48	<0.01
Brazil	4.03	2.41	1.67	0.11	4.03	0.72	5.61	<0.01
Canada	17.08	6.01	2.84	0.01	17.08	3.43	4.99	<0.01
Central America and Caribbean	5.41	2.25	2.40	0.02	5.41	0.65	8.34	<0.01
Central Asia	12.85	3.02	4.25	<0.01	12.85	0.82	15.59	<0.01
China	11.59	2.34	4.95	<0.01	11.59	3.70	3.13	<0.01
Colombia	5.69	2.01	2.83	0.01	5.69	0.53	10.81	<0.01
EU-12	10.73	3.42	3.14	<0.01	10.73	1.31	8.21	<0.01
EU-15	10.63	3.84	2.76	0.01	10.63	2.99	3.55	<0.01
Europe_Non_EU	23.31	2.00	11.64	<0.01	23.31	1.27	18.30	<0.01
India	3.38	2.58	1.31	0.20	3.38	0.60	5.58	<0.01
Indonesia	-0.53	2.16	-0.24	0.81	-0.53	0.39	-1.37	0.18
Japan	1.21	7.13	0.17	0.87	1.21	6.13	0.20	0.85
Mexico	3.73	2.15	1.73	0.09	3.73	0.93	3.99	<0.01
Middle East	5.85	2.86	2.05	0.05	5.85	0.80	7.33	<0.01
Pakistan	-4.81	3.87	-1.24	0.22	-4.81	1.13	-4.27	<0.01
Russia	11.98	2.66	4.51	<0.01	11.98	0.67	17.96	<0.01
South Africa	-2.07	4.08	-0.51	0.62	-2.07	1.19	-1.74	0.09
South America_Northern	5.44	2.09	2.61	0.01	5.44	0.75	7.26	<0.01
South America_Southern	5.34	2.14	2.50	0.02	5.34	0.44	12.22	<0.01
South Asia	3.62	4.97	0.73	0.47	3.62	1.56	2.31	0.03
South Korea	1.00	3.28	0.31	0.76	1.00	2.38	0.42	0.68
Southeast Asia	5.25	1.99	2.65	0.01	5.25	0.26	20.18	<0.01
USA	21.84	6.41	3.41	<0.01	21.84	5.16	4.24	<0.01
	Adjusted R-squared: 0.976				Adjusted R-squared: 0.976			

Table S4. Results of panel regression for commercial FAC.

	Before correcting for heteroskedasticity				After correcting for heteroskedasticity			
	coefficients	Std Error	t value	P	coefficients	Std Error	t value	P
(Intercept)	10.73	4.92	2.18	0.04	10.73	2.30	4.67	<0.01
Ln(population density)	-1.59	1.00	-1.59	0.12	-1.59	0.46	-3.41	<0.01
GDPC	0.00011	0.00006	1.60	0.12	0.00011	0.00011	1.00	0.33
Africa_Eastern	(baseline)							
Africa_Northern	0.30	0.65	0.47	0.64	0.30	0.23	1.31	0.20
Africa_Southern	-1.39	1.04	-1.34	0.19	-1.39	0.40	-3.47	<0.01
Africa_Western	-0.88	0.80	-1.11	0.28	-0.88	0.24	-3.67	<0.01
Argentina	3.84	0.69	5.57	<0.01	3.84	0.21	17.88	<0.01
Australia_NZ	10.37	1.37	7.56	<0.01	10.37	1.36	7.63	<0.01
Brazil	3.69	0.74	5.02	<0.01	3.69	0.23	15.81	<0.01
Canada	11.66	1.83	6.36	<0.01	11.66	1.34	8.69	<0.01
Central America and Caribbean	4.04	0.69	5.87	<0.01	4.04	0.22	18.09	<0.01
Central Asia	3.42	0.92	3.71	<0.01	3.42	0.33	10.33	<0.01
China	5.14	0.71	7.19	<0.01	5.14	0.18	28.92	<0.01
Colombia	4.26	0.61	6.95	<0.01	4.26	0.20	21.05	<0.01
EU-12	2.42	1.04	2.32	0.03	2.42	0.30	8.14	<0.01
EU-15	10.97	1.17	9.36	<0.01	10.97	1.43	7.69	<0.01
Europe_Non_EU	10.58	0.61	17.32	<0.01	10.58	0.49	21.50	<0.01
India	-1.69	0.79	-2.16	0.04	-1.69	0.26	-6.62	<0.01
Indonesia	2.22	0.66	3.37	<0.01	2.22	0.20	11.27	<0.01
Japan	7.03	2.17	3.23	<0.01	7.03	3.26	2.16	0.04
Mexico	4.03	0.66	6.15	<0.01	4.03	0.47	8.52	<0.01
Middle East	5.47	0.87	6.28	<0.01	5.47	0.20	26.90	<0.01
Pakistan	0.17	1.18	0.14	0.89	0.17	0.46	0.36	0.72
Russia	3.40	0.81	4.19	<0.01	3.40	0.20	17.29	<0.01
South Africa	-3.32	1.24	-2.66	0.01	-3.32	0.35	-9.42	<0.01
South America_Northern	4.48	0.64	7.04	<0.01	4.48	0.39	11.63	<0.01
South America_Southern	4.07	0.65	6.25	<0.01	4.07	0.14	29.13	<0.01
South Asia	4.03	1.52	2.66	0.01	4.03	0.66	6.12	<0.01
South Korea	3.00	1.00	3.00	0.01	3.00	1.05	2.85	0.01
Southeast Asia	3.27	0.61	5.41	<0.01	3.27	0.14	23.05	<0.01
USA	15.02	1.95	7.68	<0.01	15.02	2.43	6.19	<0.01
	Adjusted R-squared: 0.988				Adjusted R-squared: 0.988			

Top-down model

The Global Change Assessment Model (GCAM) is a partial equilibrium, dynamic-recursive model with a technology-rich representation of energy production, transformation, and consumption. The model is disaggregated into 32 energy-economy regions, 283 land use regions, and 233 water basins globally. Energy consumption and emissions outcomes from GCAM are driven by assumptions of population, labor participation rates, labor productivity, representation of resources, and technologies. GCAM is open-source software; the model used in this study along with assumptions and model inputs are available online (http://www.globalchange.umd.edu/models/gcam/). The population and GDP growth assumptions used in this paper are the same as those of the Medium Reference-No Policy scenario in (6). GCAM considers how changes in socioeconomic drivers, floor area, technology, and climate affect future building energy demand, and it has been used to study future building energy demand at global, national, and sub-national levels (7-9). It is worth noting that GCAM is not used to predict future building energy demand globally or regionally; rather, it adds value by showing the potential impacts of technology improvement and, in this study, also urban density, on building energy use. In this study, we aggregate the original 32 energy-economy regions to 11 in line with the regional break-down of the International Energy Agency (IEA) to facilitate comparison with the bottom-up analysis (Table S5).

Among several factors that affect building energy demand in GCAM, building floor area is the most important. In this study, we use GCAM version 4.2 with the building sector disaggregated into residential and commercial buildings. Detailed information of model description, structure, and data are provided in (4, 10, 11). In GCAM, commercial buildings are already assumed to only exist in urban areas. Although GCAM does not differentiate between urban and non-urban residential buildings, in this study we use urban population projections, urban population density estimates, and GDP projections to project the change in building floor area by 2050 in a given region. Thus, we effectively restrict the output of GCAM for residential buildings to urban areas.

We define two energy-efficiency scenarios for residential and commercial buildings to be analyzed by GCAM:

1. Business-as-usual scenario (BAU) represents a reference case whereby energy efficiency improvements in buildings are autonomous; that is, efficient technologies are deployed without policy intervention.

2. Advanced energy-efficiency scenario (ADV) represents a case with faster improvement in building technologies compared to the BAU scenario. The improvement rate varies between conventional and emerging technologies.

The data and assumptions for the BAU scenario are the default values in GCAM (11). The BAU scenario depicts a world with global population close to 9 billion people, global GDP grows an order of magnitude, and global primary energy consumption is tripled by 2100. There is no policy in mitigating carbon emissions in the BAU scenario with fossil fuels dominated in global energy consumption. However, there is still substantial growth in nuclear and renewable energy (12). The model uses residential and commercial floor area per capita (FAC) projections that we developed for this study.

The ADV scenario assumes faster energy efficiency improvement for all regions than is the case in the BAU scenario. In the ADV scenario, the energy efficiency improvement rate for the United States is assumed to be 0.1% per year for conventional technologies and between 0.25% and 0.75% for emerging technologies; shell efficiency is assumed to improve at 0.65% per year for residential buildings and 0.6% per year for commercial buildings (13). Compared with the BAU scenario, all regions would have higher electrification rate in the advanced technology scenario, and the impact is greater for less developed regions. The use of traditional biomass would be reduced under the advanced technology scenario but a significant amount of traditional biomass would still be consumed in some African regions.

All other inputs and parameters are the same between the BAU and ADV scenarios. In both scenarios, the energy efficiency improvement rates are slightly different across regions, depending on their economic growth and heating/cooling degree days (for shell efficiency). In general, OECD countries such as Canada, Western European countries, Japan, Australia, and Korea follow similar technology improvement rates as the one in the United States. The emerging economies, such as China and Brazil, have lower technology improvement rate, compared to that in the United States. The less developed regions like Africa are assumed to have the slowest technology improvement, constrained by both technology development and institutional factors.

Table S5. Aggregation of the original 32 energy-economic regions in GCAM to IEA regions in the top-down analysis in this study.

GCAM regions	IEA regions in the top-down analysis
China, Taiwan	CPA
Europe_Eastern	EEU
Russia, Central Asia	FSU
Central America and Caribbean, Mexico, Brazil, Argentina, Colombia, South America_Northern, South America_Southern	LAC
Middle East, Africa_Northern	MNA
USA, Canada	NAM
Southeast Asia, Indonesia, South Korea	PAS
Australia & New Zealand, Japan	POECD
Africa_Eastern, Africa_Southern, Africa_Western, South Africa	SSA
Pakistan, South Asia	SAS
EU_12, EU_15, Europe_Non_EU, European Free Trade Association	WEU

Bottom-up model

Heating and cooling energy consumption for the analysis is undertaken using 3CSEP HEB (Center for Climate Change and Sustainable Energy Policy High Efficiency Buildings) model. Although it is an engineering-economic model, it was soft-linked to the “Message” Integrated Assessment model (IAM) of IIASA during the Global Energy Assessment modeling work (14), and thus, it was harmonized with an IAM. Most of its macroeconomic and socio-demographic inputs (population, urbanization rate, etc) are from a consistent set of Message scenarios.

The model, 3CSEP HEB, has a comprehensive multi-level building type classification. Building categories are distinguished by their location (urban, rural, slum), building type (single-family, multifamily, commercial and public buildings with subcategories), building vintage (existing, new, advanced new, retrofit, advanced retrofit), and 17 climate types based on heating, cooling, and dehumidification needs. A detailed description of the model can be found in (15), with some key overviews published in (16).

One of the main goals of the model is to interrogate the extent to which global heating and cooling energy use could be brought down if today's best practice buildings were proliferated ubiquitously after a certain transition time for markets and policies to adjust. Hence this state-of-the-art scenario (deep efficiency scenario) resonates the "technical potential" concept from engineering economic forecasting analyses; nevertheless, its input data are, where possible, based on actual, ex-post data from existing best-practice buildings.

The three fundamental scenarios of energy efficiency we used in the bottom-up model:

Frozen Efficiency Scenario: Frozen Efficiency scenario assumes that the energy performance of new and retrofit buildings do not improve as compared to their 2005 levels and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling, while most of new buildings have higher level of energy consumption than in the moderate scenario due to lower compliance with building codes.

Moderate Efficiency Scenario: The rationale for this scenario is to illustrate the development of the building energy use taking into account current policy initiatives, such as building codes for new buildings. The scenario assumes a slightly accelerated renovation dynamic (i.e. the share of buildings reconstructed annually) to reflect that many countries recognized the importance of the quick implementation of energy-efficient retrofits and energy-efficient building codes.

Deep Efficiency Scenario: This scenario demonstrates how far today's state-of-the-art construction and retrofit know-how and technologies can take the building sector in reducing energy use, while also providing full thermal comfort in buildings. It assumes that, after a short period of market transformation, today's best practice in both new construction and retrofit becomes the standard. In essence, we determine the techno-economic energy efficiency potentials in the building sector.

Under each of the base scenarios above, two different retrofit dynamics are assumed to unfold into the future:

Variant 1: Retrofit rate increases linearly from 1.4% to 3% until 2025 and then stays at 3% until 2050.

Variant 2: Moderate scenario: retrofit rate increases in 5 years (i.e., in 2020) to 5%; Deep scenario: retrofit rate stays at 1.4% until 2025, then it increases to 5%.

The fundamental scenarios differ very much in their assumptions on the penetration of efficient buildings. Each assume different transitionary periods for the markets to be able to deploy 100% advanced buildings, as well as different trajectories in the acceleration of the retrofit rate. Frozen efficiency scenario simply means the same efficiency level buildings get to be built and retrofitted as today. In contrast, moderate efficiency scenario assumes there is a push in policies towards retrofits, but the energy savings of the retrofits, *ret*, and new buildings, *new*, stay moderate. It does assume some limited autonomous penetration of advanced new (*anew*) and advanced retrofitted (*aret*) buildings, especially in Europe (where it is already the law), where these achieve more noticeable levels. Deep efficiency scenario assumes that after a transitionary period (10 years) for markets to fully adopt the know-how, all *new* and *ret* will become *anew* and *aret* (except a small portion that is physically not possible, such as historic buildings, although by today we have evidence that even these can achieve passive standards).

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