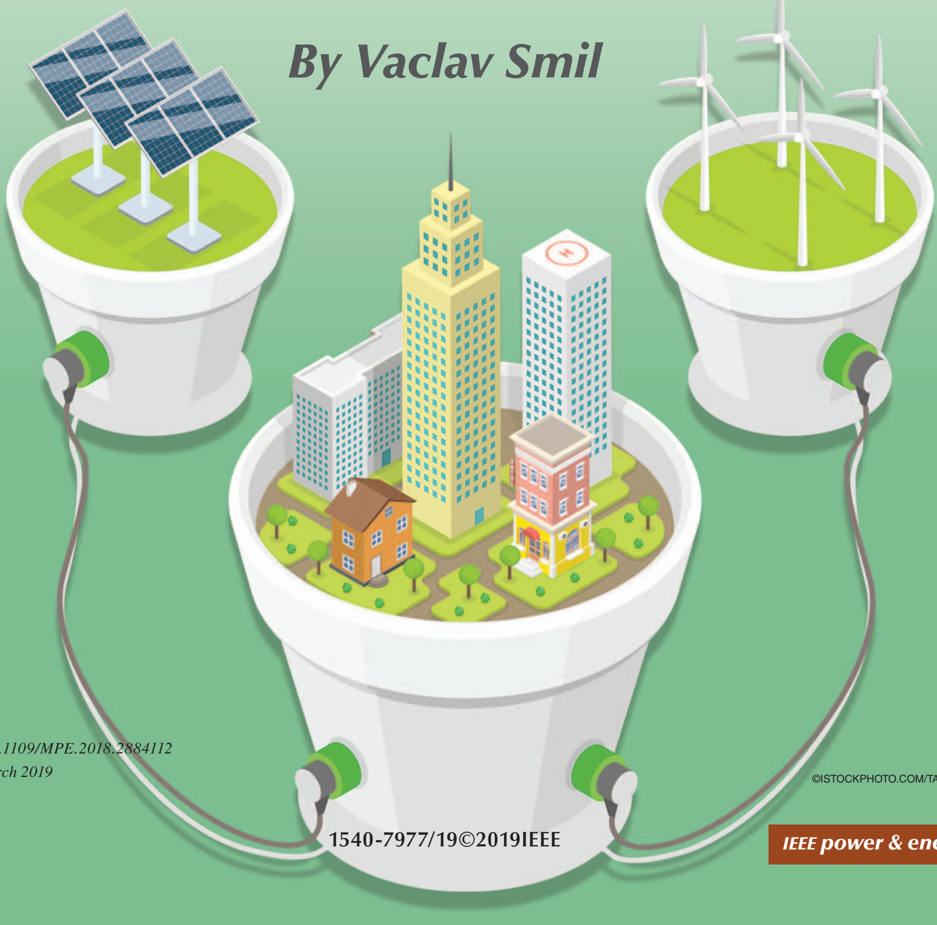
Distributed Generation and Megacities

Are Renewables the Answer?

By Vaclav Smil

DISTRIBUTED ELECTRICITY GENERATION IS THE opposite of centralized electricity production, the mode that has dominated modern commercial electrical supplies for more than a century. Rather than relying on large central stations (fossil fueled, nuclear, or hydro) and high-voltage transmission lines, distributed electricity generation depends on small-scale, decentralized, local, on-site generation, preferably by tapping renewable energy sources. This arrangement avoids long-distance transmission losses, and, once organized in a web of smart microgrids, its design improves supply stability and reliability and gives users more control. As the cost of new renewable energy conversions continues to decline, this form of electricity supply is expected to claim a rising share of overall generation. Indeed, according to Rodan Energy, distributed generation is not just the future of electricity, but also "the future of energy."



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> As with any technical innovation, some undisputed advantages of distributed electricity generation are not compatible with every scale and setting.

Such hyperbolic claims are common during the early stages of technical innovations. They appear in forecasts concerning the adoption of electric cars and, in more extreme forms, concerning battery-powered trucking, shipping, and even flying (Smil 2019). However, as with any technical innovation, some undisputed advantages of distributed electricity generation are not compatible with every scale and setting. Most notably, some proponents of omnipresent distributed generation ignore the realities of electricity consumption in places that are not suited for decentralized electricity generation, such as in large cities with their highly centralized demand for constant inputs at a multigigawatt level.

Megacities

Since 2007, more than half of the global population has been living in cities, and that share is projected to rise to 70% by 2050. The recent rapid growth of megacities (cities with a population greater than 10 million) has perhaps been the most remarkable part of this trend. In 1950, New York and Tokyo were the world's only megacities, and, by 1975, they were joined by Mexico City. By 2000, the number of megacities rose to 18, to 29 by 2015, and to 46 by 2018. Of these, 15 megacities are in China, and three are in Japan. New York, the largest U.S. city, dropped to 10th largest. Tokyo is the largest megacity, followed by Shanghai, China; Jakarta, Indonesia; New Delhi, India; Seoul, South Korea; Guangzhou, China; and Beijing. Future megacities will be added almost exclusively in Asia and Africa [Figure 1(a) and (b)].

Individual megacities have populations larger than a multitude of smaller nations. Most megacities have extraordinarily high population densities, with averages greater than 10,000 people/km^2 and the greatest numbers in city centers where populations surpass 40,000 people/km^2. The concentration of housing, industries, services, and transportation account for disproportionately high rates of consumption. Megacities can operate only because there are unprecedented concentrations of energy supplies, in general, and electricity generation, in particular. Electricity demand averages about 25 GW in Tokyo and its three surrounding prefectures (Saitama, Chiba, and Kanagawa) and 17 GW in Shanghai, while the peak demand for New York and neighboring Westchester County, New York, is 13 GW. Beijing averages about 12 GW.

Power Densities of Distributed Electricity Generation

To calculate a basic assessment of the likely extent of on-site electricity generation in megacities, compare power densities, annually averaged rates of energy output, and energy

figure 1. (a) Tokyo, the world's largest megacity, with a view centered on the commercial Shinjuku area. (Source: Morio, Wikimedia.) (b) Shenzhen in southern China is one of the newest megacities. In 1979 it was a town of 30,000 people. (Source: Hawyih, Wikimedia.)

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consumption per unit of ground area, expressed in watt per square meter. Comparing the power densities of distributed electricity generation with that of prevailing urban electricity demand yields a fundamental, realistic appraisal of opportunities and limits. There are five principal modes to generate decentralized renewable electricity, which include cultivating the following: biofuels and their subsequent combustion (with or without further treatment such as gasification); small geothermal stations; micro-hydrogeneration; small wind turbines; and photovoltaic (PV) panels on roofs, walls, or covering otherwise unoccupied land.

Because the power densities from phytomass harvests are inherently low, cultivating biofuels is completely excluded not only from all core areas of megacities but also from their less-densely developed fringes where there are patches of unused land. Generation using wood-based gas or methanol achieves power densities below 0.5 W/m^2, while cane-based and cellulosic ethanol yields 0.4 W/m^2, corn-based ethanol yields 0.25 W/m^2, and biodiesel yields just 0.1–0.2 W/m^2. These rates would be more than halved in terms of actual electricity generation. For example, providing just 10% of biofuel-based electricity for Shanghai would require a crop area that is the same size as the entire municipality (assuming 17 GW/0.25 W/m^2 = ~ 6,800 km^2 compared to the city's area of 6,340 km^2).

Similarly, typical power densities for small- to medium-sized hydro projects (with installed capacities of lower than 100 MW) are lower than 0.5 W/m^2 and are often no more than half of that value when low-capacity factors are considered. This means that small reservoirs would have to occupy areas such as those required by biofuels, and, if they were to supply more than 10% of all electricity, they would claim areas larger than those of the actual cities. This is only a theoretical consideration because very few megacities, with their waterways regulated in concrete channels or covered by modern urban development, could develop any meaningful mini-hydro generation capacities.

Very few large cities would be able to take advantage of high geothermal gradients for urban electricity generation: just imagine drilling a dense network of wells in the maze of urban underground engineering networks! Even if residents could mount small wind turbines on low towers on building roofs in the dense configurations in populated areas, the power density of their generation would be a small fraction of 1 W/m^2. Another possibility is PV systems, which is the renewable energy conversion with the highest power density and the most fitting mode of decentralized electricity generation in megacities. According to the World Bank, the average annual irradiance in East Asia is 140–150 W/m^2, and, with a 10–15% PV conversion efficiency, this would generate a gross output between 15 and 20 W/m^2. How does this compare to power densities of energy demand?

Urban Power Densities

Average urban power densities (derived from studies of nighttime light radiance) range between 10 and 35 W/m^2 and go well above 100 W/m^2 for downtown areas. A city-wide mapping of New York at the block level showed mid-Manhattan high-rise areas averaging up to 900 W/m^2 (a single block draws nearly 18 MW), and many blocks in the financial district, Midtown South, and on the East Side have densities between 400 and 500 W/m^2 (Figure 2). In contrast, residential boroughs typically use fewer than 25 W/m^2. For individual buildings, typical ranges are 15–30 W/m^2 for warehouses; 25–45 W/m^2 for homes; 50–75 W/m^2 for schools, offices, and commercial spaces; 40–90 W/m^2 for hotels; and often well over 100 W/m^2 for supermarkets and hospitals.

Projected energy usage for other structures is as follows. A two-story home might need around 50 W/m^2 (size is measured at the foundation), a 10-story office building will draw 500 W/m^2, a high-rise (40-story) apartment tower or a five-story hospital will need around 1,000 W/m^2, and a constantly air-conditioned 50-story hotel in a desert region would require 2,000 W/m^2. These rates combine the overall consumption of fuels and electricity (with electricity already dominant in high-rise buildings with near-year-round air conditioning). In post-fossil fuel megacities, so enticingly imagined by the proponents of decentralized renewable generation, electricity would also have to supply that share of demand, which now comes from fossil fuels, overwhelmingly from natural gas that is used for heating, hot water, and cooking.

Density Comparisons

Comparing average PV generation rates of 15–20 W/m^2 with the prevailing demand averages makes it clear that the two rates overlap (or come fairly close) for single-story warehouses, some retail spaces, and many detached homes in milder climates. Thus, those structures could derive significant shares of their demand from decentralized generation.

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Of course, a significant number of structures in this group will not be able to benefit because many roofs are unsuitable due to their orientation; excessive pitch; shading by other structures or trees; or the presence of heating, ventilation, and air-conditioning equipment.

In contrast, decentralized PV generation for buildings up to 10 stories high (apartments, retail, office, or hotels) with a power density of 200–800 W/m^2 would commonly require areas of PV cells 10–40 times larger than their roof areas to meet the average demand as well as the much more substantial on-site storage to manage daily and seasonal variations. Consequently, such structures could secure only small shares, typically less than 10% of the electricity required for on-site production. On-site PV power would be an entirely marginal source for high-rise buildings that average close to 1,000 W/m^2 of their foundations, hence requiring PV surfaces 50–75 times larger than their roof areas.

Installing PV walls could raise the share of on-site PV power produced by high-power-density structures, but, in many cases, any retrofitting of existing high rises (or installation of new PV windows) would be either impossible or excessively costly. Common shading in downtown canyons and suboptimal irradiation angles would require a detailed site-specific evaluation that might show some worthwhile gains or exclude such attempts. Overall gain from adding wall modules would not be enough to bring the on-site generation to even 20% of the total demand. For example, simulations for buildings in Kuala Lumpur, Malaysia, indicate that a vertical PV system on a high-rise office building typical for Malaysia could annually produce 1.7–2.9 times as much electricity as the roof installation, depending on the orientation.

Storage

All urban PV systems could work more reliably, but only with substantial storage capacities. There is an order of magnitude difference between the power-generation densities of brief noon-time maxima (well above 100 W/m^2) and annual averages, so substantial storage capacities would be needed

figure 2. Many Manhattan blocks have very high annual power densities, averaging between 500–900 W/m^2. (Source: S. Spiegelman, Wikimedia.)

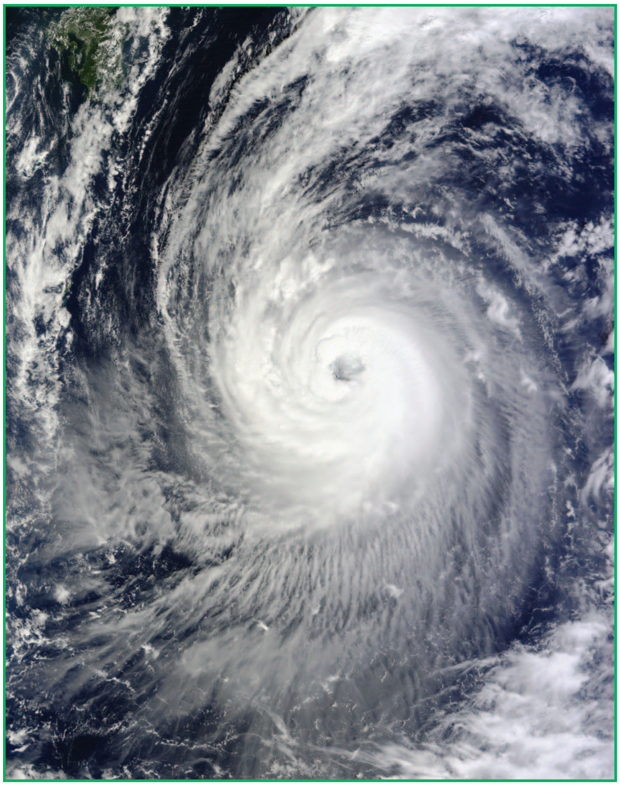

figure 3. Typhoon Phanfone approaching Japan on 5 October 2014. (Source: NASA.)

to provide an off-grid reserve. Modeling for two-family houses in Texas, United States, and in The Netherlands indicates that, to provide a two-day energy-supply backup, the minimum battery size would have to be three times the average daily electricity use. Even if a megacity were to generate just a small share of its total electricity in a decentralized manner, large storage requirements would be needed.

For example, Tokyo's most densely populated area (its 23 special wards) covers 619 km^2, houses 9.2 million people, has average irradiance of 151 W/m^2, and has a total of about 64 km^2 of roofs suitable for PV installation. PV panels that would produce 20 W/m^2 and cover all of those roofs would generate nearly 31 GWh/day while the area's current average demand is about 150 GWh/day. Even such an extreme action as covering every roof in Tokyo with PV panels would supply only 20% of the average electricity needed.

A significant storage capacity would be required to make sure that a PV storage system could meet even a 20% share of the average electricity demand during the typhoon season, when Asian cities can experience weather conditions that almost totally prevent PV generation (Figure 3). Making up for the loss of just two days of PV generation would require storage that is capable of supplying at least 60 GWh. Commercially available residential energy storage units with 13.5 kWh of usable output currently cost US$5,900 and at least US$7,000 with installation. Therefore, the city would have to install about 4.5 million such units (at a cost of more than US$30 billion) to provide a two-day energy reserve equal to just one-fifth of its electricity supply in the case of a moderate typhoon.

Predictions are always perilous. For instance, subsidies can result in such surprising outcomes such as mass-scale PV installations in large parts of Germany, where there is a relatively low irradiance rate comparable to Seattle, Washington. The capacity factors for such installations average just 10%. In the case of megacities, the physical and energetic fundamentals are clear. The gap between power densities of PV generation and power densities of electricity consumption commonly encountered in megacities cannot be bridged by existing techniques. Thus, distributed, on-site generation (PV based or any other) will not take any of the world's megacities off the electrical grid before 2050, and it will not supply even a third of their electricity demand. But it could make some valuable contributions.

For Further Reading

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Biography

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