Energy as a Contributor to Human Well-being: Electric Power Grids

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Human beings have come to depend on the availability of a sufficiently reliable, sufficiently "inexpensive" source of power for the machines that make our lives easier and allow us to sustain the complex societies that have come to depend upon power supplies. Energy is at the heart of modern life, but it is also at the heart of some of the greatest challenges to life on the planet. A key challenge we all face is how to develop a sustainable lifestyle, which includes sufficiently available sources of energy, while facing diminishing supplies of energy sources as we know them and while protecting our planet from the threats to its climate and environment related to the use of energy. There are mathematical challenges at every part of the "energy pathway" from production to storage to distribution to conservation to environmental impact. Challenges to which mathematical sciences are relevant include how best to generate energy, how to store it so it is available when needed, how to transmit and distribute it effectively and efficiently, and how to conserve it. Our electric power grid provides a case in point.

Today's electric power systems have grown up incrementally and haphazardly – they were not designed from scratch; they form complex systems that are in constant change (demand for power changes daily, even hourly; circuit breakers go out; there are unexpected disturbances; they are at the mercy of uncontrollable influences such as weather – witness the havoc resulting from hurricanes or simply high wind events). Moreover, these systems operate under considerable uncertainty. Cascading failures can have dramatic consequences, with small outages potentially leading to large blackouts (Amin and Schewe 2007). For example, on August 14, 2003, shortly after noon, a 375 megawatt generating plant in central Ohio went offline. This small change led to a cascade of events that eventually led to a large chunk of Canada and the United States going dark. All the while, human operators of the power grid were attempting to stabilize the system. Operators cannot direct the flow of power along a particular pathway, but they can make adjustments that influence power flows indirectly – using computer programs to measure the state of the system and stepping up generators or shutting down lines. But those human decisions require lots of information and a newly implemented system in the Midwest gave the operators limited information about the state of the network. When eventually three high voltage lines in Ohio overloaded and went down, the system began to lose the ability to stabilize itself. (See Robinson 2003.)

The sustainability of our electric power system raises complex challenges for the mathematical sciences. These arise from the huge number of customers; uncontrolled demand; a changing supply mix system not designed for complexity of the grid; and the fact that the grid operates close to the edge and is thus vulnerable to failures. The grid is managed through large parallel computers/ supercomputers with the system not set up for this type of management, and finding better ways to use these supercomputers to manage the power grid is called for. In addition, mathematical sciences methods are needed to improve security of the energy system in light of its haphazard construction and dynamically changing character and to find early warning of a changed state, i.e., *anomaly detection*. Anomaly detection aims at finding states of a system that are departures from the normal – anomalies -- and could if the detection occurred rapidly prevent cascading failures of the kind described above. Anomaly detection could also give us early warning of a deliberate attack on our power grid – a key concern today in the field of *energy security* – more on this below. We also need mathematical sciences methods to identify and overcome vulnerabilities and to protect the privacy of individuals under new data collection methods about electricity use.

Much has been made of the development of the "smart grid." In a lecture at the DIMACS workshop on Algorithmic Decision Theory and Smart Grid in October 2010, Massoud Amin defined the smart grid this way: The term "smart grid" refers to the use of computer, communication, sensing and control technology which operates in parallel with an electric power grid for the purpose of enhancing the reliability of electric power delivery, minimizing the cost of electric energy to consumers, improving security, quality, resilience, robustness, and facilitating the interconnection of new generating sources to the grid.

Why do we need a smart grid? The electric power grid is a massive, complex system. With sufficient information to determine what is happening in real time, grid operators would be able to contain a cascading outage or perhaps prevent one altogether. However, the grid has hundreds of thousands of miles of transmission lines and decisions have to be made really fast – in real time or faster. Power grid operators need to see several moves ahead, sorting through millions of possible scenarios, to choose an appropriate response. It could be that humans just can't respond that quickly or calculate that fast. Either we give them some tools to aid them or we put the decision making into the hands of machines. This calls for tools developed by mathematical scientists. What is called for is a new complex, adaptive system that has "self-healing properties." (Robinson 2003) Self-healing systems (not just for the smart grid) will have to deal with the entire problem lifecycle: Monitoring; detecting that something may be or may become broken or damaged; impact analysis; severity classification and notification; remediation (repairing, rebooting, or otherwise working around the problem); recording problem and corrective action (for learning purposes).

Today's "smart grid" data sources enable real-time precision in operations and control previously unobtainable (see e.g., Amin 2005, Amin and Stringer 2008, Amin and Wollenberg 2005, Farrell et al. 2002, Zhao and Villasecca 2008): New phasor systems will lead to "MRI quality" visibility of the power system. Linked with *advanced computation and visualization*, this will enable enhanced operational intelligence, advances in state estimation, real-time contingency analysis, and real-time monitoring of dynamic (oscillatory) behaviors in the system; sensing and measurement technologies will support faster and more accurate response, e.g., through remote monitoring; advanced control methods will enable rapid diagnosis and precise solutions appropriate to an "event." Traditional SCADA measurement that is widely used in monitoring and managing the power grid provides information about the status of the power grid (bus voltages; line, generator, and transformer flows; and breaker status) with a measurement every 2 to 4 seconds. New methods using phasor technology and phasor measurements provide huge amounts of additional data (voltage and current phase angles; frequency rate of change), with measurements taken many times a second. This provides challenges for the *analysis of massive data sets,* and the speed with which new data become available makes it unlikely that a human power grid operator could absorb the data rapidly enough without the aid of powerful new algorithms that aid in system understanding. The new measurements will allow us to get dynamic visibility into power system behavior; however new algorithmic methods to understand, process, visualize data and find anomalies rapidly are required.

New measurements will allow rapid understanding of how customers are using electricity, thus giving them an opportunity to save both energy and money, but also raising privacy issues. *Smart meters* will allow a customer to know which appliances are using how much energy, but might also allow others to view a customer's energy use and possibly even a customer's habits such as when they are at home and what types of devices they own. Moreover, it is even conceivable that smart meters will allow us, by understanding patterns of energy use, to learn what movie a customer is watching. To make the use of smart meters acceptable requires work on data privacy, which is another area where mathematical sciences methods, in particular *statistical and cryptographical approaches*, can help.

Mathematical challenges also arise from issues of grid robustness. For example, how will the grid respond to disturbances and how quickly can it be restored to a healthy state; in other

words, how can we design algorithms that enhance grid sustainability? *Advanced computational tools* are needed to gain wide area "situational awareness" in case of a problem and they can help with quick response to dynamic process changes, e.g., using automatic switching. For example, can we tell quickly how far we are "from the edge" and thus avoid power system collapse when voltages drop too fast? We need to develop reliable, robust models to help us achieve system understanding. How can we design "control" procedures so that the grid can quickly and efficiently respond to disturbances and quickly be restored to its healthy state? We need fast, reliable algorithms developed by mathematical scientists to respond to detected problems, algorithms that do not necessarily require human input, are able to handle multiple possible "solutions," and can figure out what to do if all possible solutions are "bad."

Increasingly, many of the critical systems we depend upon in our daily lives, such as the banking system, the transportation system, and the power system, are critically dependent on the use of modern computers. But these systems are vulnerable to deliberate attacks. *Cyber attacks* on the electric power grid are one major concern. "Cyberspace" is insecure and faced with attacks by adversaries who wish to take advantage of our dependence on it. Use of cyberspace subjects us to loss of information, loss of money, and disruption, destruction, or interruption of critical services. Cyber attacks are a national security concern and have been increasing in frequency and sophistication over several years. According to a May 2010 survey by the Center for Strategic and International Studies, 59 percent of 600 IT managers operating critical infrastructure in 14 countries reported infiltrations by "high-level adversaries such as organized crime, terrorists, or nation states." (Christian Science Monitor 2010) Adversaries can launch sophisticated "information warfare" (e.g., Russian cyber attacks on Estonia and "botnet" attacks by North Korea on the South Korean government and private industry sites). (New York Times 2007).

A cyber attack could cripple our power supply, causing not only power failures in homes, but making it impossible for major utilities such as water to operate, stalling mass transit, and endangering the safety of many people. It could also impede homeland security personnel from being able to respond, react to, and address the emerging crises. An example from Poland illustrates the ease and means by which the system may be exploited. In 2008 a 14 year-old schoolboy was able to hack into the communications system and manipulate the tram system as if it was "a giant train set." The teenager converted the television control into a device which could control all the junctions along the operating line and maneuver the trams. Four trams derailed and twelve people were hospitalized as a result of his actions. (See Telegraph 2008.) Our cities are critically dependent on our commuter train systems. Yet, a cyber attack on the signaling system could bring our commuter train traffic to a grinding halt or, worse, cause horrific train accidents.

We need to find ways to protect against cyber attacks that take advantage of vulnerabilities created by dependence on massive amounts of data generated through the smart grid. Development of fast methods of anomaly detection, *randomized algorithms* for botnet detection in order to confuse adversaries and increase the cost and risk of attacks, and *game-theoretic* approaches to competition from smart adversaries are all important mathematical sciences challenges in cyberdefense.

In sum, here are some key research challenge for the mathematical sciences: Find statistical and algorithmic methods of data analysis, advanced computational tools, and new cryptographic tools to aid us in making management and policy decisions about the electric power grid; learn how to handle the massive amount of data that arises in monitoring the grid to give us rapid awareness of anomalies so as to prevent cascading failures; find ways to protect it against failures (deliberate and otherwise); and guide us to efficient use of power while protecting the privacy of individuals.

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