Efficient, Secure Green: Digital Utopianism and the Challenge of Making the Electrical Grid "Smart"

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Electrical grids have long depended upon information infrastructures—systems for exchanging information about electricity generation, transmission, distribution, and use. But only in the last decade has the notion of a "smart grid" captured the imagination of policymakers, business leaders, and technologists. Smart grid promoters promise that information technology will simultaneously improve the efficiency, reliability, and security of the grid. This article shows how these goals have come into tension as the grid's information infrastructure has shaped, and been shaped by, government policies. It advances a three-part argument. First, digital technology and digital utopianism played a significant and underanalyzed role in restructuring the electricity industry during the 1980s and 1990s. Second, industry restructuring encouraged utilities to deploy information technology in ways that sacrificed reliability, security, and even physical efficiency for economic efficiency. Third, aligning the many goals for a smart grid will require heterogeneous engineering—designing sociopolitical and technological worlds together.

Today's electrical grid powers smart phones, smart homes, and smart cars. Yet the grid itself is not so smart. Most electrical grids cannot manage the intermittency of renewable energy sources like solar and wind, so they must rely heavily on fossil fuels. As a result, the electricity sector produces more greenhouse gas emissions than any other sector worldwide.[1] In the United States, 63 percent of the energy consumed to produce electricity is lost to the inefficiencies of fossil fuel–burning power plants. Another 5 percent is lost to transmission and distribution inefficiencies.[2] Transmission and distribution losses alone cost the United States $21 billion in 2011.[3] Power outages have been increasing in size and frequency over the past two decades, and numerous

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demonstrations have shown that the equipment running the electric grid is vulnerable to cyberattack.

Today, governments around the world are trying to solve all of these problems with a "smart grid." The United States Energy Independence and Security Act of 2007 committed the nation to developing a smart grid, defined as the "increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid."[4] The range of technologies that fall under the smart grid umbrella is vast. It includes "smart" meters that help consumers shift electricity use from times of high demand to times of low demand, electric vehicle charging stations that can provide ancillary services to the grid, satellite-based wide area measurement systems, and many more computer-managed systems.

Promises for the smart grid often ring of digital utopianism—the belief that digital information and communications technologies will revolutionize human affairs for the better. For example, in 2001 *Wired* magazine—founded to promote digital utopianism—reported that "every node in the power network of the future will be awake, responsive, adaptive, price-smart, ecosensitive, real-time, flexible, humming—and interconnected with everything else."[5] In 2003 three key policymakers promoted a smart grid in *Foreign Affairs*: "Rewiring the grid with advanced computer controls would allow power to be distributed more efficiently, safely, and securely. . . . It would at once save energy, create jobs, reduce emissions, and enhance American security."[6] And today the US Department of Energy explains how "a smarter grid works as an enabling engine for our economy, our environment and our future."[7]

To what extent can a smart grid fulfill the many promises of digital utopians? This article approaches this question by examining the smart grid as an information infrastructure. Physical infrastructures connote large and sturdy systems that enable the seamless movement of people and goods across large distances. Similarly, information infrastructures have come to connote the networks of computer and communications technologies that allow people to easily seek, gather, and distribute information on increasingly large physical and organizational scales. The smart grid is a quintessential information infrastructure, a system designed to enable power producers, transmission operators, distribution systems, and consumers to exchange information seamlessly. Can this infrastructure achieve all the goals of its participants—efficiency, reliability, and security?

By exploring this question, this article builds on a sizable body of scholarship about the relationship between information infrastructures and politics. Scholars began examining the politics of information infrastructures in the 1990s, as access to the Internet began to skyrocket. Many journalists, industrialists, and policymakers argued that the Internet would transcend the nation-state, creating a political system based on free enterprise and individual expression.[8] In perhaps the best scholarly articulation of this view, legal scholars David Post and David Johnson argued that cyberspace was a distinctive sphere of governance and that citizens of this new space would develop their own rules of conduct.[9]

However, many other law scholars and political scientists have critiqued digital utopianism for a tendency toward technological determinism and a naïve understanding of politics.[10] Lawrence Lessig and Barbara Van Schewick are among those who argue that the Internet is governed not by its users but rather by the private companies that control its architecture.[11] In a similar vein, Tim Wu and Jack Goldsmith have argued that nation-states continue to control the Web by governing the private sector that controls the Web's architecture.[12]

The field of science and technology studies has analyzed the politics of information infrastructures from a somewhat broader perspective, including systems that preceded digital technology and the Internet. For example, Geoffrey Bowker and Leigh Star have discussed how scientific and professional information infrastructures—systems for storing, standardizing, and classifying data—tend to enforce a particular worldview by defining what can, and cannot, be stated.[13] Today we have a rich literature examining the politics of information infrastructures in scientific practice.[14]

This article extends past work by examining the politics of a unique *kind* of information infrastructure, one that controls a physical infrastructure. Such computerized industrial control systems (ICS) are ubiquitous. They run petroleum refineries, water treatment plants, and myriad other industrial systems. But the information infrastructure that controls the electrical grid is perhaps the consequential ICS, because virtually all other sectors of society depend upon it. Thus, the information infrastructure that controls the grid has tremendous potential to advantage some groups at the expense of others—in short, it has tremendous potential for politics.

Historians such as Richard Hirsh and Thomas Hughes have provided excellent accounts of how the grid's *physical* infrastructure shaped, and was shaped by, politics.[15] But historians have yet to explore how the grid's *information* infrastructure has shaped, and been shaped by, a changing political and regulatory regime. This article aims to fill this niche, using industry journals such as *Electric Utility Week*, *Electric Utilities Fortnightly*, publications of the Institute for Electrical and Electronics

Engineers (IEEE), and government databases to track changing uses of and justifications for using information technology to control the electrical grid.

In discussing the evolution of the grid's information infrastructure, I draw upon historian Gabrielle Hecht's notion of a "technopolitical regime"—a system of artifacts, experts, organizations, policies, and paradigms that simultaneously produce technical and political power.[16] Thomas Hughes and Arne Kaijser have emphasized that the intertwining of so many complex technological and social elements makes technopolitical (or "sociotechnical") systems difficult to change.[17] Similarly, this article demonstrates challenges to making the grid's information infrastructure truly "smart"—that is, simultaneously economical, physically efficient, reliable, and secure.

I advance a three-part argument. First, digital technology and its proponents played a significant and underanalyzed role in helping to restructure the electricity industry during the 1980s and 1990s. Second, industry restructuring encouraged the utilities to develop and deploy information technology in ways that tended to sacrifice reliability, security, and even physical efficiency in favor of greater economic efficiency.[18] Third, aligning the many goals for a smart grid will require far more than digital technology. It will also require *heterogeneous engineering*—designing both sociopolitical and technological worlds together.[19]

The remainder of this article has four parts. First, I briefly discuss how the grid's information infrastructure evolved in the early and mid-twentieth century. The utilities designed and used information technology to centralize and expand power production, thereby increasing both economic and physical efficiency. Large, special-purpose, centralized computers supported, and were supported by, a regulatory structure that allowed utilities to operate as vertically integrated monopolies.

In a second section, I discuss how this regime changed in the 1970s as environmentalists, regulators, and the national security establishment all began to challenge the utilities' emphasis on large-scale centralized power production. The changing regulatory environment encouraged utilities to use new kinds of information technology, such as microprocessors and computer networks, to manage more distributed resources. Conversely, promises for the "microprocessor revolution" and the Internet encouraged many regulators, economists, and engineers to press for a more competitive, restructured electricity industry.

A third section discusses some of the limitations and unintended consequences of the new technopolitical regime: increased efficiency came at the expense of reliability and cybersecurity. Amid growing concerns about not only energy efficiency but also the reliability and security of the grid, policymakers and industry representatives began to argue that a "smart grid" represented a solution to all of these challenges. A fourth and concluding section briefly discusses some of the technopolitical challenges to aligning the many goals of the future smart grid.

Information for Regulated Monopolies

The grid's early information infrastructure was shaped by intertwined policies, organizations, and paradigms that together encouraged ever-expanding production and consumption of electricity. As historians such as Thomas Hughes and Richard Hirsh have discussed, in the late nineteenth and early twentieth centuries, most utilities operated as vertically integrated companies that generated, transmitted, and distributed electricity. They gained economies of scale and scope by increasing the size of their generators and networks.[20]

One reason that large networks offered economies of scope was that utilities needed to keep electricity generation and demand almost perfectly equal at all times. Thus, they could gain efficiency by increasing the load factor, defined as the ratio of the average load to the maximum load in a specified period of time. If the load factor is precisely one, then the system is constantly used at full capacity. By contrast, if a utility has a very small load factor, then it must maintain capital-intensive equipment to achieve peaks but then let that equipment sit idle most of the time.[21]

In the late nineteenth century, utility managers realized that they could reduce the load factor by expanding their networks and shaping patterns of consumption. For example, since industrial users have a relatively stable usage pattern, the utilities offered them competitive rates that would discourage them from investing in their own cogenerating facilities—that is, facilities that produce both electricity and steam. Utilities were better able to level their load curves as they expanded their networks, integrating industrial and residential areas into a single network. During World War I, different utilities began interconnecting their networks to meet wartime manufacturing demands, and such interconnections continued to increase in the 1920s.[22]

Utility companies also gained economies of scope by increasing the number of generators available to them and thereby optimizing the mix of power generation. In "economic dispatch," companies turn on the cheapest sources of power first and the most expensive sources last. For example, hydroelectric power tends to be relatively constant and cheap. Utility companies only add more expensive power sources as demand grows.[23]

In the early twentieth century, utilities managers argued that all of these economies of scale and scope made utilities natural monopolies. Managers successfully pressed for regulatory regimes that would guarantee them a return on expensive investments and enable them to expand their systems. By 1922 thirty-seven states regulated utility companies, and in 1935 the Federal Power Commission gained responsibility for regulating interstate electricity commerce.[24]

Importantly, utilities could only gain economies of scope by gathering and using information to manage electricity generation, transmission, and distribution.[25] For example, long-distance, high-voltage transmission lines enabled utility companies to bring cheap hydroelectric power to cities, but these long lines could introduce instabilities in power systems. MIT engineers developed analog computers ("mechanical brains") that could simulate the behavior of electrical networks with miniature transmission lines, transformers, and other devices.[26] As power-generating stations grew more complex, including more and more generation units, many companies also began using computers to plan for the most economic dispatch, thereby making their systems more efficient.[27]

In the late 1950s and early 1960s utility companies increasingly used computers not only to plan grid operations but also to control power systems on increasingly large scales. The engineers who developed such "process control" computers drew upon traditions of analog computing, but many were also influenced by the new field of electronic digital computing.[28] In what came to be called supervisory control and data acquisition (SCADA) systems, both analog and digital process control computers were used to manage industrial systems in a more centralized, coordinated way.[29] SCADA systems were critical to running nuclear power plants, and electrical power companies were the largest single purchaser of process control computers by 1964. The same year the *New York Times* noted that "process control computers, the blue-collar cousins of the more glamorous white-collar data processing computers," were becoming "big business," with sales growing at a rate of 30 percent per year.[30]

Information technology enabled utilities to gain ever greater economies of scale and scope and thereby increase electricity production—and profits. A 1965 feature article in *IEEE Spectrum* explained the need to computerize power plants: "With the present increasing demand for electrical power, the trend is toward larger capacity and more complex turbine-generators. . . . The instrumentation, recording, alarm systems, and the remote controls to enable the plant to be operated from the control room under very adverse conditions will produce a mass of data too great for one operator either to act upon or comprehend."[31] A manager at General Electric explained that the computers were needed because large generation plants were becoming too complex for human operators to manage: "An operator today would have to have a fantastic memory and a pair of roller skates to duplicate the ability of a computer to effectively analyze 1,200 bits of information every fifteen seconds, as will be done with future power stations."[32] The size of generators continued to rise through the 1960s, and the utilities argued that these increasingly large sources of power—many of them nuclear—would enable economies of scale. Utility companies also used computers to manage economic dispatch.[33]

In the 1960s Americans generally accepted that automation was worthwhile because it enabled expanded electricity generation and consumption. For example, the *New York Times* emphasized "the importance of the computer in speeding up the production and distribution of electricity."[34] It also explained that automation was important because the "continued growth of electric utilities is becoming about as certain as death and taxes."[35]

Importantly, the utilities made the grid smart for *economic efficiency* but not necessarily *physical efficiency*. To be sure, larger turbines and networks could improve the physical efficiency of power production and distribution. But as Richard Hirsh and David Nye have noted, utility companies promoted increased consumption, advertising electricity as a necessity of modern living.[36] Between 1920 and 1973 electricity demand grew at an average annual rate of 7 percent, despite a dip during the Great Depression. At a time when natural resources seemed unlimited, it seemed natural to increase electricity use and related improvements in living standards. Additionally, continued growth enabled utilities to continually decrease the cost of electricity. The real price of electricity fell steadily, dropping from about 320 cents per kilowatt hour in 1890 to 7 cents per kilowatt hour in 1970 (costs in inflation-adjusted 1986 dollars).[37] Information technology was a central part of this transition, allowing the utilities to build ever larger generators and more complex networks, increasing economic efficiency.

Information for Free Markets

Toward the "Distributed Utility"

In the late 1960s and early 1970s the utilities began to confront limits to economies of scale and scope. Rising prices of electricity, reliability problems, the environmental movement, and anxieties about "energy security" all contributed to the decline of the "natural monopoly" paradigm. Hirsh has argued that the utilities' "technological stasis"—their failure to innovate—created pressures to make the industry more competitive.[38] What has been less appreciated is the critical role that information technology played in the changing regulatory regime. The utilities responded to the changing regulatory environment by developing smaller and less centralized forms of electricity generation, something that only became economical with the rise of microprocessors and computer networks.

Reliability challenges led to some pressures for decentralized power generation. In 1965 the US Northeast and parts of Canada experienced a blackout that left 30 million people without power. It was the worst blackout that North Americans had yet experienced.[39] A Federal Power Commission (FPC) report on the blackout recommended that the utilities "intensify the pursuit of all opportunities to expand the effective use of computers."[40] It also emphasized that the "distribution of generation and its location closer to the load centers . . . should strengthen the network in the future by reducing some of the need to transport power over substantial distances."[41] New kinds of information technology became critical to more distributed energy generation.

Much of the impetus for more distributed forms of generation and energy management came from anxieties about "energy security" in the 1970s.[42] The 1973 Yom Kippur war and oil embargo prompted concerns about the United States' dependence on foreign oil. Some analysts argued that energy security was not only about dependence on foreign oil but also about worldwide resource limits.[43] The energy consultant Amory Lovins emerged as an influential advocate of what he termed the "soft path" to energy security. Rather than seeking economies of scale through more production and consumption, Lovins advocated using energy more efficiently. Furthermore, he opposed the development of more large, centralized, and nonrenewable sources of power, including nuclear, coal, and oil power plants. He argued that the centralization of both physical and social power represented the "hard path" to energy security, one that increased risks of large-scale power outages and pollution. He advocated decentralizing both social and technological forms of power through technologies such as solar, wind, and cogeneration facilities (plants that use waste heat from gas-, oil-, or coal-burning generators to heat nearby buildings). Lovins argued that the soft path would increase efficiency, reliability, and security.[44]

Significantly, Lovins drew analogies between energy systems and computer systems. He argued that large, centralized energy production facilities were much like mainframe computers, which "failed often and expensively," were "harder to understand and repair than small systems," and raised concerns about data security and vulnerabilities.[45] Writing in the early 1980s, he pointed to the rise of distributed computing, with its reliance on smaller computers that could "fail more gracefully."[46]

Lovins's vision was partly realized as a changing regulatory environment encouraged more decentralized power generation. The Environmental Protection Agency, created in conjunction with the Clean Air Act of 1970, began to regulate utilities' emissions of pollutants and to require environmental impact statements. In 1977 the Federal Power Commission was given expanded responsibilities as the new Federal Energy Regulatory Commission (FERC). In 1978 the Public Utilities Regulatory Policies Act (PURPA) gave FERC authority for overseeing a new program that encouraged generation from small power generators such as wind farms, solar farms, and industrial cogeneration facilities.[47] PURPA required power companies to purchase energy from such qualifying facilities (QFs) at the utility's "avoided cost." In principle, state regulators set the "avoided cost" to the amount that it would cost the utility to produce the same amount of electricity, but in practice, some states set the avoided cost at a higher rate. Between 1978 and 1996 nonutility generators expanded their share of the US electricity supply from just 3.5 percent to 11 percent.[48]

PURPA helped to decentralize some electricity generation both directly by nurturing small power producers and indirectly by forcing utilities to adopt a new business strategy. In the 1980s the majority of new generating capacity came from nonutility generators, while energy efficiency efforts reduced the anticipated growth of demand for electricity. Although utilities had invested in nuclear and other large power plants in the 1970s, these plants proved to be unnecessary because of the rise of nonutility generators and slow growth of demand. Many state regulators refused to pass on the expense of the new plants to ratepayers. For example, a five-billion-dollar nuclear power plant in New York became an expensive white elephant. Recognizing that large power plants represented a risk, utilities began investing in smaller and more distributed forms of energy generation.[49]

Significantly, the use of more decentralized forms of energy generation necessitated more distributed forms of information processing to manage ebbs and flows of electricity. One engineer explained that distributed information processing offered the utilities "local optimization and data concentration, reducing the burden on the system operator while enhancing system performance."[50] While some utilities continued to use the large, special-purpose, centralized computers of the 1950s and 1960s, purchases of standardized microprocessor-based computers tripled every year in the mid-1980s.[51] These small computers could be used to manage more distributed energy resources. One power systems engineer explained the "distributed utility" concept: "Dispersed modular resources are installed in different locations of the network, generally near the point of end use, to reap additional benefits. The resources in question may be small modular generation and storage technologies such as photovoltaics (PV), wind generators, fuel cells, battery storage, diesel engines, and perhaps demand-side management (DSM) measures."[52] In demand-side management programs, utilities used "smart" meters—devices that could measure electricity usage on an hourly basis—and time-of-use pricing plans to encourage users to shift power consumption from times of high demand to times of low demand. Utilities also offered large industrial customers lower rates around the clock if they would allow utilities to directly control some heavy loads and shut them off at times of high demand.[53] These programs both decreased the costs of producing electricity (by preventing the need to add more expensive electricity sources) and increased physical efficiency (by reducing grid congestion and in some cases overall electricity demand).

The distributed utility might seem to represent Lovins's "soft energy path," with the decentralization of both social and technological power. However, it is important to note that utilities viewed it primarily as a means for the dominant power producers to retain market control in the face of regulatory uncertainties and increased competition. In 1988 the inaugural volume of *Computer Applications in Power* explained that distributed information processing was needed because utility "operations are becoming more complex due to . . . more cogeneration and nonutility generators, and increased competition."[54] To prevent additional losses in sales and growing complexity, utilities actively worked to dissuade industrial electricity users from developing their own cogeneration facilities.[55] And in 1992 the executive director of California's Independent Energy Producers Association expressed "a high degree of suspicion" that the utilities were using DSM "to suppress the need for adding new independents, and then later in the decade will be in the mode of repowering their own plants."[56] In other words, nonutility power producers feared that demand-side management was part of the utilities' strategy for crushing the competition. Utilities were more than willing to decentralize the technological production of electricity but were displeased about decentralizing the ownership of generation.

The Microprocessor Revolution: A New Regulatory Order?

Just as the changing regulatory environment encouraged new uses of information technology, new kinds of information technology served as the rationale for what congressional researchers dubbed "a new regulatory order."[57] In the early 1980s many researchers, policymakers, and utilities executives began arguing that microprocessors and computer networking could enable a more competitive market structure, reducing or eliminating the need for regulators to establish market prices. For example, a team at MIT's Energy Lab argued that regulators should introduce more competition, explaining that "recent breakthroughs in microelectronics are a significant portion of what enables electric power to be removed from the category of a 'natural monopoly.'"[58]

The Electric Power Research Institute (EPRI), a research and development organization formed by the Edison Electric Institute in 1972 and located in the heart of Silicon Valley, helped to create a policy discourse that verged on digital utopianism.[59] For example, in 1989 the president of EPRI argued: "Silicon science . . . offers important promises for helping our customers enhance their productivity and competitiveness with smarter and more efficient electrotechnology . . . Promises for the electricity customer, and promises for the electric utility business. Promises that I'm confident will be realized as we celebrate the beginning of the new millennium."[60]

Similarly, Kurt Yeager, the head of EPRI's Generation and Storage Division, promised: "The microprocessor revolution will join with and spur all other technological innovations in the next few decades. It is both building block and mortar in creating the Second Electrical Century." In rhetoric that rang of digital utopianism, Yeager emphasized that microprocessors offered both technological and economic opportunities. For example, he explained that "microprocessor technology holds the promise of opening interactive communications with customers to help establish better control and more precise targeting of services." He claimed that microprocessors would offer electric utilities "both social and business advantages and at the same time protect the environment," creating "a win-win opportunity for our nation and the world, and the only way to meet the challenge of a sustainable future."[61]

Public utilities commissioners in some states began urging utilities to deploy microelectronics in ways that enabled more consumer choice. For example, a member of California's public utility commission argued that the utilities' load control methods were "heavy-handed" because they allowed utilities to cut off electricity supply at times of peak demand.[62] He argued that utilities should adopt spot pricing systems that were enabled by new information and communications technologies.

Some utility managers and economists were skeptical about efforts to transform markets, and especially retail markets, with microprocessors. They emphasized that consumers might not respond to price signals by shifting their usage from times of high demand to low demand. They also explained that uncertainties about the marginal price of electricity would make it difficult to send consumers accurate price signals.[63]

Utility managers were more receptive to the creation of competitive wholesale markets. They argued that nonutility generators should be forced to bid competitively for electricity sales rather than being promised generous rates by state utility commissions. Additionally, utilities with excess generating capacity wanted the opportunity to sell electricity outside of their immediate area, where they might gain a better price.

Many regulators were persuaded by promises for new digital technology. For example, the chairman of the Illinois Commerce Commission, Philip R. O'Connor, suggested that the utilities should "use the advanced information handling capabilities of computers to facilitate market-based transactions between utilities." He explained: "In a brokerage-auction market, voluntary buy-sell agreements between companies occur on an ongoing basis, allowing the most efficient generating units to be used most often. Existing computer technology provides the information management necessary to make a complex power market feasible."[64]

In the early 1980s several states began experiments in competitive bidding from nonutility generators, and federal regulators began to experiment with wholesale competition for electricity generation among the utilities. These exchanges relied upon new uses of information technology, such as electronic bulletin boards and computer networks.[65] Although the utilities had traded among themselves for decades, most exchanges were planned well in advance. Last-minute changes were managed bilaterally through phone calls. By contrast, computer networks could centralize markets by including more utilities in the bargaining process.[66]

When the 1991 Gulf War renewed concerns about energy security, wholesale competition finally moved from the stage of regional experimentation to national policy. The 1992 Energy Policy Act authorized the Federal Energy Regulatory Commission (FERC) to require that utilities make their transmission lines available to electricity generators that wanted to sell wholesale power to distributors. FERC acted aggressively on its new authority, and public utilities commissions in many states went further by requiring utilities to divest their generation assets.[67]

The Federal Energy Regulation Commission encouraged utilities to form nonprofit independent system operators (ISOs) or regional transmission operators (RTOs) to manage centralized spot markets and coordinate grid operations. Here again, information technology played a key role in the new regime. The ISOs/RTOs used computer networks (often the Internet) to create a centralized spot market on a day-ahead and hourly basis. In the new scheme, generators would bid to supply electricity at particular times, and the ISOs/RTOs would use these bids to manage economic dispatch for the system.[68] Today the US electrical grid is primarily controlled by seven different ISO/RTOs, controlling about two-thirds of the US energy supply.[69]

Some industry representatives, especially those in the burgeoning world of Internet startups, argued that information technology should be used to introduce retail competition as well as wholesale competition. They noted that competition in generation did not offer customers the information needed to participate in the electricity market and that the generators could potentially collude to drive prices up. The president of one Internet company argued that the solution to the "cartel power of generators . . . clearly lies in technology. Via the Internet, companies like ourselves can provide technological tools that enable consumers rather than generators to set electricity prices, even at those times of system peak."[70] Similarly, the CEO of an Internet startup called Nexus Energy Software promised the US Congress that "the Internet can be a powerful tool for consumers in deregulation."[71] In the late 1990s and early new millennium, several states began to offer retail choice.

Beyond Utopianism: Limitations and Trade-offs

Trading Reliability for Efficiency

Throughout the debate about electricity industry restructuring, advocates of a new regulatory order likened electricity to other kinds of markets. For example, O'Connor advocated the "creation of an auction market [for wholesale electricity] utilizing available computer technology now at work in exchange markets ranging from stocks and bonds to commodities to natural gas."[72] Similarly, the chairman of Westinghouse explained to an industry group: "It's wholly practical to treat electricity as a commodity. . . . We can build computers that are intelligent enough to make load management decisions in response to spot market prices that change every few minutes."[73] But engineers warned that electricity was a unique kind of commodity because it was used at almost precisely the instant it was produced. They warned that turning the grid into a free market could create uncertainties and instabilities, undermining reliability.

For example, in 1989 the Edison Electric Institute released a report warning that industry restructuring "could have very serious and far-reaching engineering and reliability impacts." In order to make wholesale markets competitive, generators would need to use other companies' transmission lines to "wheel" electricity to any distributor willing to buy it. This would increase the number of interactions between each generator and distributor, increasing uncertainties and the interactive complexity of the system. The institute warned that these increased uncertainties and complexity would force the utilities to plan more conservatively, increasing overall costs. The only alternative was to allow increased uncertainties and volatility to reduce reliability. The institute also warned that the physical efficiency of the system would decrease because of problems with loop flows, in which "power flows over circuits owned by many different systems before reaching the intended buyer."[74]

Similarly, the IEEE vice president for activities filed the organization's response to FERC's proposal for deregulation, explaining, "We do not subscribe to procedures that limit the engineer's role to system design while leaving economic evaluations of alternative institutional arrangements to the economist." The institute underscored "fundamental differences between electric systems in which the product must be produced at the instant it is needed, and other production and distribution systems," the "importance of reliability in the supply of electricity and the economic costs of declining reliability," and other "unique characteristics of electric power systems" that required engineering knowledge.[75] At a 1986 conference on deregulation, a professor of electrical engineering was asked to address the question of whether the physical infrastructure to support deregulation existed. He answered with a one-word slide: "No."[76]

Multiple congressional studies took note of these warnings from the engineering community and underscored the potential challenges for reliability.[77] Nonetheless, the US Congress turned the grid into a marketplace in the 1990s, leaving the engineering community to sort out the challenges of maintaining reliability. The advent of nationwide wholesale markets increased interactions between parts of the grid that had formerly been distinct, creating more opportunities for what Charles Perrow has called a "normal accident."[78]

Many engineers sought solutions to the reliability challenge in digital technology. In fact, the term SMART Grid—an acronym for

Self-Managing and Reliable Transmission Grid—was first introduced in 1997 to discuss ways of managing the reliability challenges of the restructured electricity market. The article, published in *IEEE Computer Applications in Power*, explained: "As open transmission access is becoming a reality, a major concern of electric power utilities is to maintain the reliability of the grid. Increased power transfers raise concerns about steady-state overloads, increased risks of voltage collapses, and potential stability problems. Strengthening the protection and control strategies is what utilities must do to prevent a local problem from spreading to other parts of the grid." The article argued that the falling cost of microprocessors made it feasible to deploy "smart devices" with "advanced algorithms to make local decisions based on local measurements" throughout the grid. Such smart devices would "form the line of defense at the low level and offer the most advanced protection schemes that use local information."[79]

Thus, by the late 1990s, engineers were seeing microprocessors as something that could improve reliability as well as efficiency. But in practice, it seems that many utilities were more inclined to use information technology to improve their economic efficiency rather than their reliability. Utilities had strong economic incentives to use information technology for economic gains rather than reliability. Even as industry restructuring increased the volume of electricity wheeling through the grid, utilities reduced their investments in the grid infrastructure and tried to use information technology to get more capacity out of existing infrastructure. In the early 1990s one group noted that industry restructuring, "increased competition, and societal pressure to pursue operating methods that are more economically and environmentally acceptable" were all pushing "the industry to increase the utilization of the existing system in contrast to building or upgrading T&D [transmission and distribution] capacity."[80] Another engineer noted that "improvements in computers, communications and controllers" enabled utilities to operate "the grid closer to its limits," with a high "economic payoff."[81] Unfortunately, by operating large areas closer to margins of error, utilities also risked failures on an even larger scale, and blackouts increased in frequency and size through the 1990s and early new millennium (figure 1).[82]

Utilities had the freedom to sacrifice reliability for economy because regulators had no authority to enforce reliability standards. The North American Electric Reliability Council (NERC), a group established in response to the 1965 blackout, formulated voluntary reliability standards, which FERC could recommend to the industry. However, NERC's

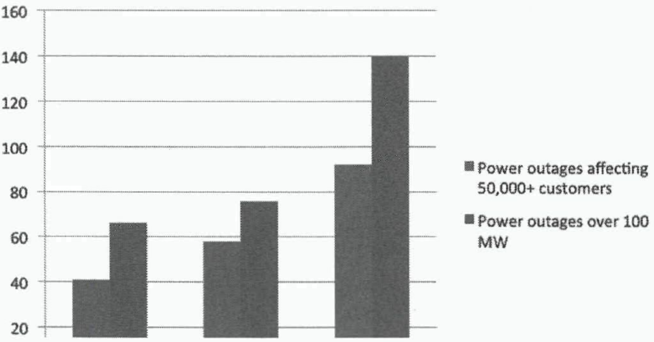

Figure 1. Increasing number of large-scale power outages. Data from Amin, "US Electrical Grid Gets Less Reliable."

recommendations tended to reflect industry preferences for economy, not policy priorities such as reliability, and neither NERC nor FERC had authority to enforce reliability standards.[83]

Trading Cybersecurity for Efficiency

The growing use of standardized microprocessors and personal computers also contributed to new concerns about cyberattacks. In 1988 the very first issue of *IEEE Computer Applications in Power* predicted that with the rise of interconnected, standardized computers, "data security will also become a greater risk." It explained: "Widespread service interruptions can result from 'willful acts' by saboteurs with computer expertise. . . . It will be necessary to put greater emphasis on security-related problems in the future."[84]

Concerns about computer viruses and attacks on the electricity infrastructure continued to grow after the 1993 effort to destroy the World Trade Center and the 1995 Oklahoma City bombings. Not long after the Oklahoma City attacks, President Bill Clinton commissioned a study of critical infrastructure security. In 1997 the President's Commission on Critical Infrastructure Protection noted: "Today, the right command sent over a network to a power generating station's control computer could be just as devastating as a backpack full of explosives."[85] The report expressed concern about the growing use of standardized information technology in the electrical grid and other critical infrastructures and recommended that the federal government increase funding for cybersecurity research.[86]

This recommendation sparked considerable research on ways to increase the resilience of electricity networks. Once again, engineers sought solutions in microprocessor and network technologies. For example, in 1999 EPRI and the Defense Department began sponsoring a study on complex interactive networks and systems. EPRI's final report argued that the grid would become more secure through a number of "intelligent" mechanisms, such as "adaptive islanding," in which parts of the grid would be cut off from compromised parts of the grid to protect their integrity, and "self-healing," in which algorithms would slowly bring the grid back to its normal state and optimize its operation after an attack.[87]

The terrorist attacks of September 11, 2001, only amplified concerns about the security of the nation's critical infrastructure. In 2002 a National Research Council study on the role of science and technology in combating terrorism advocated combating the "insider threat" to power systems by developing and deploying "smart controls . . . that limit the manipulation of the system outside normal operating settings—perhaps utilizing artificial intelligence or redundant controls."[88]

Although EPRI conducted considerable research into computer security as well as the Y2K problem, most utilities denied any serious risk. In 1999, when a hacker group called L0pht claimed that it could shut down the electrical grid, a spokesperson for the Edison Electric Institute responded that hacking was a "minimal issue," because utilities had computer firewalls. However, security experts argued that firewalls were a "Maginot Line" and that the utilities should be using encryption—something they did not do.[89] In 2004 the General Accounting Office showed that the number of attempted security breaches on critical infrastructures was increasing with the growing use of more economical and standardized commercial off the shelf (COTS) hardware and software.[90]

Utilities could be lax about cybersecurity because regulatory agencies had no authority to enforce standards. While FERC was overseeing industry restructuring, it had no authority over cybersecurity standards. In the wake of the September 11 attacks, the Department of Homeland Security (DHS) was created and given responsibility for critical infrastructure protection, but it did not gain the authority to mandate private-sector changes.[91]

The "Smart Grid" Paradigm Emerges

Early in the new millennium, policymakers, industrialists, and environmentalists began to argue that a "smart grid" would solve all of the grid's woes—rising costs, greenhouse gas emissions, unreliability, and cyberinsecurity. In June 2003 a group of business, labor, and environmental organizations founded the Energy Future Coalition (EFC) to help build political coalitions around technologies that could improve the energy efficiency and security of the United States. The EFC argued that a smart grid "could boost the economy, reduce the impact of energy production and consumption on the environment, and enhance the security of the network," and it pointed to work by EPRI.[92] The following month, a group of policymakers who worked with the EFC and had long pressed for market solutions to the problem of climate change published similar arguments in *Foreign Affairs.* They also noted: "Public recognition that the electricity network is inefficient and shockingly vulnerable to disruption and attack is the first step toward building support for a 'smart' grid."[93]

These final words were prophetic, for just one month later, the largest blackout in North American history hit the United States and Canada, affecting about 50 million people and leaving some areas without power for four days.[94] In the days and weeks following the blackout, scientists, engineers, and policymakers increasingly called for more "smart grid" technology.[95] For example, New Jersey governor James McGreevy argued:

> The current grid works like an old telephone switchboard, but a smart grid would function more like the Internet. It would move us away from the centralized power-plant model and allow the widespread use of smaller, cleaner and more decentralized sources of power like fuel cells or solar panels. A smart grid would also be self-healing—using digital data and computer systems to seamlessly and automatically route power around problem areas.
>
> By making our energy use more efficient, the smart grid would also make electricity more affordable and would reduce the number of costly and polluting power plants that we need to construct. Finally, the ability to easily plug decentralized renewable energy into the grid would be a major step toward weaning our nation off of fossil fuels.[96]

Thus, in the early 2000s the smart grid came to represent the future solution to all of the grid's woes. It promised to improve economy, physical efficiency, reliability, and security.

Yet, as we have seen, the grid had been getting "smart" for a long time. And while digital technology helped to enable a new regulatory regime, it has yet to revolutionize the electricity industry and achieve all of our goals for the grid. In fact, scholars continue to dispute whether information technologies designed to achieve free markets actually improved

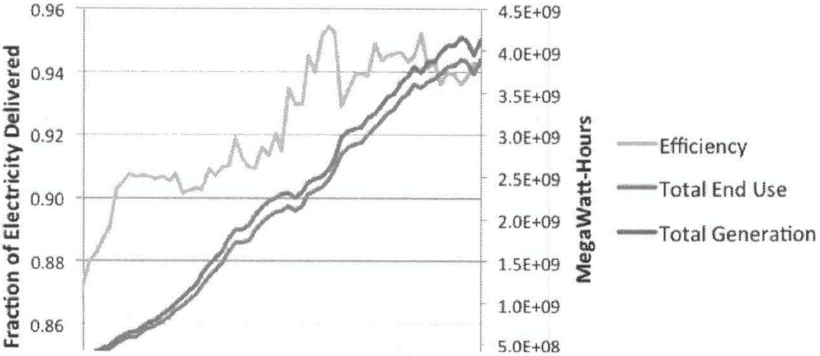

Figure 2. Efficiency of the US electricity grid, 1950–2010. Plot based on data provided by the Energy Information Administration.

economic efficiency.[97] The transaction costs of the restructured industry are significant. For example, the start-up costs of the California ISO have been estimated at $1 billion, and its annual budget is about $200 million.[98] The facility proved to be more challenging to build than initially expected and was opened late.[99] Retail electricity prices have continued to climb in many states.[100] The electricity market remains incomplete due to regulatory fragmentation. FERC has authority to establish the wholesale market structure, but state utility commissions have authority over retail markets. While some states have offered consumers retail choice, many have not. And in practice, relatively few residential customers enjoy the sophisticated tools needed to make real-time decisions about electricity usage. The relatively inflexible demand for electricity was one reason that a few companies were able to manipulate western electricity markets in 2000 and 2001, rapidly increasing wholesale electricity prices, creating blackouts across California, and bankrupting two of California's largest electric utilities.[101] While information technology enabled industry restructuring, it is not clear that this brought the promised gains in economy.

It is also unclear to what extent the current market structure has increased physical efficiency. Demand-side management programs have certainly decreased peak electricity demand, lowered costs, and increased physical efficiency all at once. But as increasingly large volumes of electricity have been traded across the grid in wholesale markets, operators have struggled with increasing congestion and loop flows.[102] The new regulatory environment discouraged utilities from investing in transmission infrastructure. Physical efficiency increased in the 1970s

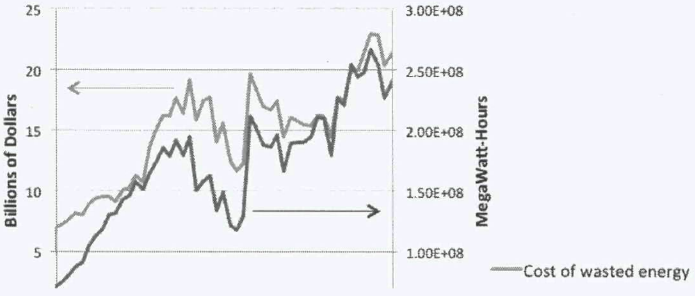

Figure 3. Energy wasted due to transmission and distribution losses. Plot based on data provided by the Energy Information Administration. The cost of the energy is estimated based upon the average retail rate. Since retail costs and transmission losses both vary in location-specific ways and are likely to be positively correlated, this is likely a low estimate.

and 1980s but leveled off in the 1990s (figure 2). Both the amount and cost of energy wasted in transmission and distribution have grown significantly since restructuring (figure 3).

While it is unclear just how much distributed and networked utilities increased efficiency, it is clear that the new information infrastructure has entailed trade-offs between the goals of efficiency, reliability, and security. Here again, social institutions have played a critical role in making the grid smart for some purposes but not for others. When FERC was overseeing the process of restructuring in the 1990s and early new millennium, it had no enforcement authority for either reliability or cybersecurity. That began to change in the wake of the 2003 blackout. The Energy Policy Act of 2005 aimed to make NERC more independent of the electricity industry, and it empowered FERC to establish and enforce reliability standards. The act made cybersecurity standards a part of reliability. In 2009 the American Recovery and Reinvestment Act awarded grants for smart grid research and development, with the requirement that all grantees develop a plan for managing cybersecurity.

Nonetheless, a recent report by the Department of Energy (DOE) inspector general found that thirty-six of ninety-nine grant awardees fell short of cybersecurity standards in their initial proposals. The DOE granted awards to these groups, telling them to revise their cybersecurity plans. But years later, the projects still "did not include a number of security practices commonly recommended for federal government and industry systems."[103] Additionally, FERC's regulations on cybersecurity still exempt almost all small and medium-sized power plants, covering less than one-third of the total electricity generation in the United States.[104] No federal agencies have developed mandatory cybersecurity standards for electricity distribution systems.[105] A recent report by the General Accounting Office emphasized that regulatory fragmentation continues to pose a challenge to securing the electrical grid.[106]

Even if regulators were empowered to enforce more stringent reliability and security standards, they would confront trade-offs between the practices and skills required to achieve reliability and cybersecurity. Most information security experts work in office environments, and they manage security through frequent updates and tough password rules. By contrast, the computers controlling the electrical grid are difficult or impossible to update because they must operate around the clock, and tough password rules could be dangerous for operators who must manage contingencies in a fast-paced environment. The penetration testing favored by information security experts has repeatedly crashed industrial control systems. In the business world, information security techniques are merely inconvenient; in the world of grid operations, they carry very physical consequences.[107]

Finally, the different time scales for the information technology industry and the utilities industry create tensions between the goals of cybersecurity and reliability. Information technology companies are accustomed to products that are obsolete within a few years, and their business model is to "ship it Tuesday, get it right by version 3."[108] By contrast, utilities managers have traditionally invested in equipment designed to last many decades, and they evolve systems slowly and incrementally so as to maintain high levels of reliability.[109] Unfortunately, utilities have been investing in insecure information technology for decades, and they continue to invest in insecure technology today. Information security experts emphasize that security cannot be effectively "bolted on" to an information system; it must be designed in from the beginning. Thus, utilities will likely be patching vulnerabilities for a long time to come.

The Smart Grid: Chimera or Future Reality?

As this brief history suggests, the metaphor of a "smart" grid has stuck because of its flexibility—its ability to appeal to environmentalists, economists, and the national security establishment. The utilities initially deployed large, special-purpose, centralized computers to manage increasingly large power plants and networks, but as regulators began to push for more sustainable systems, the utilities found advantages in using standardized microprocessors and computer networks to manage distributed energy resources.

Yet the microprocessor and Internet "revolutions" did not revolutionize the electricity industry. To be sure, standardized microprocessors and distributed information processing enabled more competitive wholesale markets and thereby helped decentralize both physical and social control over electricity generation. But this transformation also required a new regulatory regime. Regulators, utilities, and industry practices all shaped the evolution of the grid's information infrastructure and the goals it achieved. Left to their own devices, utilities would have used distributed computing and energy resources to crush the competition for electricity production. That is, they would have used information technology to decentralize physical but not social power. I have argued that microprocessor and Internet technologies shaped, and were shaped by, the changing regulatory regime.

I have also argued that the grid's information infrastructure was designed to increase economic efficiency but that the shift to standardized microprocessors and computer networks tended to prioritize economic efficiency over reliability, security, and to some extent even physical efficiency. Thus, when proponents of a smart grid conjure a vision of digital utopia, they unfortunately obscure the potential for new risks and trade-offs.

How can we best align the goals of efficiency, security, and reliability? Although it is too early to answer this question, this account suggests that our vision for the smart grid must account for the ways that technologies, government policies, business practices, and engineering skills are intertwined in technopolitical regimes. Some of the most promising smart grid architectures under consideration today represent a transformation not only of technologies in the grid but of the entire regime.

For example, a system consisting of loosely coupled microgrids—neighborhood-sized systems that can operate apart from the bulk electrical grid, generating and distributing their own electricity—may best align the goals of the smart grid. To be sure, there are still trade-offs in microgrids. It is more expensive to generate renewable energy in a distributed manner than in large solar or wind farms. Many regions would continue to require renewable energy from distant sources (such as hydroelectric generators), and microgrids gain some resilience through connections to the larger grid.[110] However, distributed resources waste less energy in transmission, thereby increasing resource efficiency. And though one microgrid might fail, the rest would be able to continue on without disruption, increasing both reliability and security. This resilience is one reason that the US military, universities, and some technology research campuses have invested heavily in microgrids.[111]

Unfortunately, there are significant social and political barriers to deploying a nationwide system of microgrids. Many utilities view microgrids as a threat to their existence rather than an alternative business model.[112] Instead of investing in the technologies that would enable wide-scale deployment of microgrids—technologies such as energy storage and self-islanding systems—utilities have invested in technologies that enable them to remain competitive without radically changing their business model.

When viewed in historical perspective, the most striking aspect of today's smart grid efforts is their conservatism. Most smart grid efforts focus on "smart meters"—devices that can track electricity consumption of individual households on an hourly basis. Smart meters can be used to charge time-of-use (TOU) rates, thereby encouraging consumers to use electricity at times of low demand, when it is less expensive. Yet residential smart meters are simply an expansion of DSM strategies the utilities began pursuing in the 1980s. As we have seen, utilities pursued DSM because it allowed them to defer investments in new sources of electricity generation, including cleaner energy generation. Similarly, some utilities today are weighing investments in smart meters against investments in cleaner coal-powered plants, treating them as trade-offs rather than as complementary parts of a more sustainable system.[113]

Public utilities commissions in many states encourage this conservative approach to smart grid architecture. Some commissions have allowed utilities to recover the costs of investing in smart meters on the grounds that they can save consumers money in the near term, but they are much less persuaded of the value of electricity storage and distributed renewable resources.[114]

Nonetheless, some consumer groups are challenging the conservative approach to smart grids. In many states, consumer groups have formed to oppose smart meters, arguing that they pose risks to public health and privacy. They have also objected to the ways that states allow utilities to pass on the initial installation costs to ratepayers, increasing bills in some states. California is among states to allow customers to "opt out" of smart meter installations. In this context, more radical proposals—such as microgrids—begin to look appealing. One industry analyst recently noted: "I view smart meters as a top-down technology, whereas microgrids are bottom-up. They can work together. But in California, where there's been a rebellion against smart meters, the microgrid may be more appealing, especially if it's designed by the end-user."[115]

Thus, the grid may become "smart" in many different ways. Today many different groups—consumers, utilities, and government regulators—are vying to determine just how the grid will get smart. Contrary to promises of digital utopians, information technology alone will not suffice to align the many goals for the grid—economic efficiency, physical efficiency, reliability, and security. Our ability to align these goals will ultimately require heterogeneous engineering—the simultaneous restructuring of information and physical infrastructures, regulatory systems, and industry structures. Only then can we hope to fulfill the smart grid's promise to power a sustainable future.

Notes

1. US Environmental Protection Agency, Global Emissions, http://www.epa.gov/climatechange/ghgemissions/global.html.

2. Calculated from the US Energy Information Administration, *Annual Energy Review 2011*, http://www.eia.gov/totalenergy/data/annual/diagram5.cfm.

3. This is only an estimate, calculated by multiplying the wasted energy by the average retail price of electricity. These numbers are given in ibid.

4. The smart grid is discussed in Title XIII of the 2007 Energy Independence and Security Act, http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/EISA_Title_XIII_Smart_Grid.pdf.

5. Steve Silberman, "The Energy Web," *Wired*, July 2001, http://www.wired.com/wired/archive/9.07/juice.html?pg=1&topic=&topic_set=. For more on *Wired* and the history of digital utopianism, see Fred Turner, *From Counterculture to Cyberculture* (Chicago: University of Chicago Press, 2006).

6. Timothy Wirth, Boyden Gray, and John D. Podesta, "The Future of Energy Policy," *Foreign Affairs* 82, no. 4 (2003): 132–55.

7. US Department of Energy, "The Smart Grid: An Introduction," http://energy.gov/oe/downloads/smart-grid-introduction-0.

8. See, for example, Esther Dyson, George Gilder, George Keyworth, and Alvin Toffler, "Magna Carta for the Knowledge Age," August 22, 1994, http://www.alamut.com/subj/ideologies/manifestos/magnaCarta.html; and John Perry Barlow, "A Declaration of the Independence of Cyberspace," February 8, 1996, https://projects.eff.org/~barlow/Declaration-Final.html. For a discussion of these texts, see Turner, *From Counterculture to Cyberculture.*

9. David R. Johnson and David Post, "Law and Borders—the Rise of Law in Cyberspace," *Stanford Law Review* 48 (1995): 1367–1402.

10. Langdon Winner, "Cyberlibertarian Myths and the Prospects for Community," *ACM SIGCAS Computers and Society* 27, no. 3 (1997): 14–19; Mihaela Kelemen and Warren Smith, "Community and Its 'Virtual' Promises: A Critique of Cyberlibertarian Rhetoric," *Information, Communication, & Society* 4, no. 3 (2001): 370–87; Turner, *From Counterculture to Cyberculture*; Andrew Murray, "Review Article: The Regulatory Edge of the Internet," *International Journal of Law and IT* 11, no. 1 (2003): 87–97. For a review of different political stances on the Web, see Steven Miller, *Civilizing Cyberspace: Policy, Power, and the Information*

Superhighway (Reading, MA: Addison Wesley, 1996); Philip E. Agre, "Real-Time Politics: The Internet and the Political Process," *Information Society* 18, no. 5 (2002): 311–31.

11. Lawrence Lessig, *Free Culture: How Big Media Uses Technology and the Law to Lock Down Culture and Control Creativity* (New York: Penguin Group USA, 2004); Lessig, *Code: And Other Laws of Cyberspace, Version 2.0* (New York: Basic Books, 2006); Barbara Van Schewick, *Internet Architecture and Innovation* (Cambridge, MA: MIT Press, 2010).

12. Jack L. Goldsmith and Tim Wu, *Who Controls the Internet? Illusions of a Borderless World* (New York: Oxford University Press, 2006).

13. Geoffrey Bowker, *Memory Practices in the Sciences* (Cambridge, MA: MIT Press, 2005); G. C. Bowker and S. L. Star, *Sorting Things Out: Classification and Its Consequences* (Cambridge, MA: MIT Press, 2000).

14. See, for example, Steven J. Jackson et al., "Understanding Infrastructure: History, Heuristics, and Cyberinfrastructure Policy," *First Monday* 12, no. 6 (2007), http://firstmonday.org/ojs/index.php/fm/article/viewArticle/1904/1786; David Ribes and Thomas A. Finholt, "The Long Now of Technology Infrastructure: Articulating Tensions in Development," *Journal of the Association for Information Systems* 10 (May 2009): 375–98; Paul N. Edwards et al., "Introduction: An Agenda for Infrastructure Studies," *Journal of the Association for Information Systems* 10 (May 2009): 364–74; Christine Borgman, *Scholarship in the Digital Age: Information, Infrastructure, and the Internet* (Cambridge, MA: MIT Press, 2007).

15. Thomas Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore, MD: Johns Hopkins University Press, 1983); Richard Hirsh, *Technology and Transformation in the American Electric Utility Industry* (Cambridge: Cambridge University Press, 1989); R. F. Hirsh and A. H. Serchuk, "Momentum Shifts in the American Electric Utility System: Catastrophic Change—or No Change at All?," *Technology and Culture* 37, no. 2 (1996): 280–311; Richard Hirsh, *Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility Industry* (Cambridge, MA: MIT Press, 1999); Sharon Beder, *Power Play* (New York: New Press, 2003).

16. Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity after World War II* (Cambridge, MA: MIT Press, 1998); Hecht, "Technology, Politics, and National Identity in France," in *Technologies of Power: Essays in Honor of Thomas Parke Hughes and Agatha Chipley Hughes,* ed. Michael Thad Allen and Gabrielle Hecht (Cambridge, MA: MIT Press, 2001), 253–94.

17. Hughes, *Networks of Power*; Arne Kaijser, "Redirecting Infrasystems toward Sustainability," in *Individual and Structural Determinants of Environmental Practice,* ed. Anders Biel, Bengt Hansson, and Mona Martensson (Burlington, VT: Ashgate, 2003), 152–79.

18. I use "economic efficiency" in the commonsense way of reducing costs. This is similar to the formal concept of productive efficiency, in which a particular good (in this case, electricity delivered to a particular location) is produced for the lowest possible short-run cost. It is distinct from the notion of allocative efficiency, in which the ideal combination of goods is produced for the lowest cost. Allocative efficiency might include long-run outcomes such as the preservation of national resources, but in practice, the costs of global warming and using nonrenewable resources are neither well understood nor included in the cost of electricity. It is also different from the concept of physical efficiency because it

includes costs such as labor. Physical resources are often wasted in the efforts to achieve economic efficiency (e.g., goods are produced more cheaply in China than in the United States, but physical resources are wasted in the process of shipping them around the world). For a discussion of the different ways that "efficiency" has been used in the sustainability debate, see Calum Gunn, "Energy Efficiency vs. Economic Efficiency?," *Energy Policy* 25, no. 4 (1997): 445–58.

19. For discussions of heterogeneous engineering, see Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch, eds., *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge, MA: MIT Press, 1987); Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Ballistic Missile Guidance* (Cambridge, MA: MIT Press, 1990).

20. Hirsh, *Technology and Transformation*; Hughes, *Networks of Power*.

21. Hughes, *Networks of Power*, 206–7; Hirsh, *Technology and Transformation*, 80–82.

22. Hughes, *Networks of Power*; Hirsh, *Technology and Transformation*.

23. Utilities used the phrase "economic dispatch" as early as 1940. See Gordon D. Friedlander, "Computer Controlled Power Systems Part II," *IEEE Spectrum* 2, no. 5 (1965): 72–91.

24. Hughes, *Networks of Power*, 206–7; Beder, *Power Play*, 30; Hirsh, *Technology and Transformation*, 80–82.

25. For examples of very early automation, see Nathan Cohn, "As We Were," *IEEE Computer Applications in Power* 1, no. 1 (1988): 4–8.

26. See the discussion in David Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (Baltimore, MD: Johns Hopkins University Press, 2002); Larry Owens, "Vannevar Bush and the Differential Analyzer: The Text and Context of an Early Computer," *Technology and Culture* 27, no. 1 (1986): 63–95.

27. Gordon D. Friedlander, "Computer Controlled Power Systems Part I," *IEEE Spectrum* 2, no. 4 (1965): 60–81; Friedlander, "Computer Controlled Power Systems Part II."

28. The paradigmatic digital process control computers were the machines used in the semi-automatic ground environment (SAGE), an air defense command and control system. SAGE was influenced by both analog and digital computing research traditions. See Paul N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge, MA: MIT Press, 1996); Rebecca Slayton, *Arguments That Count: Computing, Physics, and Missile Defense, 1949–2012*, Inside Technology (Cambridge, MA: MIT Press, 2013).

29. For discussion of analog process control computers, see James S. Small, *The Analogue Alternative: The Electronic Analogue Computer in Britain and the USA, 1930–1975* (New York: Routledge, 2001); Bill Aspray, "Calculating Power: Edwin L. Harder and Analog Computing in the Electric Power Industry," in *Sparks of Genius: Portraits of Electrical Engineering Excellence*, ed. Frederik Nebeker (Piscataway, NJ: IEEE Press, 1994), 159–200.

30. Gene Smith, "Blue-Collar Computers Run Plants, Roll Steel, Grind Pulp and Mix Cake," *New York Times*, November 22, 1964, F1; Gilbert Burck, "'On Line' in 'Real Time,'" *Fortune* 69, no. 4 (1963): 141.

31. Friedlander, "Computer Controlled Power Systems Part I."

32. Gene Smith, "Automation Due in Power Plants," *New York Times*, February 5, 1961, F1.

33. Gene Smith, "Computer to Get New Power Role," *New York Times*, July 6, 1958, F1. For example, in 1958 the analog "early bird" computer—which was initially used to plan for the most economic dispatch—was put in charge of controlling economic dispatch for about forty-one steam-generating units to supply about 7 million people in Alabama, Florida, Georgia, and Mississippi.

34. Gene Smith, "Power Industry Adds Computers," *New York Times*, October 8, 1964, 63.

35. Gene Smith, "Utility Growth Continues Apace," *New York Times*, August 7, 1960, F1.

36. Hirsh, *Technology and Transformation*; David Nye, *Consuming Power* (Cambridge, MA: MIT Press, 1999).

37. Hirsh, *Technology and Transformation.*

38. Ibid.

39. Federal Power Commission, "Report to the President on the Power Failure in the Northeastern United States and the Province of Ontario on November 9–10, 1965" (1965).

40. Federal Power Commission, "Prevention of Power Failures: Part I" (1967), 91. It is worth noting that contemporary observers expressed ambivalence about the role of computers in the blackout. See, for example, Art Buchwald, "Lights Out, Computers in There Punching," *Los Angeles Times*, November 18, 1965, D1.

41. Federal Power Commission, "Prevention of Power Failures: Part I."

42. The blackout was also seen as a security issue, but the phrase "energy security" only emerged in response to the oil crisis of the early 1970s. Although the phrase "atomic energy security" was occasionally used during the 1940s and 1950s, the phrase "energy security" was first used in the *New York Times* in 1971, when a Nixon-commissioned investigation into an increase in oil prices recommended policies to improve energy security. Philip Shabecoff, "US Panel Issues Oil-Price Study," *New York Times*, May 4, 1971, 1.

43. See, for example, Donella Meadows et al., *The Limits to Growth* (New York: Universe Books, 1972). The utilities were quite defensive about the limits to growth; see Theodore Nagel, "Operating a Major Electric Utility Today," *Science* 201, no. 4,360 (1978): 985–93.

44. Amory Lovins, "Energy Strategy: The Road Not Taken?," *Foreign Affairs* 55 (October 1976): 65–96; Lovins, *Brittle Power* (Andover, MA: Brick House Publishing, 1982).

45. Lovins, *Brittle Power*, 209.

46. Ibid., 210.

47. In 1978 President Jimmy Carter signed PURPA as part of the National Energy Act, proclaiming it vital to "the economic health and well-being and, indeed, even the national security of our country." Richard Halloran, "Energy Act Is Signed," *New York Times*, November 10, 1978, A1.

48. Vicki Norberg-Bohm, "Creating Incentives for Environmentally Enhancing Technological Change," *Technological Forecasting and Social Change* 65 (2000): 125–48.

49. Sarah Glazer, "Deregulating Electric Power," in *Editorial Research Reports 1987*, vol. 2, issue 19 (Washington, DC: Congressional Quarterly, 1987), 601–16, http://library.cqpress.com/cqresearcher/cqresrre1987112000.

50. Lee Smith, "DA/DSM Directions," *IEEE Computer Applications in Power* 7, no. 10 (1994): 24–26.

51. Walter Esselman and Giora Ben-Yaacov, "EPRI-Developed Computer Programs for Electric Utilities," *IEEE Computer Applications in Power* 1, no. 4 (1988): 18–24; Ulf Sandberg and Mats Faxer, "Personal Computers for Real-Time Control of Power System Distribution Networks," *IEEE Transactions on Power Apparatus and Systems* PAS-103, no. 7 (1984): 1720–24.

52. Narayan Rau and Yih-heui Wan, "Optimum Location of Resources in Distributed Planning," *IEEE Transactions on Power Systems* 9, no. 4 (1994): 2014–19.

53. See, for example, A. A. Garcia, "Demand Side Management Integration: A Case History," *IEEE Transactions on Power Systems* 2, no. 3 (1987): 772–78; William LeBlanc, "Development and Implementation of an Agricultural Load Management Project: A Case Study," *IEEE Transactions on Power Systems* 3, no. 4 (1988): 793–97. Demand-side management can also refer to the use of more energy efficient appliances that reduce overall demand for electricity. This was initially resisted by the utilities and was embraced only after regulations allowed the utilities to recoup some of the savings from lowered electricity consumption. Hirsh and Serchuk, "Momentum Shifts."

54. Fred I. Denny, "Future Computer Applications in Power," *IEEE Computer Applications in Power* 1, no. 1 (1988): 11–14. The journal also noted a "trend away from computer centralization but toward data centralization" and predicted: "More computer hardware will be used at more locations, and there will be more highly integrated communications systems to facilitate sharing data bases and or functions. Some operating functions will be decentralized, but this will require coordination at a central level."

55. See, for example, "PG&E Marketing Unit Works Full-Time on Heading Off Cogeneration Projects," *Electric Utility Week*, April 6, 1987, 5.

56. Quoted in Hirsh and Serchuk, "Momentum Shifts," 308–9.

57. Congressional Research Service, US Library of Congress, "Electricity: A New Regulatory Order?" (Washington, DC: Congressional Research Service, 1991).

58. R. E. Bohn et al., *Deregulating the Electric Utility Industry: Final Report* (Cambridge: Massachusetts Institute of Technology, Energy Laboratory, 1982), http://hdl.handle.net/1721.1/60494.

59. Hirsh, *Technology and Transformation.*

60. Cheryl Romo, "Electric Power: On the Cusp of the Millennium," *Public Utilities Fortnightly* 124, no. 1 (1989): 49.

61. Kurt Yeager, "Creating the Second Electrical Century," *Public Utilities Fortnightly* 126, no. 6 (1990): 7.

62. The commissioner spoke as part of a panel that included MIT Energy Lab researcher Richard Tabor. "California Energy Commissioner Calls for Spot Pricing of Electricity," *Electric Utility Week*, July 16, 1984, 9.

63. Evan Davis, Scott Grusky, and Fereidoon Sioshansi, "Automating the Distribution System: An Intermediary View for Electric Utilities," *Public Utilities Fortnightly* 123, no. 2 (1989): 22.

64. "Three Bills in Illinois Aim for Transition to Competitive Electric Market," *Electric Utility Week*, May 13, 1985, 7. It is worth noting that in future years O'Connor worked in the energy services industry, becoming vice president of Constellation NewEnergy. His CV is online at http://efile.mpsc.state.mi.us/efile/docs/13720/0058.pdf.

65. See, for example, "'The Sky Did Not Fall' in the First Year of FERC's Bulk-Power Experiment," *Electric Utility Week*, October 28, 1985, 3; "Utilities in

Western States Improve Communications with Computer Link," *Electric Utility Week*, January 13, 1986, 7.

66. Seth Blumsack, Jay Apt, and Lester Lave, "Lessons from the Failure of US Electricity Restructuring," Carnegie Mellon University Tepper School of Business, Pittsburgh, 2006.

67. Hirsh, *Power Loss.*

68. Blumsack, Apt, and Lave, "Lessons."

69. "The ISO/RTO Council," http://www.isorto.org/site/c.jhKQIZPBImE/b.2603295/k.BEAD/Home.htm. Ryan Ellis has argued that these spot markets effectively centralized control of the network. For example, the Electric Reliability Council of Texas (ERCOT) coordinates the functions of control rooms that had previously been managed by ten different utilities. See Ryan Ellis, "Networks, Deregulation and Risk: The Politics of Critical Infrastructure Protection" (PhD diss., University of California at San Diego, 2011). However, the rise of new electricity generators and independent transmission companies complicates efforts to make generalizations about centralization or decentralization.

70. House Committee on Commerce, *Electricity Competition——Volume 1*, March 18, April 22, May 6, 1999, 313.

71. House Committee on Commerce, *Electricity Competition——Volume 2*, May 13, 20, 26, July 1, 1999. Similarly, the Edison Electric Institute, an industry group, testified before Congress that "customers will have more choices in the future. . . . Through home automation computers can manage electricity use to reflect changes in electricity prices so as to reduce customer costs." House Committee on Commerce, *Electricity Regulation: A Vision for the Future*, May 15, 1996, 106.

72. Philip R. O'Connor et al., "The Transition to Competition in the Electric Utility Industry," *Journal of Energy Law and Policy* 8 (1987): 236.

73. "Westinghouse Chief Sees Big Technical Strides in T&D: Path to Deregulation?," *Electric Utility Week*, March 7, 1983, 5.

74. "Mandatory Wheeling Could Hurt Reliability, EEI Report Says," *Electric Utility Week*, January 23, 1989, 7.

75. "FERC Bid to Increase Competition Stirs Engineering vs. Economics Debate," *Electric Utility Week* (October 5, 1987): 8.

76. "Deregulation vs. Reliability, Obligation to Serve and Captive Customers," *Electric Utility Week*, September 22, 1986, 10.

77. See, for example, Office of Technology Assessment, *Electric Power Wheeling and Dealing: Technological Considerations for Increasing Competition* (Washington, DC: US Government Printing Office, 1989); US Library of Congress, "Electricity: A New Regulatory Order?"

78. Charles Perrow, *Normal Accidents: Living with High-Risk Technologies* (1984; Princeton, NJ: Princeton University Press, 1999).

79. Khoi Vu, Miroslav Begovic, and Damir Novosel, "Grids Get Smart Protection and Control," *IEEE Computer Applications in Power*, October 1997, 40–44.

80. M. K. Donnelly, J. E. Dagle, and D. J. Trudnowski, "Impacts of the Distributed Utility on Transmission System Stability," *IEEE Transactions on Power Systems* 11, no. 2 (1996): 741.

81. Anjan Bose, "Power System Stability: New Opportunities for Control," in *Stability and Control of Dynamical Systems and Applications*, ed. Derong Lu and Panos J. Antsaklis (Boston: Birkhauser, 2003), http://gridstat.eecs.wsu.edu/Bose-GridComms-Overview-Chapter.pdf.

82. Massoud Amin, "U.S. Electrical Grid Gets Less Reliable," *IEEE Spectrum* 48, no. 1 (2011): 80.

83. United States–Canada Power System Task Force, "Final Report on the August 14, 2003 Blackout in the United States and Canada" (2004).

84. Denny, "Future Computer Applications."

85. President's Commission on Critical Infrastructure Protection, "Critical Foundations: Protecting America's Infrastructures" (1997).

86. Kathi Brown, *Critical Path: A Brief History of Critical Infrastructure Protection* (Fairfax, VA: Spectrum Publishing Group, 2006).

87. EPRI, *Complex Interactive Networks/Systems Initiative: Final Summary Report* (Palo Alto: EPRI, 2003), 4-7–4-12.

88. National Research Council, *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism* (Washington, DC: National Academies Press, 2002), 190.

89. "Computer 'Hackers' Make Utilities Uneasy, but Most Say the Threat Is Exaggerated," *Electric Utility Week*, November 1, 1999, 1.

90. GAO, *Critical Infrastructure Protection: Challenges and Efforts to Secure Control Systems* (GAO-04-628T) (Washington, DC: Government Printing Office, 2004), http://www.gao.gov/products/GAO-04-628T.

91. The DHS National Cyber Security Division's Control Systems Security Program has issued recommended best practices, and its industrial control systems Cyber Emergency Response Team (CERT) issues alerts to the industry about vulnerable systems.

92. Energy Future Coalition, "Challenge and Opportunity: Charting a New Energy Future" (2003).

93. Wirth, Gray, and Podesta, "The Future of Energy Policy." Wirth was a Democrat in the House of Representatives from 1975 to 1986 and then served one term in the Senate. He organized hearings on climate change in 1988, outlined cap and trade rules that became law in the 1990 Clean Air Act, and served as lead negotiator on the Kyoto protocol in the mid-1990s. Gray was a lawyer and chief architect of the 1990 Clean Air Act, and John Podesta was Clinton's chief of staff.

94. J. R. Minkel, "The 2003 Northeast Blackout—Five Years Later," 2008, http://www.scientificamerican.com.

95. See, for example, Select Committee on Homeland Security, *Implications of Power Blackouts for the Nation's Cybersecurity and Critical Infrastructure Protection*, 108th Cong., 1st sess., September 4, 23, 2003, 62.

96. James McGreevy, "An Energy Plan," *New York Times*, August 24, 2003, http://www.nytimes.com/2003/08/24/nyregion/an-energy-plan.html.

97. For a recent survey of about thirty studies, each with different findings, see GAO, *Electricity Restructuring: Ferc Could Take Additional Steps to Analyze Regional Transmission Organizations Benefits and Performance* (GAO-08-987) (Washington, DC: Government Printing Office, 2008), http://www.gao.gov/products/GAO-08-987.

98. Blumsack, Apt, and Lave, "Lessons."

99. "California ISO, PX Officials Tell PUC New Start-Up Date Is 90% Firm," *Electric Utility Week*, January 12, 1998, 10.

100. There is some evidence that prices might have risen more rapidly without restructuring. See Emily Hickey and Lon Carlson, "An Analysis of Trends in Restructuring of Electricity Markets," *Electricity Journal* 23, no. 5 (2010).

101. It is worth noting that in the wake of the crisis, policymakers and industry representatives pressed for "smart grid" technologies that could improve efficiency. Senate Committee on Energy and Natural Resources, *BPA in Promoting Energy Conservation and Renewables*, 107th Cong., 1st sess., August 13, 2001, 4, 50.

102. It is difficult to estimate the costs of congestion. Analysts have developed several different ways of measuring the economic costs of congestion. These generally focus on the additional cost of generating expensive electricity locally when transmission limitations make it impossible to purchase cheaper electricity over large distances. Bernard Lesieutre and Joseph Eto, *Electricity Transmission Congestion Costs: A Review of Recent Reports* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2003).

103. Gregory Friedman, *Audit Report: The Department's Management of the Smart Grid Investment Grant Program* (Washington, DC: Department of Energy, 2012), http://energy.gov/sites/prod/files/OAS-RA-12-04.pdf.

104. Andrew Ginter to ICS Perspectives, 2011, http://blog.industrialdefender.com/?p=813. FERC regulations apply to plants with "an aggregate highest rated net Real Power capability of the preceding 12 months equal to or exceeding 1500 MW in a single Interconnection." This consists of no more than 163 plants (and possibly many fewer). The most recent FERC ruling on Version 4 of the Critical Infrastructure Protection Reliability Standards (CIP-002-4) can be found online: http://www.ferc.gov/whats-new/comm-meet/2012/041912/E-6.pdf.

105. Friedman, *Audit Report.*

106. GAO, *Challenges in Securing the Electricity Grid* (GAO-12-926T) (Washington, DC: GAO, 2012), http://www.gao.gov/products/GAO-12-926T.

107. Joe Weiss, *Protecting Industrial Control Systems from Electronic Threats* (New York: Momentum Press, 2010).

108. Ross Anderson, "The Economics of Information Security," *Science* 314 (2006): 610.

109. Tom Tiernan, "Investor Pool for Smart Grid Firms Expands, as Capital Pours in from Old, New Sources," *Electric Utility Week*, August 25, 2008, 1.

110. For a recent analysis of the costs of various solar deployment options, see Galen Barbose, Naim Darghouth, and Ryan Wiser, *Tracking the Sun V* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2012).

111. For an overview of several microgrid models, see NYSERDA, *Microgrids: An Assessment of the Value, Opportunities, and Barriers to Deployment in New York State* (New York: New York State Energy Research and Development Authority, 2010).

112. It should be noted that this attitude may be changing, since microgrids can provide demand response for utilities. See Phil Carson, "Grid-Tied Microgrids: A Utility's Best Friend?," 2012, http://www.intelligentutility.com/article/12/01/grid-tied-microgrids-utilitys-best-friend.

113. Margaret Ryan, "Gridweek Analysis: Smart Grid Losing to EPA," September 19, 2012, http://energy.aol.com/2011/09/19/gridweek-analysis-smart-grid-losing-to-epa/.

114. For a discussion of regulatory barriers to adoption of the smart grid, see Peter Behr, "Smart Grid Costs Are Massive, but Benefits Will Be Larger, Industry Study Says," *New York Times*, May 25, 2011.

115. Carson, "Grid-Tied Microgrids."