COMMENT

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Much of lower Manhattan, New York, was without power after Hurricane Sandy in October 2012.

The smart-grid solution

Massoud Amin outlines how the United States should make its electricity infrastructure self-healing to avoid massive power failures.

As a young boy in Iran in the mid-1960s, I often accompanied my father and my mother to rural villages where, as a physician and a Red Cross representative, they voluntarily treated people. I witnessed how electricity improved the lives of families who were scratching out livings on parched plots of land. Suddenly, communities had irrigation, new schools and medical facilities. More babies survived, and businesses moved in.

Later, in New York City, I experienced the chaotic blackout of July 1977 when lightning strikes cut power to nine million residents for 24 hours. There were fires, cases of looting and thousands of arrests, but also tales of strangers helping others. Deeply affected by the ability of electricity to transform lives, I pursued a career in electrical engineering.

More than 30 years on, the US power system still experiences extensive failures. In the past decade, extreme weather conditions and unprecedented storms — such as Hurricane Katrina in 2005 and Hurricane Sandy in 2012 — have left millions of people without electricity for days or weeks. Power failures and disruptions cost the US economy between US$80 billion and $188 billion each year[1].

I believe that to become resilient, the US power system must transition to a 'self-healing smart grid' — one that can detect and isolate disturbances and adapt to minimize disruption until the problem is fixed. China has already invested $7.3 billion and will spend $96 billion on its own smart-grid technologies by 2020 to conserve power, secure energy supplies and reduce carbon dioxide emissions[2]. The European Union, South Korea, Brazil and other South American countries are following suit.

Three factors hinder improvements to the US system. First, investment is too low. Since 2010, President Barack Obama's stimulus plan has channelled $3.4 billion towards a US smart grid; industry has added another $4.3 billion. The full cost will be around $400 billion, or $21 billion to $24 billion a year for 20 years (see go.nature.com/it1ww3). But smart grid benefits amount to $79 billion to $94 billion a year, and the technology ▶

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could reduce carbon dioxide emissions by 12–18% by 2030 (ref. 2). Second, matching supply and demand is technologically challenging. And third, the fragmentation of the US electricity system across states and funding agencies means that the improvement will require a national strategy.

On any given day in the United States, about half a million people are without power for two or more hours. The number of major US power failures caused by weather rose from two to five a year between the 1950s and 1980s. These figures have increased drastically since. From 2008 to 2012, there were between 70 and 130 failures a year, constituting two-thirds of all power disruptions and affecting up to 178 million customers (electricity meters), as changing weather patterns impact an ageing infrastructure (see go.nature.com/vcaqqd).

The US power system still relies on technology from the 1960s and 1970s. The electricity sector is second from the bottom of major industries in terms of research and development (R&D) spending as a fraction of net sales; only pulp and paper is worse. Electricity R&D received just 0.17% of net electricity sales from 2001 to 2006, and the figure has not risen since. A 2011 report[3] by the World Economic Forum, a non-profit organization, ranked US electricity infrastructure below 20th place in a list of the world's nations in most of nine categories.

Electricity needs are changing and growing fast. For example, use of the social network Twitter, and the underpinning infrastructure it needs to operate, adds more than 2,500 megawatt hours of demand globally per year that did not exist five years ago. This is equivalent to a city of 825,000 homes. Factor in Internet-based television, video streaming, online gaming and the digitization of medical records, and the world's electricity supply will need to triple by 2050 to keep up.

Smart grids can measure when consumers use most power, allowing utility providers to charge variable rates according to supply and demand. Variable pricing gives consumers incentive to shift their electricity use to times when demand is low, so that they can use energy more efficiently.

Much of the technology and systems thinking behind self-healing power grids comes from the military aviation sector. I worked for many years on damage-adaptive flight systems for F-15 fighter jets, optimizing logistics and studying the survival of squadrons. In January 1998, when I moved to the Electric Power Research Institute (EPRI) in Palo Alto, California, I helped to bring these concepts to power systems and other crucial infrastructure networks, including those of energy, water, telecommunications and finance.

There are 16 programmes on smart grids at various US organizations, amounting to several billions of dollars of investment per year. These include the EPRI and the National Science Foundation in Arlington, Virginia, as well as the US departments of homeland security, energy and defence. More than 100 public and private projects — many on smart meters — address the electricity system, but there is no coordinated national decision-making body.

Jurisdiction over the grid is split. The bulk of the electric system is under federal regulation, but the distribution grid is under the purview of state public utility commissions. Local regulations stymie the motivation for any utility to lead a regional or nationwide effort. Government policies shift with election cycles, variously championing energy independence, clean energy, environmental protection, jobs and so on.

> ***"The payback of smart-grid technologies is three to seven times greater than the money invested."***

Yet the economic argument is clear: the payback of smart-grid technologies in the United States is three to seven times greater than the money invested, and grows with each sequence of grid improvement. As of March 2012, the $2.96 billion invested in US smart-grid projects generated at least $6.8 billion and supported 47,000 full-time jobs — 12,000 of them directly among manufacturers, information technology and technical service providers, and the rest among supply chains and related services[4].

SELF-HEALING GRID

A smart grid consists of a series of independent small power systems, or 'microgrids', linked by a stronger, smarter high-voltage power-grid backbone (see 'Smart grid').

The first step in upgrading the US electricity system is to install secure software sensors, fast processors and automation devices across the entire network. These upgrades are needed in every switch, circuit breaker, transformer and bus bar (the huge conductors that transport electricity from generators) to allow transmission lines to communicate with each other. Millions of electromechanical switches must be replaced with solid-state electronic circuits to handle high transmission voltages of 345 kilovolts and more.

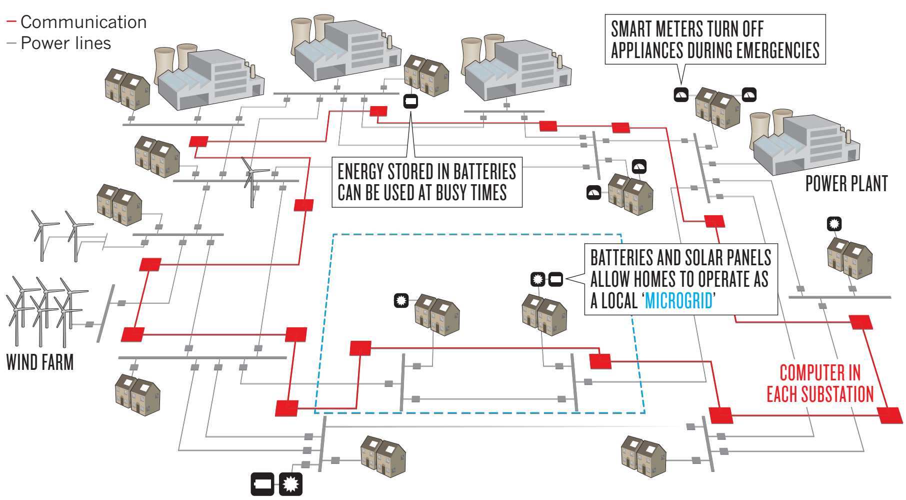
Next, local electricity generation, storage and distribution systems should be improved to increase the self-sufficiency of end-users. In the longer term, flow-directing technologies would be added to even out fluctuations and differences between energy supply and demand. Electricity might be redirected at times of peak load. Transmission routes must be built to link customers to new power stations, including wind farms, solar plants and other generators of renewable energies, most of which are remotely located. Energy-storage devices placed within the grid can compensate for varying flow, voltage or frequency by providing or absorbing energy.

New concepts for minimizing energy losses during conversions between alternating current and direct current are receiving renewed interest, especially in microgrids. Solar photovoltaics, batteries and computers make or use direct current, but current is most efficiently transmitted over large distances in its alternating form.

Cost-effective solutions will vary by region and utility, and by the equipment and threats involved. Coastal areas that are vulnerable to storm surges and flooding might need underground substations to be rebuilt on the surface. Inland, where high winds and rain produce most damage, overhead lines could be buried underground.

Customer demand, supportive policies and

SMART GRID | Digital and communications devices installed throughout a power system can track usage and minimize and manage disruptions.



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innovation-based business opportunities will drive the market for the necessary generation, storage and distribution of technologies. Surveys show that consumers are increasingly taking an interest in energy efficiency, digital demand and the cost of energy disruptions. Once people question why power cuts are preventing them from working on their computers, utilities will come under pressure to fix their networks.

Manufacturers, in turn, must integrate customer feedback into their R&D roadmaps and improve the coordination of standards, funding and R&D to drive down costs and broaden the market. Related, enabling technologies will be needed, including energy-management systems and communication technologies. Smart-grid systems must be able to interact across centralized and decentralized electrical networks, and support advanced services such as net metering, load aggregation and real-time energy monitoring.

A policy framework will be needed to provide incentives for collaboration between state utilities and federal agencies. Although some of the money would be from the public purse, regulatory agencies should incentivize electricity producers to plan and co-fund the process. Strategies need to be developed for raising money through taxes or through power-usage rates. A public–private national bank that invests in infrastructure should be created to fund repairs and upgrades by lending money on a sustainable basis according to performance metrics.

The smart electricity grid will enhance resilience in the face of extreme weather and promote economic growth by enabling commerce and technology development. The twenty-first-century digital economy fundamentally depends on these investments. ■

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2. Pacific Northwest National Laboratory. *The Smart Grid: An Estimation of the Energy and CO2 Benefits* (PNNL, 2010); available at http://go.nature.com/vopsii.
3. World Economic Forum. *The Global Competitiveness Report 2011–2012* (WEF, 2011).
4. US Department of Energy. *Economic Impact of Recovery Act Investments in the Smart Grid* (DOE, 2013).

ILLUSTRATION BY PHIL DISLEY

What would you cut?

Four insiders explain how they would make the savings in US science required by the budget sequester.

DAVID GARMAN AND ARMOND COHEN

DOE duplications and managers

Principal at Decker Garman Sullivan; executive director at the Clean Air Task Force

Money-saving reforms can sometimes enhance science. Consider the US Department of Energy (DOE) — the largest funder of research in the physical sciences in the United States. A significant amount of DOE money that is intended for science and engineering never reaches researchers. We suggest three steps that could yield substantial savings and improve results.

First, undertake a rigorous research and development (R&D) portfolio review to illuminate programme duplications, leverage complementary strengths, and focus R&D efforts on the most pressing needs. Basic research has the potential to yield revolutionary rather than evolutionary improvements to energy technology. Yet the department's applied R&D programmes are institutionally isolated from one another in four different offices, each led by a politically appointed assistant secretary. These R&D offices are also isolated from basic science research, which is housed in yet another office in a wholly ▶

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