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REVIEW

City-integrated renewable energy for urban sustainability

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To prepare for an urban influx of 2.5 billion people by 2050, it is critical to create cities that are low-carbon, resilient, and livable. Cities not only contribute to global climate change by emitting the majority of anthropogenic greenhouse gases but also are particularly vulnerable to the effects of climate change and extreme weather. We explore options for establishing sustainable energy systems by reducing energy consumption, particularly in the buildings and transportation sectors, and providing robust, decentralized, and renewable energy sources. Through technical advancements in power density, city-integrated renewable energy will be better suited to satisfy the high-energy demands of growing urban areas. Several economic, technical, behavioral, and political challenges need to be overcome for innovation to improve urban sustainability.

Since 2007, a greater percentage of the global population has been living in urban areas than in rural areas. Increased urbanization is expected to continue, with two-thirds of the world's population projected to live in urban areas by 2050, a net urban influx of 2.5 billion people (*1*). Cities today are generally not equipped to address dramatic urban growth and strain on existing infrastructure in a sustainable way, especially with respect to their energy systems.

To be sustainable, cities must themselves, or in the resources that they command, become low-carbon, resilient, and livable (*2*). Although there can be considerable variation in methods for evaluating the emissions footprint of cities (*3*), with 54% of the population living in urban areas, it is estimated that cities are currently responsible for 60 to 70% of anthropogenic greenhouse gas emissions (*4*). The two main strategies for transitioning to a low-carbon city are to shift from fossil fuels to cleaner energy sources and to reduce urban energy consumption levels. The low-carbon transition can be accomplished through energy-efficiency measures, behavioral interventions, and incorporating carbon sinks such as urban parks. Cities and their energy systems should also be resilient to natural and human-made threats (*2*). The energy systems of cities are increasingly vulnerable to the effects of climate change and extreme weather, including storms, flooding, and sea-level rise, and also to natural and human-induced disasters. In addition, urban energy systems directly affect the well-being and happiness of urban inhabitants. Health conditions, economic competitiveness, cultural appeal, and social, gender, and racial equality are influenced by high-energy sectors such as transportation, food production, and water quality.

Here we evaluate some of the more promising recent technological advancements that could help urban areas become sustainable cities. Many opportunities exist, but focusing on city-integrated renewable energy—defined as distributed, non–fossil fuel energy generated locally in urban areas—has the potential to help cities meet several sustainability needs. Many of these renewable sources increase regional energy independence and can be redundant with other sources, thus increasing resiliency. Although there are several existing barriers to their adoption, solutions will involve increased power densities of renewable energy technologies, improved infrastructure capable of supporting widespread integrated energy generation systems, and increased urban energy efficiency, particularly in the buildings sector.

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City-integrated renewable energy

About 75% of power generated globally is consumed in cities (*5*). Generating city-integrated energy at the site of energy use could substantially contribute to the environmental, economic, and social aspects of urban sustainability. Four characteristic advantages of such distributed energy systems include the ability to (i) offer low to zero carbon emissions, (ii) offset capital-intensive investments for network upgrades, (iii) impart local energy independence and network security, and (iv) motivate social capital and cohesion (*6*).

With limited available installation space, renewable energy generation within urban areas poses particular challenges. We use the balance between the high energy demand of cities and the available energy density supplied by renewable sources as a starting point for an analytic framework for decarbonized urban spaces (Fig. 1). However, in the waves of innovation that will be needed, strategies ranging from space-based solar energy to small modular nuclear power systems, deep geothermal systems, and other generation options could transform the energy landscape. In addition to reducing greenhouse gas emissions, these strategies may reduce the consumption of water, air, and other resources.

Solar energy

Recent economic and technical advances have made city-integrated solar technologies increasingly attractive. Since 2010, the installed price of solar energy has dropped by as much as 50% (*7*). Despite substantial economic progress and anticipated cost parity with fossil fuels, renewable energy technologies have often been criticized for their low power densities, making them inappropriate for urban applications. Conservative estimates of the power density of solar photovoltaics are around 10 W/m^2 (*8*), assuming an average direct solar irradiation of 100 W/m^2, which is typical for the United Kingdom, and a photovoltaic efficiency of 10%. However, the solar resource is highly region-dependent, and in some regions, annual direct solar irradiation can exceed 300 W/m^2 (*9*). Many of the regions expected to experience the greatest increase in urbanization are located in solar-rich regions. For example, the majority of the total land area of India experiences an annual direct solar irradiation of over 200 W/m^2 (*10*). Additionally, the efficiency of photovoltaics has increased steadily and has already surpassed 40% in the laboratory, using concentrated multijunction cells (*11*). Hence, under optimal conditions, the power density of photovoltaics could exceed 120 W/m^2.

Several studies have estimated the photovoltaic potential of existing cities. City-integrated photovoltaics have the potential to satisfy 62% of the current electricity needs of Oeiras, Portugal (*12*), and 66% of the electricity needs of Bardejov, Slovakia (*13*). High-efficiency commercially available photovoltaics only on suitable rooftops could satisfy 19.7 to 31.1% of the daily electricity demand and 47.7 to 94.1% of the morning peak electricity demand of Mumbai, India (*10*). With a 20% adoption rate, solar-powered urban microgrids could reduce the grid demand in Cambridge, MA, to almost zero at midday (*14*).

Heating accounts for 40 to 50% of the global energy demand and 75% of the energy demand within the buildings sector (*15*). Urban solar thermal energy, specifically for space and domestic water heating, has been an area of particular research interest. With efficiencies up to 80% (*15*), solar hot-water systems offer a thermal power density up to 240 W_t/m^2 under optimal conditions (W_t, watt-thermal), whereas the global averaged thermal power density of solar heat collectors is 67 W_t/m^2 (*16*). Because domestic solar hot-water heaters are low-cost and compact, one study showed that 84% of urban households in China could install the system on their rooftops (*17*). Solar thermal energy is also used for passive and active space heating. A study of five Australian cities showed that the use of a Trombe wall could offer energy savings up to 17% (*18*). Seasonal solar thermal energy storage is an approach that stores solar thermal energy collected in the summer for heating in the colder months. This technology provides up to 91% of the total energy needs of a large residential building in Richmond, VA (*19*).

The exploitability of the solar resource is highly affected by urban form. Although taller buildings offer higher surface-to-volume ratios, allowing for increased facade-integrated solar technologies, they also increase the risk of vertical obstruction and shading (*20*). Although building facades provide almost triple the area of building roofs, they received only 41% of the total irradiation in Karlsruhe, Germany (*21*). However, an optimized urban form could increase the solar irradiation on facades by up to 45% in greater London, whereas an increase of only 9% is possible for rooftops (*22*).

Geothermal energy

Geothermal energy has been harnessed for both electricity and heat. A typical geothermal plant has an electrical power density of 283 W/m^2 (*23*), but some plants are estimated to have a total power density of nearly 800 W/m^2 (*16*). Geothermal plants can be placed on multiple-use lands, sharing space with activities such as farming and skiing. However, the surrounding land can be affected by subsidence, erosion, landslides, and induced seismicity (*16*, *23*). When taking into account all such affected areas, the typical electrical power density of a geothermal power plant is estimated to be 50 to 80 W/m^2 (*16*). Geothermal energy is more efficiently extracted as heat. Iceland's Hellisheidi combined heat and power plant is able to generate hot water at 25,000 W$_t$/m^2 (*16*). Most cities, however, are located in areas with far fewer geothermal resources. Conventional geothermal resources would only produce a mere 0.017 W/m^2 of electricity in the United Kingdom (*8*), but deep (>10 km) geothermal power could transform this baseload resource into a far more substantial (>10%) element of urban energy supply (*24*). The power density of deep enhanced geothermal systems is between 0.59 and 1.19 W/m^2, depending on the available resource temperature (*25*).

Although the use of geothermal energy for electrical generation in cities is limited, more than 60 countries are using geothermal energy for household, commercial, and industrial heat (*16*). The thermal power densities in most regions are relatively high, even at moderate depths. In the United States, the average thermal power density of ground-source heat pumps is 40 W$_t$/m^2 for horizontal closed loops buried just 1 to 2 m deep and 100 W$_t$/m^2 for boreholes at least 150 m deep (*16*). Ground-source heat pumps for heating and cooling in Chinese urban buildings could reduce energy consumption by 10 to 15% in civil buildings and 25 to 30% in public buildings (*26*). Ground-source heat pumps could also meet the heating demands of 58 to 70% of buildings in Westminster, London, and, if a well-organized district heating system was used, all heating demands could be satisfied throughout the urban area (*27*).

Urban areas may be particularly well suited for ground-source heat pumps because of the urban heat-island effect, a phenomenon in which human activities cause cities and metropolitan areas to be warmer than their surrounding rural areas. The increased anthropogenic heat fluxes into the subsurface of a city result in elevated groundwater temperatures, enhancing the geothermal resource. In Karlsruhe and Cologne, Germany, the anthropogenic heat fluxes could sustainably provide 32 and 9% of the annual residential space heating needs, respectively (*28*). The anthropogenic influence on the subsurface temperature is greater in megacities such as Shanghai, where the existing heat content in the urban aquifer is 22 times the annual heating demand of the city (*29*).

Wind energy

Urban wind energy provides opportunities for not only renewable electrical generation but also ventilation, pollution dispersion, and mitigation of the urban heat-island effect. Urban wind energy has not been widely adopted, largely because of challenges and concerns related to installation space, low and turbulent urban wind-speed characteristics, vibration, noise, safety, shadow flicker (periodic shadows cast by the rotating blades of wind turbines), and aesthetics (*30*). Although modern wind farms typically produce 2 to 3 W/m^2 with horizontal-axis wind turbines (HAWTs), counter-rotating vertical-axis wind turbines (VAWTs) can achieve 30 W/m^2 (*31*). In addition to increased power density, VAWTs offer several advantages

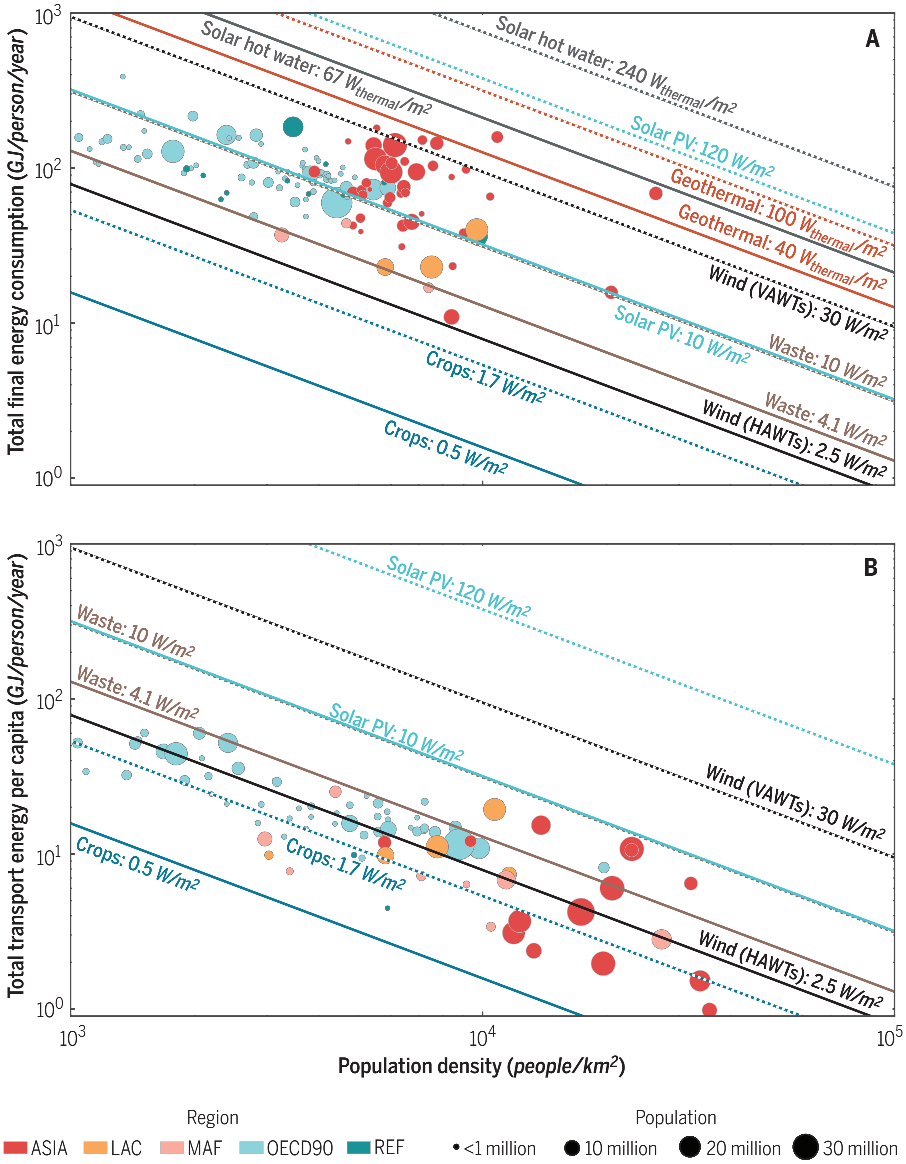

Fig. 1. City-integrated renewable energy potential. (**A**) Potential for renewable sources to satisfy total final urban energy consumption and (**B**) urban transportation energy demands. Solid lines represent typical performance. Dotted lines represent potential performance, based on optimal conditions and technologies currently available in the laboratory. All resources are evaluated based on electric power densities, except geothermal energy and solar hot water. Geothermal energy is evaluated based on thermal power densities for horizontal closed loops buried 1 to 2 m deep at the low end and boreholes at least 150 m deep at the high end. Data on total final energy consumption and region definitions are from (*77*), city population size and density data are from (*78*), and transportation data are from (*79*). "Waste" refers to LFGTE. PV, photovoltaics. Population is indicated by circle sizes, and regions are indicated by circle colors (ASIA, Asia excluding OEDC90 countries; LAC, Latin America and the Caribbean; MAF, the Middle East and Africa; OEDC90, member countries of the Organization for Economic Cooperation and Development as of 1990; REF, Eastern Europe and the former Soviet Union).

that are particularly relevant to the urban environment. These include lower dependence on wind direction, ability to handle higher turbulence and varied wind speeds, lower manufacturing costs, and decreased impact on birds and aircraft (*30*). Another benefit is that the generator and gear box can be installed at ground level, allowing building-mounted turbines to be more easily serviced (*30*).

Numerous researchers have investigated urban wind-flow characteristics, resulting in estimates of its potential for urban electricity generation. Excluding thermal energy needs, urban wind could provide 33% of residential building electricity needs with HAWTs in urban areas of New Zealand (*32*) and 40% with VAWTs in San Cataldo, Sicily (*33*). There are limited examples of existing urban wind projects. In Bahrain, the World Trade Center twin towers use three vertically arranged HAWTs, providing 11 to 15% of the electrical energy needs (*30*). Although the two VAWTs installed at the Pearl River Tower in Guangzhou, China, provide only 5% of its energy needs (*30*), they offer several design advantages. The curved glass facade of the building funnels air to the VAWTs at speeds of 1.5 to 2.5 times the ambient wind speed, allowing the turbines to generate 15 times more energy than freestanding wind turbines could (*34*). Additionally, by allowing wind to pass through the building, wind-induced forces on the building are reduced, which in turn reduce the quantity of steel and concrete needed to maintain the building's stability (*34*).

Biomass energy

Power densities for biomass energy are highly dependent on the regional climate, because it affects which plants are able to grow locally. Conventional crops have a range of power densities from roughly 0.05 to 1.7 W/m^2; the highest densities come from crops grown in tropical locations with genetic modification, fertilizer, and irrigation (*8*). The ongoing debate over biofuel sustainability and social and environmental justice considerations places this potential energy source in a complex and unsatisfactory position. Direct combustion of urban biomass offers at least a clearer life-cycle path to evaluate than conversion and use of biomass as biofuels. If short-rotation poplar was grown on marginal lands in Boston, for example, it could satisfy 0.6% of the yearly primary energy demand in Massachusetts (*35*).

Given the low power densities, urban agriculture may be better suited for food than for energy. Urban farms help reduce urban heat-island effects, mitigate urban stormwater impacts, and lower the energy needed for food transportation (*36*). A life-cycle analysis of a community farm in South London has shown that urban food supply systems can achieve reductions in greenhouse gas emissions that are potentially larger than those of parks and urban forests (*37*).

Energy from urban waste

Although not entirely renewable, energy from waste could play a key role in sustainable urban energy. Urban residents produce roughly twice the waste of their rural counterparts (*38*). Increased global urbanization is expected to result in increases in municipal solid waste (MSW) (Fig. 2). Typical management strategies include recycling, burning, or landfilling. Although recycling can reduce the life-cycle energy, it may not be economically or energetically realistic for some waste.

Energy from waste may be derived from landfill-gas-to-energy (LFGTE) systems and waste-to-energy (WTE) plants. Landfill gas is generated through the biological degradation of organic materials in MSW, typically consists of methane (50 to 60%) and carbon dioxide (40 to 50%), and can be collected and burned to generate energy. The average LFGTE power density that could be extracted from this gas is estimated to be 4.1 W/m^2, but, if optimized, a theoretical power density of 10 W/m^2 is feasible (*39*). In a WTE plant, MSW is incinerated, generating 0.6 MWh per ton of MSW on average (MWh, megawatt-hour), with the potential to generate up to 1.8 MWh per ton (*40*). Additionally, many WTE plants use cogeneration, providing useful heat. If all of the MSW generated in the United States in 2011 was sent to WTE plants, enough energy would be produced to power and heat 12 and 8% of American households, respectively (*40*). Additionally, carbon-capture systems can be integrated into WTE plants, reducing carbon dioxide emissions by an estimated 90% (*41*).

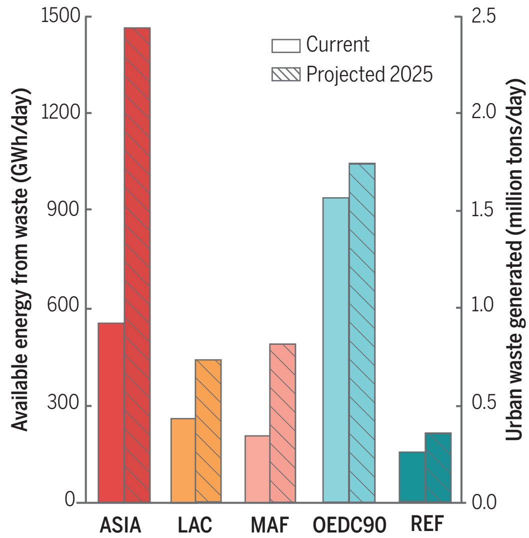

Fig. 2. Estimates of current and projected generation of urban waste. The amount of MSW that is generated daily (solid bars) and the projected daily waste production by 2025 (striped bars) in each region are indicated on the right axis [data are from (*38*)]. If all urban waste were to be burned in WTE plants, the corresponding energy that would be generated, based on an average waste energy value from (*40*) that includes nonrecyclable plastics, is indicated on the left axis.

Opportunities for reducing energy consumption

Two major sectors for reducing energy consumption are buildings and transportation. To limit global climate change to 2°C above preindustrial levels, the greatest global investment is required in the buildings sector (an estimated incremental expenditure of $300 billion/year for 2015–2020) for both retrofitting and constructing new buildings to high energy-efficiency standards (*42*). The next largest investment is required for transportation vehicles, with an estimated additional expenditure of $70 billion/year (*42*).

Building efficiency improvements

Buildings account for 40% of the world's energy consumption and 30% of annual greenhouse gas emissions (*43*). To accommodate the growing urban population, new buildings are needed. Eighty percent of all buildings that will stand in India in 2030 had yet to be constructed as of 2010 (*44*). This new construction creates opportunities not only for energy-efficient and climate-resilient buildings but also for local optimization of urban form. New buildings could be made 70% more efficient than existing buildings through the use of insulated windows, modern gas and oil furnaces, and more efficient air conditioners (*45*). Strategies for zero-energy buildings involve minimizing the energy use of a building, especially for heating and cooling, and adopting renewable energy technologies to meet the remaining minimal energy needs (*46*).

Retrofitting existing buildings saves embodied energy, avoids generating waste from building demolition, and is often more cost-effective than constructing new buildings. Despite these advantages, the rate at which the current building stock is retrofitted is startlingly slow. In the United States, the existing commercial building stock is being retrofitted at a rate of roughly 2.2% a year, with the median energy savings from these retrofits at roughly 11% per building (*47*). Most of these retrofits consist of minimally invasive measures with short payback periods, such as lighting and HVAC (heating, ventilation, and air conditioning system) replacements. Integrated energy-efficiency measures are needed to reach savings as high as 50% (*48*). These measures include upgrades to the building envelope, mechanical systems, lighting and electrical systems, and system controls, as well as changes in tenant behavior (*48*).

Transportation

The five potential metrics for the decarbonization of urban transportation are (i) fuel carbon intensity, (ii) energy intensity, (iii) vehicle occupancy rate, (iv) trip distance, and (v) the number of motorized trips (*49*). These metrics are each discussed below.

Fuel carbon intensity

Fuel carbon intensity is a measure of greenhouse gas emissions per unit energy. To reduce this metric, cleaner energy sources are required and may be achieved through fuel substitution or vehicle electrification. Although fuel substitution with biofuels requires minimal changes to the vehicle and fueling infrastructure and reduces global carbon dioxide emissions when evaluated over the life cycle of the fuel, tailpipe carbon dioxide emissions may be comparable to those produced by fossil fuels (*50*). To eliminate tailpipe pollution, vehicles powered by hydrogen or electricity may be better suited for urban transportation. Although roughly 96% of hydrogen production today uses conventional methods with fossil fuels (*51*), there are numerous emerging low-carbon production methods (*52*). However, cost and energy storage remain major obstacles. The electrification of the transportation sector is expected to grow rapidly, with plug-in hybrid vehicles predicted to account for 58% of new light-duty vehicle sales in the United States by 2030 (*53*). This growth requires improvements in low-cost, compact, long-lasting battery technologies and vehicle charging infrastructure. The environmental benefit of electrifying urban transportation will largely depend on the emissions from the electricity generation. The required energy needs for transportation could be achieved, or partially achieved, using city-integrated renewable energy (Fig. 1B).

Energy intensity

Energy intensity is the energy required to move a vehicle one kilometer. Achievable advances in engine technology can improve the fuel economy of automobiles by over 50% and trucks by over 30% (*54*). Although such improvements are possible, the greatest reduction requires a systems approach, taking into account numerous other factors including vehicle lightweighting, accessory load management, powertrain systems optimizations, and aerodynamics. Advances in lightweight materials show particular promise: Passenger vehicle fuel efficiency can be improved by 6 to 8% for each 10% reduction in weight (*55*).

Vehicle occupancy rate

Public transportation and carpooling are commonly used strategies to increase vehicle occupancy rates. A higher urban density increases the attractiveness of public transportation. For reasonable spatial and temporal availability, the urban density threshold for public transportation is estimated to be 5,000 people/km^2 (*56*). Cities with population densities below this threshold are those with the highest percentage of their transportation needs being met by private motorized vehicles (Fig. 3).

Trip distance and number of motorized trips

Trip distances and the numbers of trips taken per year per person depend on the built environment. A city with high density and mixed-use development allows for shorter trips that are more conducive to nonmotorized means, such as walking and biking. The built environment must include safe infrastructure to facilitate nonmotorized transportation. A study of five U.S. cities found that bicycle ridership increased between 21 and 171% within one year of building protected bicycle lanes (*57*). Bicycle use and walking are much more common in other areas of the world. Globally, 37% of trips are nonmotorized, with the greatest use of nonmotorized transport (50%) in the Asia-Pacific region and Africa and the least (8%) in North America (*58*).

Other factors

The urban transportation landscape is changing with increased car-sharing programs and the emergence of self-driving cars. It is still somewhat unclear what effect these will have on energy consumption, because they may result in increased low- or even no-occupancy motorized transportation. One model predicts that shared autonomous vehicles could reduce the number of cars in use by a factor of 10, but the total motorized distance traveled would increase by 11% (*59*).

Challenges of dramatic urban decarbonization

Economic challenges

Some believe that it is too expensive to invest in dramatic decarbonization; however, it may be even more expensive not to. Global infrastructure needs for 2015–2020 are ~$6.7 trillion/year under business-as-usual scenarios, and the incremental costs of low-carbon infrastructure are on the order of –$70 billion/year to $450 billion/year (*60*). Although these are global estimates, port cities with populations over 1 million are particularly vulnerable to infrastructure expenditures related to coastal flooding. Nearly 40 million people and $3 trillion of assets are currently exposed to a 1-in-100-years coastal flood event (*61*). By the 2070s, the exposed population could grow by a factor of 3 and the value of vulnerable assets could increase 10-fold under the combined effects of sea-level rise, subsidence, increased urban populations, and economic growth (*61*). Despite the global need for climate adaptation, investment in adaptation is a small part of the overall urban economy. In a study of ten megacities, investment in climate adaptation was at most 0.33% of a city's gross domestic product (GDPc) and substantially less in developing countries (*62*).

Technical challenges

Some of the main technical challenges for implementing city-integrated renewable energy are the uncertainty and variability in urban energy use and the methods used to account for the associated emissions (*3*). Municipal governments typically measure emissions using a territorial approach, primarily counting emissions that enter the atmosphere within the jurisdiction's geographic boundary (*63*). There is increasing interest in accounting for emissions on a consumption basis, allocating all emissions in global supply chains to the points at which products and services are consumed (*64*). This approach emphasizes the mitigation potential of households and includes a wider range of emission sources, including transportation, energy, food, goods and services, water, waste, and home construction.

Cities differ in both their energy needs and their available energy resources. Hot and cold climates have substantial air conditioning and heating needs, respectively. Cities with more industrial processes typically consume more energy; however, they also have increased potential for district heating and combined heat and power. Urban form also strongly influences transportation energy needs. Available energy resources depend on the status of the electrical grid, location of renewable resources, and socioeconomic conditions. There is considerable variation in energy use not only between cities but also between neighborhoods within the same city. For example, average household carbon footprints in the San Francisco Bay Area vary between neighborhoods according to income, vehicle ownership, household size, home size, carbon intensity of electricity production, population density, and other factors (Fig. 4) (*65*).

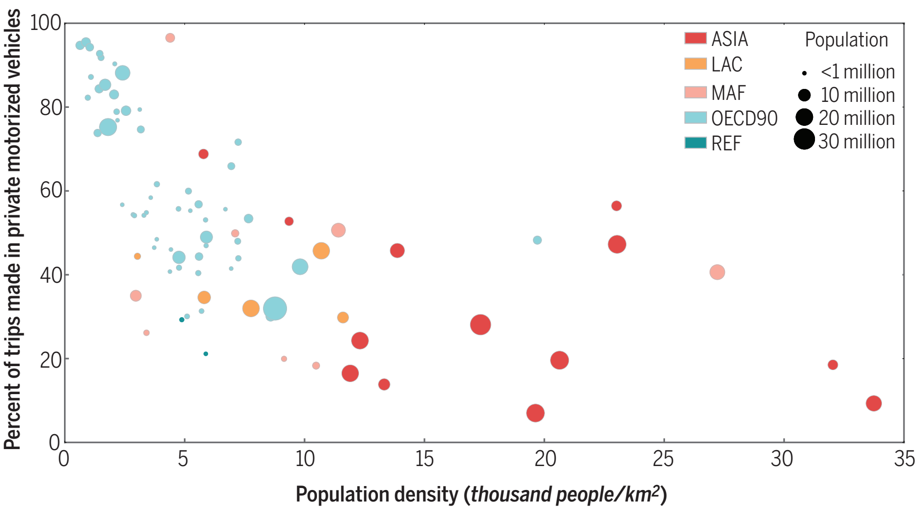

Fig. 3. Relative use of private motorized vehicles. Plotted are the percentages of trips taken using private motorized vehicles, relative to urban population densities. Data are from (*79*).

Given the uncertainty and variability in urban energy systems and urbanization dynamics, a flexible and adaptive solution is necessary. Poor visibility, aging infrastructure, and spatially and temporally variable energy generation from distributed renewable energy sources have made the current electrical grid susceptible to frequent disturbances that can lead to cascading failures. One solution would be a smart grid with integrated energy storage. A smart energy grid should not be limited to electricity; rather, electricity, thermal, and gas grids should be combined and coordinated, emphasizing the role of district heating in future sustainable cities (*66*). Even if a smart gird is well monitored and controlled, the high variability of renewable energy resources requires adequate storage. As the prices of batteries go down and their performances improve, distributed electrical storage shows potential not only in standalone units but also in the electric vehicle fleet. Electric vehicles can provide ancillary services to the grid, such as voltage and frequency regulation, peak power leveraging, and reactive power support to enhance the operational efficiency, secure the electric grid, and reduce power system operating costs (*67*). Electric vehicles couple well with renewable resources. For example, installation of photovoltaics in parking lots in Frauenfeld, Switzerland, could supply 15 to 40% of the future electric vehicle energy demand in that city (*68*), and urban electric vehicle strategies in cities in developing countries could particularly benefit the poor.

Opportunity for thermal storage is growing. Using thermal storage could double the photovoltaic capacity of Shanghai, for example (*69*). Although water remains the most widely used material for sensible heat storage, other methods, such as packed beds and phase change materials, are emerging (*70*). Thermochemical heat storage offers the greatest potential energy density and does not suffer from heat losses during storage, but development efforts are at an early stage.

Behavioral challenges

From the mundane decisions of whether or not to unplug a cellphone charger or take public transportation to more momentous decisions such as installing solar panels on a roof, behavior shapes how we live our lives and the energy choices we make. On an individual level, the effect is minimal, but in aggregate it is substantial. Occupant behavior, for example, can double the energy consumption of a building (*71*). Similarly, driving style can influence a vehicle's fuel consumption by up to 20% (*72*). A lack of information, or selfishness, may lead us to make poor energy choices, even when they are not in our individual and collective best interest (*73*).

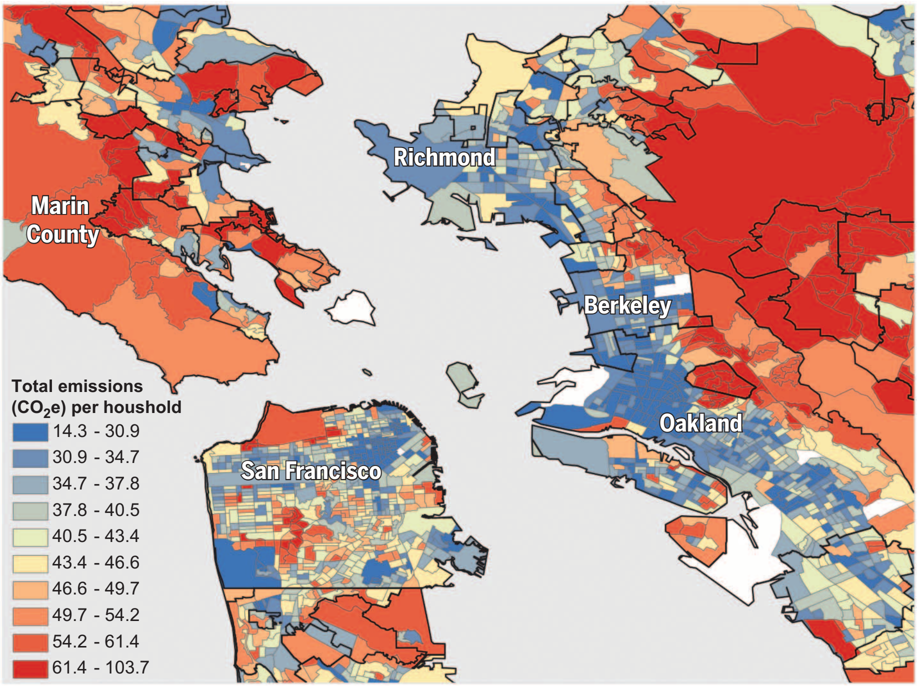

Fig. 4. Neighborhood variation in household carbon footprints. The map shows the average household carbon footprint of census block groups in selected San Francisco Bay Area cities. The color gradient indicates deciles from the lowest to the highest carbon footprint. Data are from the model developed in (*65*) and are available at http://coolclimate.berkekey.edu.

Conventional power generation systems, typically located outside of cities and neighborhoods, are out of sight and, therefore, out of the minds of general consumers. This apathy has led to major misunderstandings. For example, only 12% of Americans could pass a basic electricity literacy test (*73*). There is not only a lack of understanding of electricity fundamentals but also of the economic value of energy efficiency and renewable energy generation. For example, most businesses remain uninterested in investing in renewable power, because energy generation is outside their core business goals, despite the increased profit margins that these installations could enable.

A harmful misconception is that freedom and social well-being are best achieved through abundance and excessive consumption. Often, efficiency improvements are outpaced by increased consumption. For example, the floor area of new single-family detached houses in the United States has increased so much since 1978 that single-family housing uses more energy than multi-family housing both per household and per person, despite the efficiency gains achieved through the enforcement of new building codes (*74*). Even WTE programs indirectly encourage increased consumption. Coupled with increased consumption is a strong sense of entitlement. Whereas conventional power plants have typically been located outside of cities and neighborhoods, renewable energy generation is best placed in resource-optimal sites and/or close to the end user. Unfortunately, there has been strong resistance to this, because many people prefer such development to happen elsewhere ("not in my backyard"). Individuals often find their time and comfort to be more important than that of others and choose private vehicle use over public transportation, leading to increased congestion, delays, and inconvenience for the broader community. Not only do individuals need to understand how their behavior affects energy use, society, and the environment but, more importantly, they need to care.

Policy challenges

Although each country suffers its own political challenges, similarities can be found in the treatment of renewable energy and energy-efficiency measures. The research and development funding in these areas is nonexistent in some countries and undersupported in others, slowing innovation. Global research and development funding in renewable energy fell 3% in 2012 and 2% in 2013 (*75*).

Subsidies and incentives are often inconsistent. Unlike those for conventional generators, policies aimed at encouraging renewable power technologies have changed frequently, discouraging widespread adoption of the technologies (*73*). When incentives are removed abruptly, projects can be abandoned before completion and companies can be bankrupted. Additionally, frequently changing subsidies make it increasingly difficult to obtain financing for renewable energy projects. In the United States, policy variation between states deters investment, complicates compliance, discourages interstate cooperation, and encourages tedious and expensive litigation (*76*). An effort to promote renewables has to be sustained, orerly, substantial, predictable, credible, and ramped (*73*).

Policy-makers have focused their efforts on technical challenges. Although there are still opportunities for technical improvements, more comprehensive policies are needed to overcome economic and behavioral challenges. Emphasis is needed on government efforts to increase public understanding of energy systems and the environmental impact of behavioral choices.

An innovation agenda for urban sustainability

Achieving a sustainable urban energy system will require a dramatic rethinking of our infrastructure, information systems, and critical social and environmental justice issues. We pose here a number of immediate opportunities to "green" the process of urban evolution, as well as pressing research questions for sustainable cities, both theoretical and practical. We recommend analysis and practice to reach sustainability goals, accompanied by a new suite of data-intensive metrics on which to base planning decisions.

Renewable generation and reductions in consumption

Although city-to-city and regional variations are important to consider, many city governments could immediately (i) encourage energy storage and low-carbon generation at the building level through smart net-metered urban distribution networks; (ii) reclassify electric vehicles as appliances, so that electric vehicle purchases could be amortized into building capital budgets; and (iii) provide intra-city and city-suburban mass transit in the cleanest and most inclusive forms possible. In the near term, the following research questions should be addressed.

Can networked smart buildings themselves become the building blocks of a low-carbon city? Buildings that are designed to create clean energy, store excess generation, and feed this stored energy back into the regional matrix when demand or prices warrant would be key elements of an energy-smart network.

Do cities have an optimal size or density? Urban infrastructure exists at scales that are immediate in terms of buildings and transportation embarkation-disembarkation points but also complex and decentralized in terms of networks that supply food and water to the formal city center and suburbs. Many services that are seen as "citywide" may, in fact, be better suited to regional distribution or even remote management. The trend toward megacities, particularly in Asia, presents opportunities for improvements to infrastructure, such as mass transit, and livable high-density housing. At the same time, walkability and quality of life, as well as the potential for reduced carbon emissions, are all degraded if urbanism forces the mass movement of people, goods, water, and energy. Similarly, although increased population density may reduce transportation energy use, the resulting increased power density demand may not be appropriately met by city-integrated renewable energy, unless multiple sources are combined. These linkages of physical and managerial infrastructure open both theoretical and practical questions of scale in provision and planning.

Overcoming challenges to dramatic decarbonization

Economic, technical, behavioral, and policy challenges have been identified as barriers to dramatic urban decarbonization. However, there are several immediate actions that can be taken to begin to address these: (i) Economically value clean urban environments specifically through the positive environmental justice benefits, and use this valuation to invest in disadvantaged communities. (ii) Standardize carbon and water accounting to improve resource efficiency today and enable a transition to resource and pollution markets over time. (iii) Mix fee-bates (fees associated with polluting vehicles that finance clean vehicle purchases) and congestion pricing to improve urban air quality and reclaim city centers for pedestrians and social spaces. Meanwhile, the following pressing research questions remain.

Can urbanization in emerging economies become a force for sustainability and equality? The unprecedented growth in population and resource demands in large Asian cities has made the urban environment more polluted and more of a resource drain than any other demographic trend over the past four decades. Resource allocation, combined with a new focus on quality of life, should become a means to reverse the trends that have swept Asia. These development trends will ultimately be played out in Africa and elsewhere.

How will we give environmental justice a more central role? Arguably the most central issue in urban sustainability is whether city management can move to a paradigm where environmental justice is not an occasional response to crises of inequality but one where we reap the benefits of proactive and inclusive planning, design, and operation. It is important that renewable energy generation, improved energy-efficiency technologies, and low-carbon transportation are widely accessible, particularly to low-income populations that typically lack ownership of their residential buildings and have the longest commutes. Improvements in walkability, urban parks, and air quality should make cities more livable for all inhabitants.

Ultimately, these and other questions will require a new coordination of technical, social, behavioral, and market innovations. Cities planned around resource demands, or personal automobiles, have been tried and ultimately found lacking in their ability to create sustainable spaces. A wave of innovations in physical form, function, and ideally justice and equity offers a new path toward low-carbon sustainable cities. The challenge is to accelerate innovation and deployment so that cities can substantially reduce greenhouse gas emissions in ways that make them more livable and equitable, not less so.

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REVIEW

Emerging solutions to the water challenges of an urbanizing world

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The top priorities for urban water sustainability include the provision of safe drinking water, wastewater handling for public health, and protection against flooding. However, rapidly aging infrastructure, population growth, and increasing urbanization call into question current urban water management strategies, especially in the fast-growing urban areas in Asia and Africa. We review innovative approaches in urban water management with the potential to provide locally adapted, resource-efficient alternative solutions. Promising examples include new concepts for stormwater drainage, increased water productivity, distributed or on-site treatment of wastewater, source separation of human waste, and institutional and organizational reforms. We conclude that there is an urgent need for major transdisciplinary efforts in research, policy, and practice to develop alternatives with implications for cities and aquatic ecosystems alike.

Water has become a challenge of global dimensions (*1*). Many researchers and policy-makers have focused on large water users such as agriculture, the impact of future droughts on food security, and the quality of receiving water, giving little thought to the ability of cities to handle the urban water cycle adequately (*2*). Urban water management (UWM) has recently gained more attention, in part due to the comprehensive Sustainable Development Goal on Water (SDG-6) (*3*). The generally accepted approach to UWM builds on a well-established socio-technical system that, at least in the more affluent part of the world, has solved most of the water and hygiene-related problems afflicting cities at the turn of the 20th century. The core centralized services are the provision of safe drinking water, urban hygiene (for the purpose of public health), and protection against flooding (*4*), complemented by water pollution control.

UWM in high-income countries

The UWM system relies on investment-intensive, usually underground, pipe networks that provide single-quality drinking water and evacuate stormwater and wastewater. In many places, reservoirs and long-distance water conveyance systems compensate for inadequate local water resources. In addition, water and wastewater treatment plants provide an interface to the aquatic environment, treating raw water for drinking-water purposes and wastewater for water pollution control. Indeed, the main components of the UWM system have been considered the most important medical advance since 1840 (*5*) and still serve as the prevailing model for prospering cities worldwide (*6*). An additional important infrastructure—besides water supply and wastewater removal and treatment—is the stormwater drainage system. On a local level, the built environment has a strong influence on the natural hydrological characteristics of a catchment. A substantial part of the global urban area of 658,760 km^2 (*7*) comprises impermeable surfaces. This leads to a higher surface runoff and a faster response time to the rain event (*8*). Without adequate drainage infrastructure, unwanted urban flooding events will occur.

In the process of urban water use, waste is produced in the form of wastewater. However, wastewater also contains important resources, including water, organic matter, heat, and nutrients such as phosphorus and nitrogen (Table 1). For example, the amount of nitrogen passing through the human metabolism on a global scale and therefore potentially ending up in wastewater is on a par with major components of the nitrogen cycle. For a population of 9 billion, nitrogen in wastewater would be of the same order of size as the anthropogenic production of 35 Mt of reactive nitrogen per year (about 25% of the present production) suggested as the upper boundary for a "safe operating space" of humanity (*9*). In view of the large losses of nitrogen in agricultural production (*10*), the world can only be kept within the suggested boundary with a dramatic increase in nitrogen recycling from wastewater.

The current UWM approach has worked so well because it delivers its main services securely at a good quality to a majority of people in a region. Its institutional side is characterized by planning and investment processes traditionally delegated to municipal water authorities. These actors follow well-formulated regulatory codes in their operations and rely primarily on highly specialized technical expertise.

The downsides of the current UWM system are its strong dependence on large quantities of water (Fig. 1), high investment costs, and a need for stable institutions, as well as long planning horizons and inefficient use of resources. Whereas most of these disadvantages have different implications depending on the context, inefficient use of resources is a global issue. Despite the high amounts of energy in wastewater (Table 1), wastewater management is a net consumer of energy, and recycling of nitrogen is only possible to a very

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