OPINION

Transdisciplinary electric power grid science

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When a tenth of humanity lost power over 2 days in India in July 2012, technical failure was not the only culprit. Like many recent blackouts, this outage resulted from couplings among systems, including extreme weather exacerbated by climate change, human operator errors, suboptimal policies, and market forces. Predictions that climate change intensifies droughts and tropical cyclones presage more weather-induced blackouts. Even without weather disasters, small disturbances can trigger cascading failures, and so can ill-designed electricity markets (1) and dependence on cyber infrastructure.

Reliable electricity provides more than convenience; it fuels economies, governments, health care, education, and poverty reduction. As populations shift to cities and consume more energy, confronting the multifaceted challenges to reliable electricity becomes paramount.

However, enhancing reliability is no easy task. Upgrades can provide safety buffers, yet economic pressures can quickly consume new capacity. The opposing objectives of reliability and cost balance such that massive blackouts, albeit rare, continue to plague electric power systems (2). Regulation is not a panacea either: suppressing small blackouts, for instance, may increase the risk of large ones (2), a phenomenon that also plagues forest fires (3). Because blackouts are inevitable, ensuring that critical services survive during blackouts should compete for investment with preventing them. Scientific understanding of decades-long feedbacks surrounding electrical infrastructure (including weather, policy, public sentiment, markets, and novel technologies) should inform wise investment in robustness or resilience (e.g., harden against storm damage or build distributed generation?).

The "smart grid," which monitors and controls electrical infrastructure in detail, promises enhanced reliability and efficiency, but it introduces concerns over privacy and cyber-physical interdependence. Furthermore, no computer can reliably control power grids that span continents. Thus, human operators also control the grid, occasionally making errors that trigger blackouts. We sorely lack convincing scientific analyses of the interactions among human operators, protocols, automatic controls, and physical grids.

A third objective increasingly shapes power systems: sustainability. Renewable, distributed energy sources may confer resilience and mitigate climate change. However, the intermittent generation from wind and solar remains costly, and polluting fossil fuels fill the gap when renewables fall short of demand. Furthermore, moving power from windy or sunny locations to cities couples distant regions. Connections among regions of a power grid spread risk, like in other infrastructures (e.g., default among banks or viruses among computers). Using models to determine optimal connectivity is a problem that transcends disciplines (3).

Tradeoffs of Model Complexity

Power grid modeling is not merely an academic exercise; in fact, models keep the lights on. Every hour, operators run thousands of simulations to determine the consequences of plausible disturbances. However, power grid failures are difficult to model because they involve so many complicated mechanisms.

The tradeoffs of model complexity apply to any complex system. Stylized models can reveal the big picture and generate hypotheses, but throwing away rich data can relegate these models to irrelevance. For instance, many stylized models of cascading failures in power grids treat blackouts as epidemics that spread between adjacent nodes. By contrast, real blackouts also spread nonlocally: after a component fails, voltages and currents change throughout the network, potentially triggering failures hundreds of miles away. Thus, naive topological models of power grids offer little insight (4).

At the other extreme, models resembling flight simulators capture many details (usually of the physics and not of the human operators and traders). However, detailed models can obscure the important aspects and can require parameters difficult to measure.

Grand Challenges

Accurately yet insightfully modeling the feedbacks surrounding electrical infrastructure is the first grand challenge for transdisciplinary power grid science. New smart grid measurement devices provide orders of magnitude more data with which to validate models. However, limited access to data severely impedes research.

Validated models enable the next grand challenge: improve and transform power grids to meet 21st century pressures. Reliable electricity must reach more people demanding more energy in more places. Even in developed countries, reliability continues to lag. Robustness against threats from interdependence and malicious attacks will require transdisciplinary understanding. These challenges span engineering, physics, complex networks, computational science, economics, and social sciences.

Ecology can also contribute. Like ecosystems, power grids consist of many species—generators, consumers, operators, traders—subject to environmental pressures. Multiscale feedbacks drive both ecosystems and power grids to homeostasis or to collapse.

Unlike biological systems, however, power grids cannot rely on natural selection to adapt. It is up to us. Scientists, engineers, policy makers, and funding agencies must collaboratively tackle the challenges. Integrating and transcending disciplines will enable new ideas to shape the electric power system, the lifeblood of modern civilization.

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