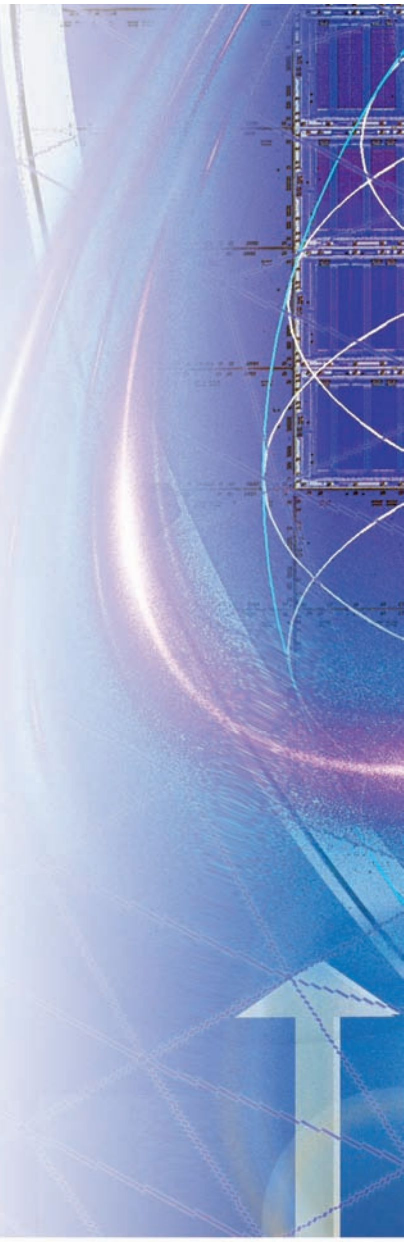
For the Good of the Grid

by S. Massoud Amin



THE EXISTING ELECTRICITY INFRASTRUCTURE EVOLVED TO ITS TECHNOLOGY composition today from the convolution of several major forces, only one of which was technologically based. Today opportunities and challenges persist in world-wide electric power networks, including reducing transmission congestion, increasing system/cyber security, and increasing overall system and end-use efficiency while maintaining reliability. And many other challenges engage those who plan for the future of the power grid: producing power in a sustainable manner (embracing renewable fuels while accounting for their scalability limitations; e.g., increased use of land and natural resources to produce higher renewable electricity will not be sustainable, and lowering emissions from existing generators), delivering electricity to those who don't have it (not just on the basis of fairness but also because electricity is the most efficient form of energy, especially for things like lighting), using electricity more wisely as a tool of economic development, and pondering the possible revival of advanced nuclear reactor construction.

Conservation and Efficiency: Where Are We and How Did We Get Here?

To prepare for a more efficient, resilient, secure, and sustainable electrical system, it is helpful to remember the historical context, associated pinch-points, and forcing functions.

As the readers of *IEEE Power & Energy Magazine* know, the trends of worldwide electrical grid deployment, costing trillions of dollars and reaching billions of people, began very humbly. Some obvious electrical and magnetic properties were known in antiquity. In the 17th and 18th centuries, partially through scientific experiments and partially through parlor games, more was learned about how electric charge is conducted and stored. But only in the 19th century, with the creation of powerful batteries, and through insights about the relations between electric and magnetic force, could electricity in wires service large-scale industries—first the telegraph and then telephones.

And only in the 1880s did the first grids come into being for bringing electrical energy to a variety of customers for a variety of uses, at first mostly for illumination but later for turning power machines and moving trolley cars. The most important of these early grids, the first established big city grid in North America, was the network built by Thomas Edison in lower Manhattan. From its power station on Pearl Street, practically in the shadow of the Brooklyn Bridge, Edison's company supplied hundreds and then thousands of customers. Shortly thereafter, Edison's patented devices, and those of his competitors, devices such as bulbs, generators, switching devices, generators, and motors, were in use in new grids in towns all over the industrialized world.

From a historical perspective the electric power system in the United States evolved in the first half of the 20th century without a clear awareness and analysis of the system-wide implications

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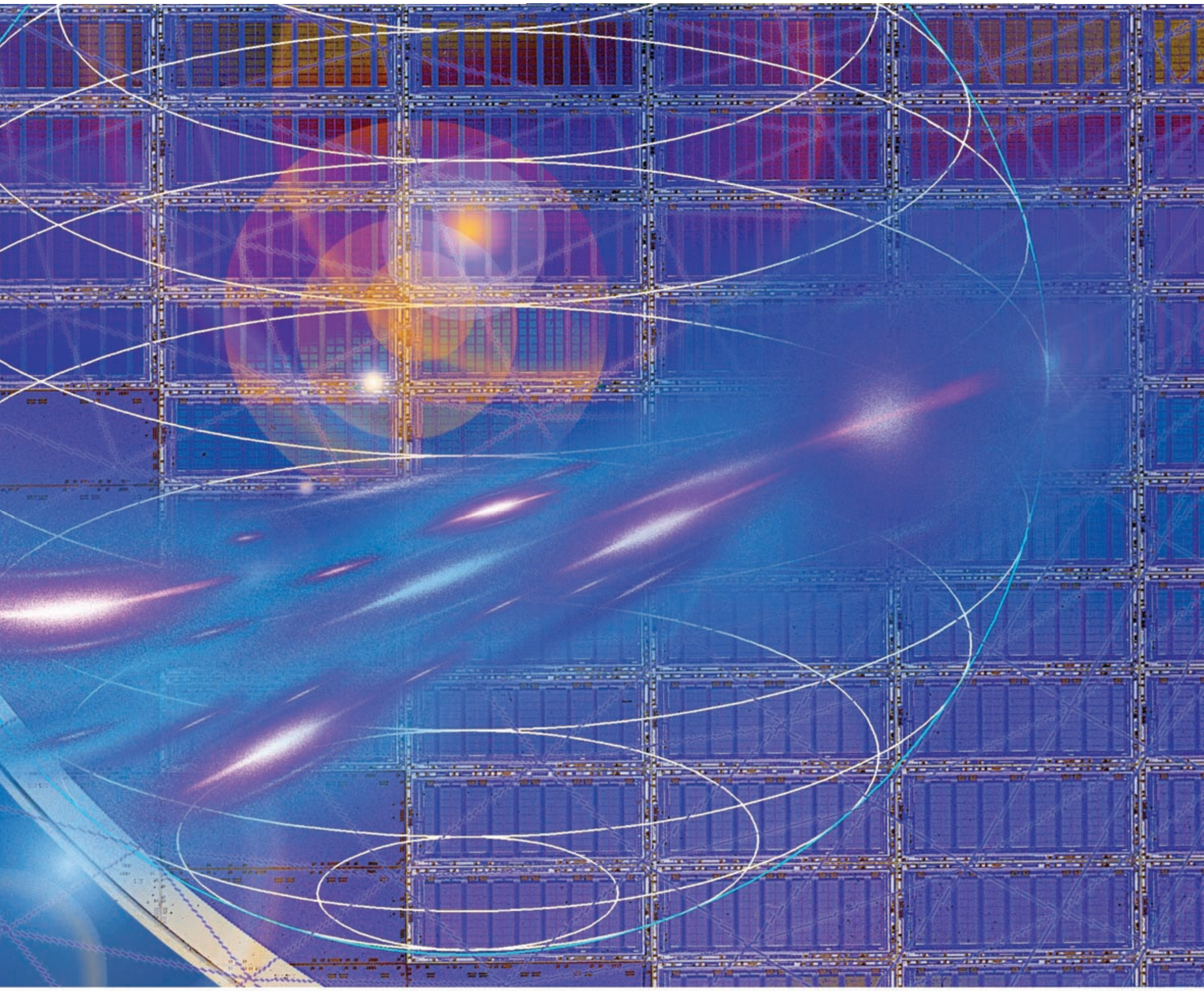
Toward Increased Efficiencies and Integration of Renewable Resources for Future Electric Power Networks



of its evolution. In 1940, 10% of the energy consumption in America was used to produce electricity. By 1970, this had risen to 25%, and by 2002 it had risen to 40%. (Worldwide, current electricity production is near 17 billion kilowatt-hours per year, with the United States, Canada, and Mexico responsible for about 30% of this consumption.) This grid now underlies every aspect of our economy and society, and it has been hailed by the National Academy of Engineering as the 20th century's engineering innovation most beneficial to our civilization. The role of electric power has grown steadily in both scope and importance during this time, and electricity is increasingly recognized as a key to societal progress throughout the world, driving economic prosperity, security, and improving the quality of life. Still, it is noteworthy that at the time of this writing there are about 1.4 billion people in the world with no access to electricity, and another 1.2 billion people who have inadequate access to electricity (meaning that they experience outages of four hours or longer per day).

Once "loosely" interconnected networks of largely local systems, electric power grids increasingly host large-scale, long-distance wheeling (movement of wholesale power) from one region or company to another. Likewise, the connection of distributed resources, primarily small generators at the moment, is growing rapidly. The extent of interconnectedness, like the number of sources, controls, and loads, has grown with time. In terms of the sheer number of nodes, as well as the variety of sources, controls, and loads, electric power grids are among the most complex networks made.

In the coming decades, electricity's share of total energy is expected to continue to grow, as more efficient and intelligent processes are introduced into this network. Electric power is expected to be the fastest-growing source of end-use energy supply throughout the world. To meet global power projections, it is estimated by the U.S. Department of Energy (DOE)/Energy Information Administration (EIA) that over US$1 trillion will have to be spent during the next ten years. The electric power industry has undergone a substantial degree of privatization in a number of countries over the past few years. Power generation growth is expected to be particularly strong in the rapidly growing economies of Asia, with China leading the way.

The electric power grid's emerging issues include creating distributed management through using distributed intelligence and sensing; integration of renewable resources; use of active-control high-voltage devices; developing new business strategies for a deregulated energy market; and ensuring system stability, reliability, robustness, and efficiency in a competitive marketplace and carbon-constrained world.

In addition, the electricity grid faces (at least) three looming challenges: its organization, its technical ability to meet 25-year and 50-year electricity needs, and its ability to increase its efficiency without diminishing its reliability and security.

As an example of historical bifurcation points, the 1965 Northeast blackout not only brought the lights down, it also marked a turn in grid history. The previous economy of scale, according to which larger generators were always more efficient than small machines, no longer seemed to be the only risk-managed option. In addition, in the 1970s two political crises—the Mideast war of 1973 and the Iranian Revolution in 1979—led to a crisis in fuel prices and a related jump in electric rates. For the first time in decades, demand for electricity stopped growing. Moreover, the prospects of power from nuclear reactors, once so promising, were now under public resistance and the resultant policy threats. Accidents at Brown's Ferry, Alabama, in 1974 and Three Mile Island, Pennsylvania, in 1979 and rapidly escalating construction costs caused a drastic turnaround in orders for new facilities. Some nuclear plants already under construction were abandoned.

In the search for a new course of action, conservation (using less energy) and efficiency measures (using available energy more wisely) were put into place. Electrical appliances were re-engineered to use less power. For example, while on the average today's refrigerators are about 20% larger than those made 30 years ago, they use less than half the electricity of older models. Furthermore, the Public Utility Regulatory Policy Act (PURPA) of 1978 stipulated that the main utilities were required to buy the power produced by certain independent companies that cogenerated electricity and heat with great efficiency, providing the cost of the electricity was less than the cost it would take the utilities to make it for their own use.

What had been intended as an effort to promote energy efficiency turned out, in the course of the 1980s and 1990s, to be a major instigator of change in the power industry as a whole. First, the independent power producers increased in size and in number. Then they won the right to sell power not only to the neighboring utility but also to other utilities further away, often over transmission lines owned by still other companies. With the encouragement of the Federal Energy Regulatory Commission (FERC), utilities began to sell off their own generators. Gradually the grid business, which for so long had operated under considerable government guidelines since so many utilities were effective monopolies, became a confusing mixture of regulated and unregulated companies.

Opening up the power industry to independent operators, a business reformation underway for some years in places like Chile, Australia, and Britain (where the power denationalization process was referred to as "liberalization") proved to be a bumpy road in the United States. For example, in 2001 in the state of California the effort to remove government regulations from the sale of electricity, even at the retail level, had to be rescinded in the face of huge fluctuations in electric rates, rolling blackouts, and amid allegations of price fixing among power suppliers. Later that year, Enron, a company that had grown immense through its pioneering ventures in energy trading and providing energy services in the new freed-up wholesale power market, declared bankruptcy.

Restructuring of the U.S. power grid continues. Several states have put deregulation into effect in a variety of ways.

New technology has helped to bring down costs and to address the need for reducing the emission of greenhouse gases during the process of generating electricity. Examples include high-efficiency gas turbines, integrated "microgrids" of small generators (sometimes in the form of solar cells or fuel cells), and a greater use of wind turbines.

Much of the interest in restructuring has centered around the generation part of the power business and less on expanding the transmission grid itself. About 25 years ago, the generation capacity margin, the ability to meet peak demand, was between 25–30%—it has now reduced to less than half and is currently at about 10–15%. These "shock absorbers" have been shrinking; e.g., during the 1990s actual demand in the United States increased some 35%, while transmission capacity has increased only 18%. In the current decade, the demand is expected to grow about 20%, with new transmission capacity lagging behind at under 4% growth.

In the past, extra generation capacity served to reduce the risk of generation shortages in case equipment failed and had to be taken out of production, or in case there was an unusually high demand for power, such as on very hot or cold days. As a result, capacity margins, both for generation and transmission, are shrinking. Other changes add to the pressure on the national power infrastructure as well. Increasing inter-regional bulk power transactions strain grid capacity. New environmental considerations, energy conservation efforts, and cost competition require greater efficiency throughout the grid.

As a result of these "diminished shock absorbers," the network is becoming increasingly stressed, and whether the carrying capacity or safety margin will exist to support anticipated demand is in question. The most visible parts of a larger and growing U.S. energy crisis are the result of years of inadequate investments in the infrastructure. The reason for this neglect is caused partly by uncertainties over what government regulators will do next and what investors will do next.

Growth, environmental issues, and other factors contribute to the difficult challenge of ensuring infrastructure adequacy and security. Not only are infrastructures becoming more complexly interwoven and more difficult to comprehend and control, there is less investment available to support their development. Investment is down in many industries. For the power industry, direct infrastructure investment has declined in an environment of regulatory uncertainty due to deregulation, and infrastructure R&D funding has declined in an environment of increased competition because of restructuring. Electricity investment was not large to begin with. Currently, the power industry spends a smaller proportion of annual sales on R&D than do the dog food, leather, insurance, or many other industries—less than 0.3%, or about US$600 million per year.

Most industry observers recognize this shortage of transmission capability, and indeed many of the large blackouts in recent years can be traced to transmission problems, either because of faults in the lines themselves or in the coordination of power flow over increasingly congested lines. However, in the need to stay "competitive," many energy companies, and the regional grid operators that work with them, are "flying" the grid with less and less margin for error. This means keeping costs down, not investing sufficiently in new equipment, and not building new transmission highways to free up bottlenecks.

Chief Grid Problems

Several cascading failures during the past 40 years spotlighted our need to understand the complex phenomena associated with power network systems and the development of emergency controls and restoration. In addition to the mechanical failures, overloading a line can create power-supply instabilities such as phase or voltage fluctuations. For an ac power grid to remain stable, the frequency and phase of all power generation units must remain synchronous within narrow limits. A generator that drops 2 Hz below 60 Hz will rapidly build up enough heat in its bearings to destroy itself. So circuit breakers trip a generator out of the system when the frequency varies too much. But much smaller frequency changes can indicate instability in the grid: in the Eastern interconnect, a 30-MHz drop in frequency reduces power delivered by 1 GW.

According to data from the North American Electric Reliability Corporation (NERC) and analyses from the Electric Power Research Institute (EPRI), average outages from 1984 to the present have affected nearly 700,000 customers per event annually. Smaller outages occur much more frequently and affect tens to hundreds of thousands of customers every few weeks or months, while larger outages occur every two to nine years and affect millions. Much larger outages affect 7 million or more customers per event each decade. These analyses are based on data collected for the U.S. DOE, which requires electric utilities to report system emergencies that include electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of bulk power delivery systems, and fuel problems.

Coupling these analyses with diminished infrastructure investments, and noting that the cross-over point for the utility construction investment versus depreciation occurred in 1995, we analyzed the number and frequency of major outages along with the number of customers affected during 1991–2005. These data from the NERC's Disturbance Analysis Working Group (DAWG) are a subset of the total outages that are required to be reported to DOE's EIA. Going through the more comprehensive data sets from DOE's EIA, during 2001–2005 there were 162 outages of 100 MW or more, and 150 outages affecting 50,000 consumers or more (Figure 1). In addition, analyzing outages in 2006 (NERC's data), in one year we had 24 occurrences over 100 MW and 34 occurrences over 50,000 or more consumers.

Two paradoxes of restructuring lie at the core of the power infrastructure investment problem, one technical and one economic. Technically, the fact that electricity supply and demand must be in instantaneous balance at all times must be resolved with the fact that new power infrastructure is extraordinarily complex, time consuming, and expensive to construct. Economically, the theory of deregulation aims to achieve the lowest price through increased competition. However, the market reality of electricity deregulation has often resulted in business-focused drive for maximum efficiency to achieve the highest profit from existing assets and not resulting in lower prices or improved reliability. Both the technical and economic paradoxes could be resolved by knowledge and technology.

Whether or not the power industry renews its traditional levels of investment in research and in new transmission lines and the government clarifies its regulatory role in the making and dispatching of electricity, the grid will have to go on functioning. Fortunately, several recent innovations promise to make better use of the existing electrical network.

Options and Possible Futures: What Will It Take to Succeed?

Revolutionary developments in both information technology and material science and engineering promise significant improvement in the security, reliability, efficiency, and cost effectiveness of all critical infrastructures. Steps taken now can ensure that critical infrastructures continue to support population growth and economic growth without environmental harm.

As a result of demand growth, regulatory uncertainty, and the increasing connectedness of critical infrastructures, it is quite possible that in the near future the ability, for example, of the electricity grid to deliver the power that customers require in real time, on demand, within acceptable voltage and frequency limits, and in a reliable and economic manner, may become severely tried. Other infrastructures similarly may be tested.

At the same time, deregulation and restructuring have added concern about the future of the electric power infrastructure (and other industries as well). This shift marked a fundamental change from an industry that was historically operated in a very conservative and largely centralized way as a regulated monopoly, to an industry operated in a decentralized way by economic incentives and market forces. The shift impacts every aspect of electrical power including its price, availability, and quality. For example, as a result of deregulation, the number of interacting entities on the electric grid (and hence its complexity) has been dramatically increasing while, at the same time, a trend toward reduced capacity margins has appeared. Yet when deregulation was initiated, little was known about its large-scale, long-term impacts on the electricity infrastructure, and no mathematical tools were available to explore possible changes and their ramifications.

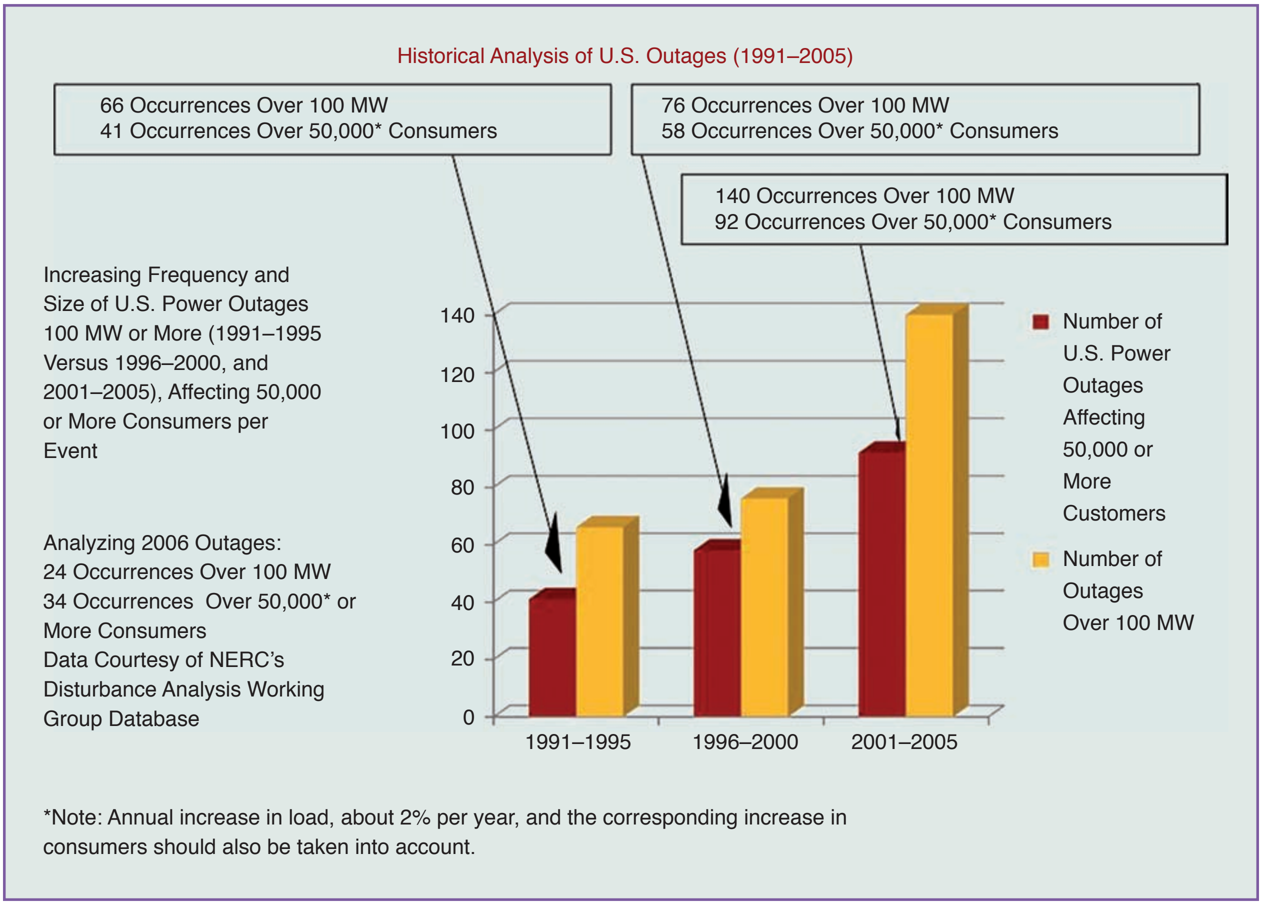


figure 1. Historical analysis of outages 1991–2005 (please also note that annual increases in load, about 2% per year, and corresponding increase in consumers should also be taken into account).

It was in this environment of concern that the smart self-healing grid was conceived. One event in particular precipitated the creation of its foundations: a power outage that cascaded across the western United States and Canada on 10 August 1996. This outage began with two relatively minor transmission-line faults in Oregon. But ripple effects from these faults tripped generators at McNary dam, producing a 500-MW wave of oscillations on the transmission grid that caused separation of the primary West Coast transmission circuit, the Pacific Intertie, at the California-Oregon border. The result: blackouts in 13 states and provinces costing some US$1.5 billion in damages and lost productivity. Subsequent analysis suggests that shedding (dropping) some 0.4% of the total load on the grid for just 30 minutes would have prevented the cascading effects and prevented large-scale regional outages (note that load shedding is not typically a first option for power grid operators faced with problems).

From a broader perspective, any critical national infrastructure typically has many layers and decision-making units and is vulnerable to various types of disturbances. Effective, intelligent, distributed control is required that would enable parts of the constituent networks to remain operational and even automatically reconfigure in the event of local failures or threats of failure. In any situation subject to rapid changes, completely centralized control requires multiple, high-data-rate, two-way communication links; a powerful central computing facility; and an elaborate operations control center. But all of these are liable to disruption at the very time when they are most needed (i.e., when the system is stressed by natural disasters, purposeful attack, or unusually high demand).

When failures occur at various locations in such a network, the whole system breaks into isolated "islands," each of which must then fend for itself. With the intelligence distributed, and the components acting as independent agents, those in each island have the ability to reorganize themselves and make efficient use of whatever local resources remain to them in ways consonant with the established global goals to minimize adverse impact on the overall network. Local controllers will guide the isolated areas to operate independently while preparing them to rejoin the network, without creating unacceptable local conditions either during or after the transition. A network of local controllers can act as a parallel, distributed computer, communicating via microwaves, optical cables, or the power lines themselves, and intelligently limiting their messages to only that information necessary to achieve global optimization and facilitate recovery after failure.

Over the last 12 years, efforts in this area have developed, among other things, a new vision for the integrated sensing, communications, protection, and control of the power grid. Some of the pertinent issues are why/how to develop protection and control devices for centralized versus decentralized control and issues involving adaptive operation and robustness to various destabilizers. However, instead of performing in vivo societal tests that can be disruptive, we have performed extensive "wind-tunnel" simulation testing (in silico) of devices and policies in the context of the whole system along with prediction of unintended consequences of designs and policies to provide a greater understanding of how policies, economic designs, and technology might fit into the continental grid, as well as guidance for their effective deployment and operation.

If organized in coordination with the internal structure existing in a complex infrastructure and with the physics specific to the components they control, these agents promise to provide effective local oversight and control without need of excessive communications, supervision, or initial programming. Indeed, they can be used even if human understanding of the complex system in question is incomplete. These agents exist in every local subsystem—from "horseshoe nail" up to "kingdom"—and perform preprogrammed self-healing actions that require an immediate response. Such simple agents already are embedded in many systems today, such as circuit breakers and fuses as well as diagnostic routines. The observation is that we can definitely account for loose nails and to save the kingdom.

Another key insight came out of analysis of forest fires, which researchers in one of the six funded consortia that I had the privilege of leading found to have similar "failure-cascade" behavior to electric power grids. In a forest fire the spread of a spark into a conflagration depends on how close together are the trees. If there is just one tree in a barren field and it is hit by lightning, it burns but no big blaze results. But if there are many trees and they are close enough together, which is the usual case with trees because nature is prolific and efficient in using resources, the single lightning strike can result in a forest fire that burns until it reaches a natural barrier such as a rocky ridge, river, or road. If the barrier is narrow enough that a burning tree can fall across it or it includes a burnable flaw such as a wooden bridge, the fire jumps the barrier and burns on. It is the role of first-response wild-land firefighters such as smoke jumpers to contain a small fire before it spreads by reinforcing an existing barrier or scraping out a defensible fire line barrier around the original blaze.

Similar results hold for failures in electric power grids. For power grids, the "one-tree" situation is a case in which every single electric socket had a dedicated wire connecting it to a dedicated generator. A lightning strike on any wire would take out that one circuit and no more. But like trees in nature, electrical systems are designed for efficient use of resources, which means numerous sockets served by a single circuit and multiple circuits for each generator. A failure anywhere on the system causes additional failures until a barrier, say, a surge protector or circuit breaker, is reached. If the barrier does not function properly or is insufficiently large, the failure bypasses it and continues cascading across the system.

One of the most important of these enabling technologies is the proposal to "fly" the grid more like the way an advanced jet fighter is actually flown. Modern warplanes are now so packed with sophisticated gear as to be nearly impossible to operate by human skill alone. Instead they rely on a battery of sensors and automatic control agents that quickly gather information and act accordingly. While working at EPRI during 1998–2003, I had the opportunity to propose just such a complex adaptive system for operating large regional power grids. In avionics, sensing parameters like the fighter's angle of attack with respect to the position, speed, and acceleration cause automatic controllers to assist the pilot in stabilizing the aircraft via adjusting wing flaps, ailerons, or the amount of engine thrust to achieve a more optimal flight path. The grid equivalent of this would be a heightening of the "situational awareness" of the grid and allowing fast-acting changes in power production and power routing, thus altering the stream of electrical supply and demand on a moment-by-moment basis.

The elements of such a smart, self-healing grid [Figure 2(a) and (b)] would include, first, a wide-area monitoring network of sensors linked together in a number of ways: through time signals from the global positioning service (GPS), commands through secure Internet, and through sensor-to-sensor communication via dedicated fiber optics. The information from the sensory level would continually be passed on to the control level, which might consist of another network of smart devices, in this case semi-autonomous control mechanisms coordinated with a myriad of grid components, such as transformers, generators, parts of generators (responsible for such things as boiler temperature, steam pressure, etc.), switches, and circuit breakers. Some of these adaptive software provisions are already in place in many grids, but a still more thorough integrative and automatic approach will be needed to help overburdened human grid operators cope with the growing demand for electrical power in the most efficient manner possible using the equipment available at any moment. This design is based on wide-area intelligent, adaptive protection and control systems. It has the abilities to 1) identify and evaluate the impact of impending failures on the power or communication system; 2) perform system-wide vulnerability assessment incorporating the power system, protection system, and the communication system; 3) enable the power system to take self-healing actions through reconfiguration; 4) perform power system stabilization on a wide-area basis; and 5) monitor and control the power grid with a multi-agent system designed to reduce the power system vulnerability. Notice that the new grid architecture would operate in a bottom-up manner, with distributed components in the field telling the higher management levels how and where electrical currents should be sent, rather than in the old-style top-down architecture wherein decisions were imposed from above.

Data will be gathered from all parts of the system and analyzed in real time, resources will be dispatched on a regional basis to keep up with load changes, and power electronic devices will provide instantaneous control of power flow. To add intelligence to an electric power transmission system we need to have independent processors in each component and each substation and power plant. These processors must have a robust operating system and be able to act as independent agents that can communicate and cooperate with others, forming a large distributed computing platform. Each agent must be connected to sensors associated with its own component or its own substation so that it can assess its own operating conditions and report them to its neighboring agents via the communications paths. Thus, for example, a processor associated with a circuit breaker would have the ability to communicate with sensors built into the breaker and communicate those sensor values using high-bandwidth fiber communications connected to other such processor agents. Finally, consumers will be integrated fully into electricity markets by electronic meters with two-way communications.

An Example: The Galvin Electricity Initiative

Under an EPRI and Galvin Foundation contract, I had the privilege of leading Task 3 of the Galvin Electricity Initiative during March 2005–February 2006. Task 3 was focused on technology scanning, mapping, and foresight.

The process used to scan technology led to clearer insight on current science and technology assets when looked at from a consumer-centered future perspective, rather than just incremental contributions to today's electric energy system and services. Some of these incremental contributions were (with the benefit of hindsight):

- ✔ early dominant corporations
- ✔ needs of initial installation locations
- ✔ government regulations
- ✔ technology state of the art at key historical development points
- ✔ scale—system grew geographically with space-filling dynamics rather than through emergent technology dynamics
- ✔ pace and insertion of power using devices from all sectors of society
- ✔ inertia of installed equipment and financial capital amortization.

This has resulted in a system today that has inherent resistance to new enabling technology assimilation. At best, this incumbent electric energy system can grow and possibly improve performance through incremental technology adoption—a diffusion dynamic that may not be fast and effective enough to meet the needs of the 21st century. "Pushing harder" will likely have limited effect on this dynamic.

In contrast, the system or systems that may best meet consumer needs for the 21st century will need to be

- ✔ scalable, robust, and multimodal
- ✔ configured so as to allow for technology breakthroughs to be exploited rapidly and effectively
- ✔ able to meet diverse consumers' needs and give them service choices
- ✔ provide market dynamics such as elasticity between price and performance
- ✔ aligned economically and politically to give simultaneous incentives to the major providers, users, and stakeholders.

A model or metaphor for the development of the existing and 21st century electric energy providing systems is the "Wintel" versus Mac models, respectively, for personal computing. ("Wintel" refers to the Windows operating system running on Intel microprocessors, a term often used to indicate the close alliance between Intel and Microsoft.) Windows and Intel were

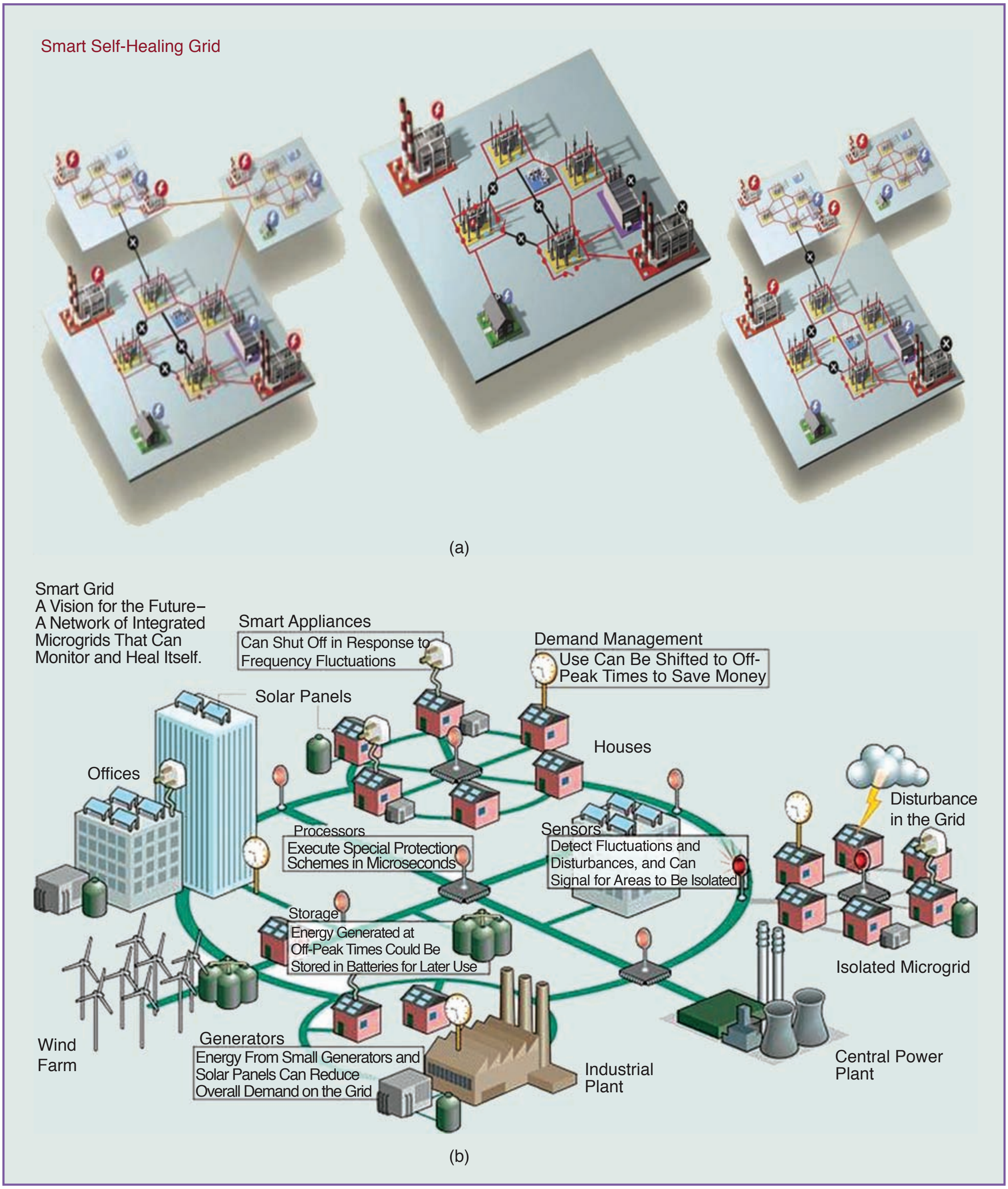


figure 2. (a) The future power system will employ integrated network control to coordinate all major power system functions on a regional basis, enabling more flexible system operations to meet changing customer needs (source: Amin and Schewe, "Preventing blackouts," *Scientific American*, May 2007, used with permission). (b) Infrastructure integration of microgrids and diverse generation/storage resources into a system of a smart self-healing grid (source: "Upgrading the grid," *Nature,* vol. 454, pp. 570–573, 30 July 2008, used with permission).

the major driving forces for the existing PC system. The dynamic was based on supply-side engineering and limited by technology improvement and the economics of consumers' ability to absorb new products. The Mac approach, in this metaphor, was, from the start, based on consumer needs and choices and the development dynamic was to assemble the appropriate technology to meet those needs. This could be a model for a path to the perfect 21st-century electricity enterprise.

To identify broader science and technology innovations, the following technology capability gaps were identified in Task 3. The technologies include software (including ubiquitous computational ability with defect-free software integrated into the power system that enables dynamic control through fast simulation and modeling with full system visualization); hardware for thermal energy storage; ac and dc microgrids; advanced (post-silicon) power electronics devices (valves); high-efficiency lighting, refrigerators, motors, and cooling; efficient, reliable, cost-effective plug-in hybrid electric vehicles (PHEVs), and technologies and systems that enable "hardened" end-use devices.

Examples of Selected Technologies

To highlight a few selected subareas, scenarios, and R&D opportunities, consider the following two examples that may be achievable within a decade as part of proof-of-concept pilot demonstrations.

Example 1: Limited Supply of Fossil Fuels

In this scenario, in part due to competitive demands of developing countries such as China, India, and other nations, we are faced with constrained availability of oil, natural gas, and other imported fossil fuels. Other characteristics include the following:

- ✔ high dependency on foreign energy sources
- ✔ reduction of economic security, personal liberty, and freedom
- ✔ bottleneck caused by current centralized energy system
- ✔ environmental pollution and inefficient energy sources

while persisting consumer demands are

- ✔ reliable, fail-safe energy system
- ✔ affordable, efficient energy management
- ✔ security and freedom
- ✔ environmentally friendly.

The teams mapped the following solution/technologies to extend the existing PowerZone (Technology PowerZone is trademark of Dr. Lockwood Carlson, Lockwood Carlson Consulting, LLC and is used here with permission) (see Figure 3):

- ✔ microgrid technology
- ✔ generation/nuclear fusion
- ✔ distribution/carbon nano technology
- ✔ storage/advanced battery technology
- ✔ energy management/energy management software.

Technology opportunities that were identified include:

- ✔ massive redundancy provides seamless responses to any energy disruption
- ✔ reduction of demand from the centralized power grid system
- ✔ active consumer choices to optimize the performance of the system
- ✔ provide universal power source
- ✔ better economic security, personal freedom, mobility, and liberties.

The detailed technology interaction matrix along with the high, medium, and low ranking are given in Figure 4.

In Example 1, the highest scores for technology utilization are advanced computer hardware, advanced materials, catalyst technologies, and high-confidence energy management software. The source technologies include nuclear fusion, biofuel factories, fuel cells, and computerized energy devices.

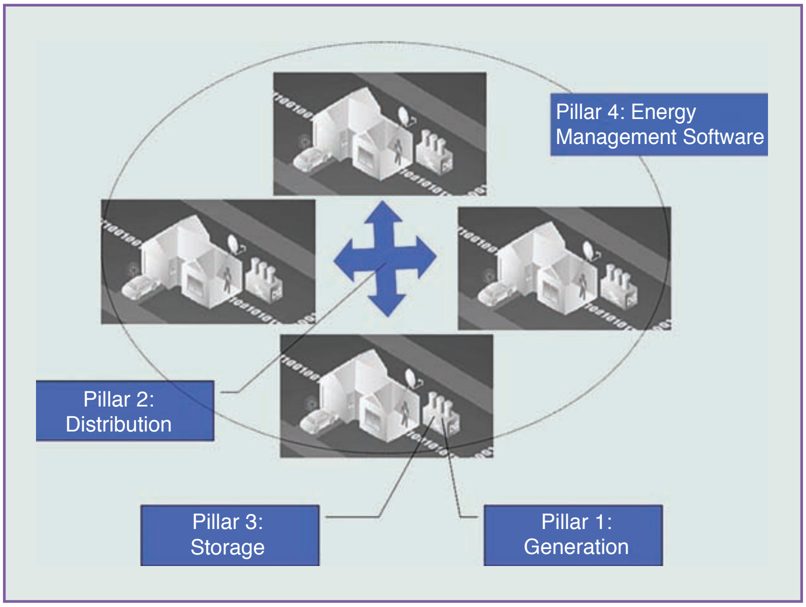


figure 3. Solution/technologies to extend the existing PowerZone (reprinted courtesy of EPRI and Primen, 2001).

Example 2: A Consumer-Centered, Not Central-Station and Macrogrid, Focus

In this example, concentrating on local area networks and microgrids, three critical technologies were identified:

- ✔ intelligent power system management
  - advanced power system control
  - load-shedding and demand response
  - price-sensitive appliance controllers
  - fast multiresolution modeling and simulation
- ✔ distributed micropower
  - green microturbines
  - storage technologies

✔ transparent multilateral energy marketplace
- willingness-to-pay market research
- closed-loop economics with transparent feedback.

The ten innovative technologies to enable this scenario are shown in Figure 5. These technologies range from advanced power system control to fast multiresolutional modeling and simulation, as well as identifying strategies for extending the PowerZone (via formation of alliances in this case) and development of new technologies as indicated in Figure 6.

A Recommended Path Forward

The next steps beyond the Galvin Electricity Initiative include more carefully analyzing alternatives and identifying demonstration testing requirements via the use of advanced simulation with subsystem component functionalities extrapolated from today's state of the art in distributed power sources, transmission and distribution modalities, storage and power conditioning technology, etc. Based on these outcomes, a small-scale breadboard demonstration (with a limited number of small-scale, real-world components) could be set up and used for testing with an aim toward the design and development of potential real-world alpha site tests.

As indicated earlier, a novel approach would be to develop a proof-of-concept system that grows and organizes itself by individual user's needs, drawing on a multiplicity of electricity power and energy components "no architecture" architecture.

The researchers outline a specific approach that incorporates many of the insights and recommendations of the Task 3 effort. These efforts could result in the ultimate development of a "system" (or a metasystem of systems) that would be robust, efficient, scalable, and have low impedance to new technology insertion. There are several alternative configurations with varying costs and performance levels; they range from completely distributed power systems (including "small" direct current systems and distributed generation technology), to somewhat distributed, to fully integrated (retrofit of the current system). One such example is indicated next.

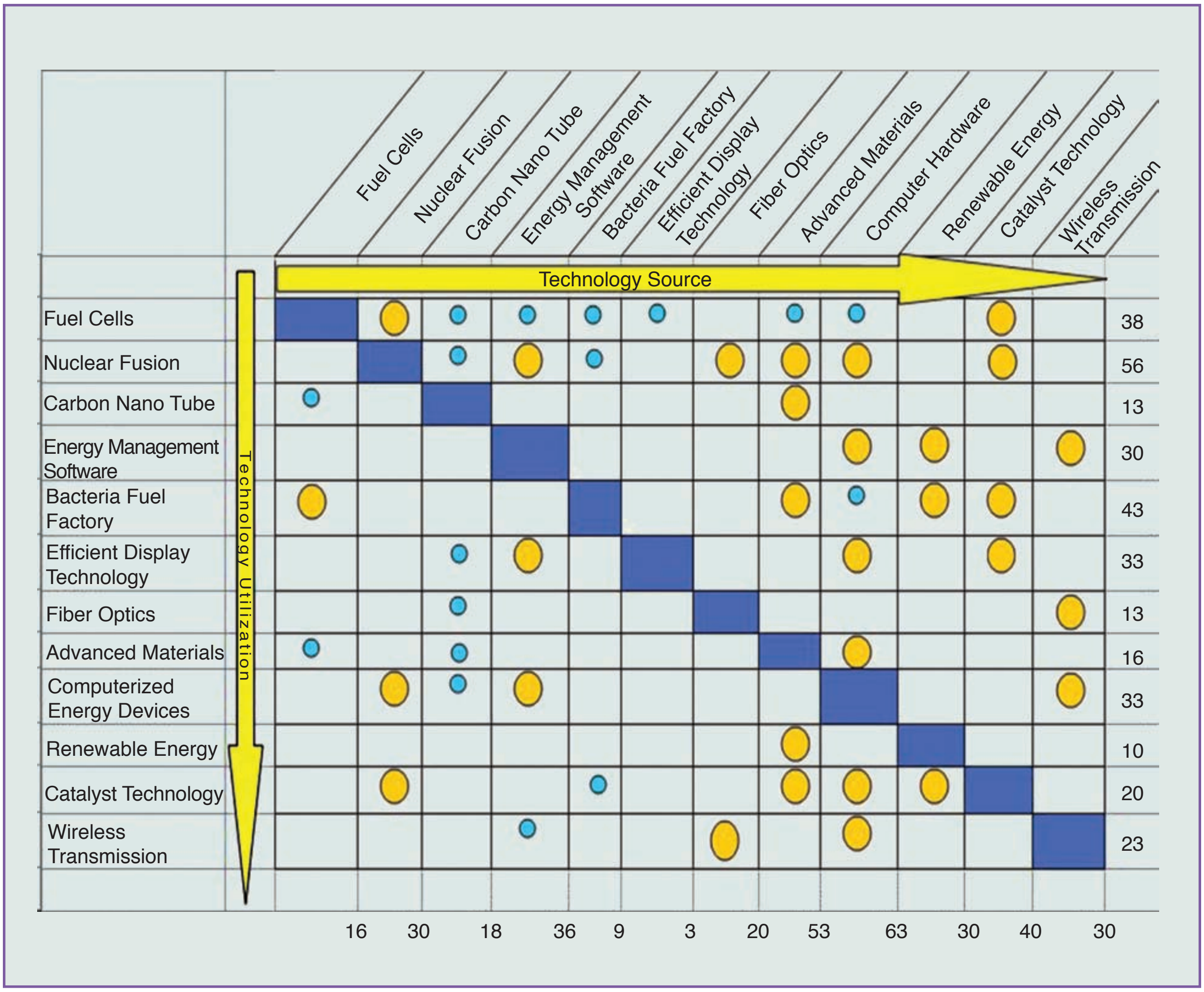


figure 4. Technology interaction matrix and ranking of the various technology opportunities for Example 1.

An Example of a "Disruptive Model": The No-Architecture Architecture

The concept of a no-architecture architecture is to provide a system that grows and organizes itself at the local level based on individual user needs and drawing on a multiplicity of electricity power and energy components (generation, transmission, distribution, power conditioning, distributed generation, storage, etc.). In this sense it is an emergent system. It could be a complement or supplement to the existing macrogrid structures. Such a system will become more effective as users are added, new technology is assimilated, and organizational patterns develop. These would also provide demonstrated performance templates for more conventional top-down systems architectures.

The first step would be a detailed planning and computer-simulation-based proof of concept (in-silico testing) and use of advanced simulation with subsystem component functionalities starting from today's state of the art in distributed power sources, transmission and distribution modalities, power conditioning technologies, etc. Based on these outcomes, a small-scale breadboard demonstration (with a limited number of small-scale real world components) could be set up and used for testing with an aim toward the design and development of a potential real-world alpha site test.

Next Steps

How to control a heterogeneous, widely dispersed, yet globally interconnected system is a serious technological problem in any case. It is even more complex and difficult to control it for optimal efficiency and maximum benefit to the ultimate consumers while still allowing all its business components to compete fairly and freely. A similar need exists for other infrastructures, where future advanced systems are predicated on the near perfect functioning of today's electricity, communications, transportation, and financial services.

From a national perspective, a key grand challenge before us is how do we redesign, retrofit, and upgrade the nearly 220,000 miles of electromechanically controlled system into a smart self-healing grid that is driven by a well-designed market approach?

Creating a smart grid with self-healing capabilities is no longer a distant dream; we've made considerable progress. But considerable technical challenges as well as several economic and policy issues remain to be addressed. Funding and sustaining innovations, such as the self-healing grid, remain a challenge as utilities must meet many competing demands on precious resources while trying to be responsive to their stakeholders, who tend to limit R&D investments to immediate applications and short-term return on investment. In

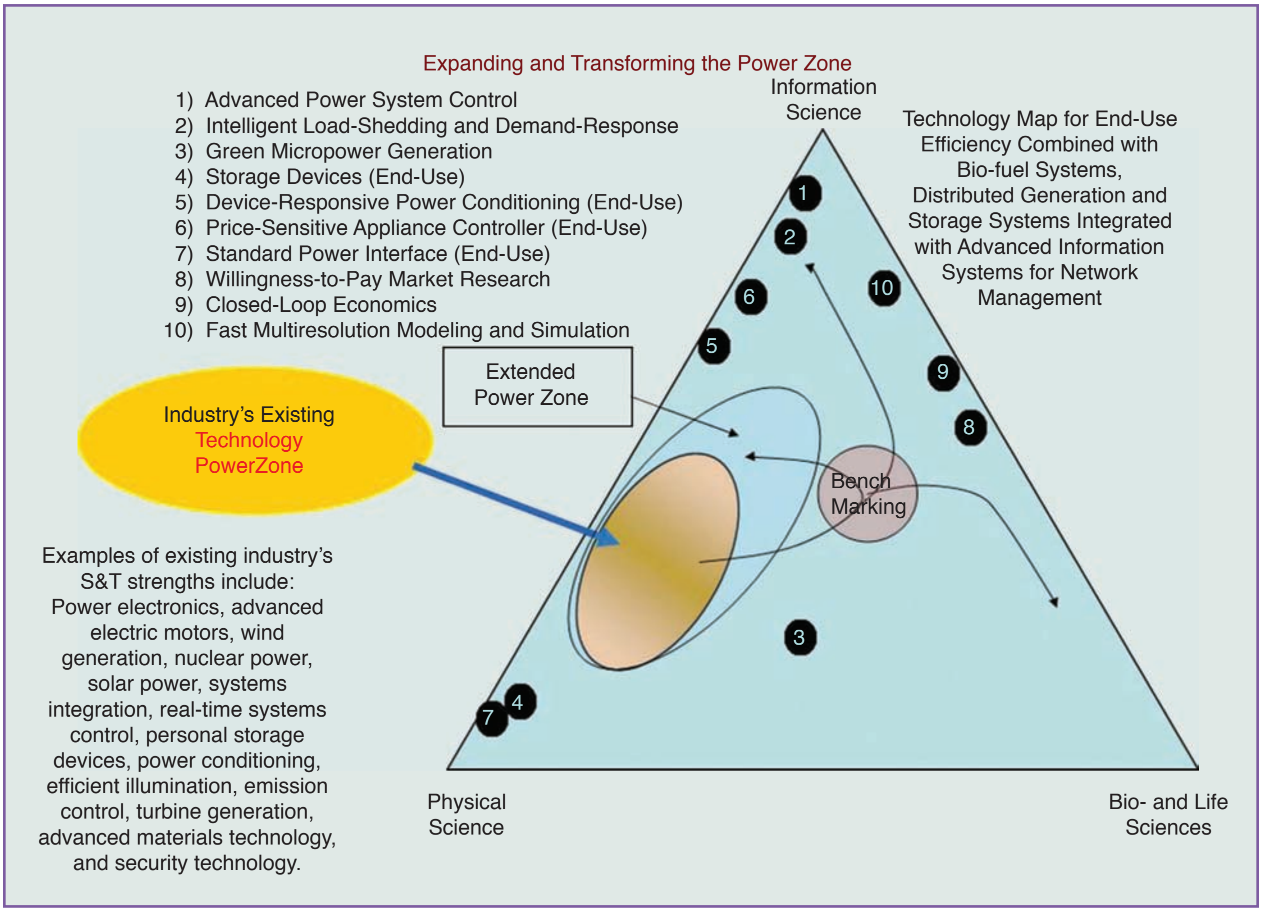


figure 5. Transition to a consumer-centered, not central station and macrogrid, focus (Example 2).

addition, utilities have little incentive to invest in the longer term. For regulated investor-owned utilities there is added pressure caused by Wall Street to increase dividends.

Several reports and studies have estimated that for existing technologies to evolve and for the innovative technologies to be realized, a sustained annual R&D investment of US$10 billion is required. However, the current level of R&D funding in the electric industry is at an all-time low. The investment rates for the electricity sector are the lowest rates of any major industrial sector with the exception of the pulp and paper industry. The electricity sector invests at most only a few tenths of a percent of sales in research—this is in contrast to fields such as electronics and pharmaceuticals in which R&D investment rates have been running between 8–12% of net sales—and all of these industry sectors fundamentally depend on reliable electricity.

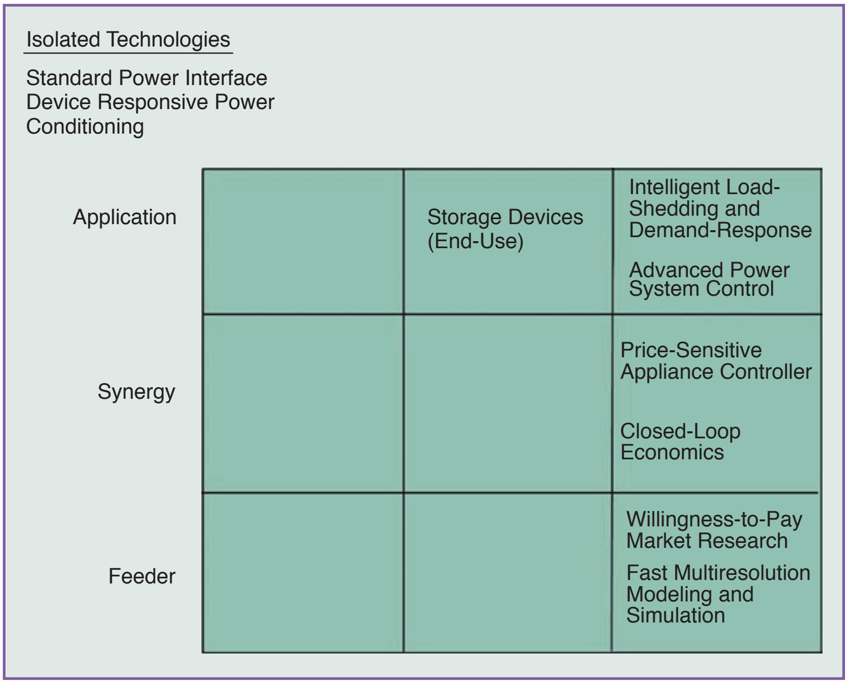


figure 6. R&D strategy matrix for a consumer-centered, not central station and macrogrid, focus (Example 2).

A balanced, cost-effective approach to investments and use of technology can make a sizable difference in mitigating the risk. Electricity shall prevail at the quality, efficiency, and reliability that customers demand and are willing to pay for. On the one hand, the question is, "Who provides it?" On the other hand, it is important to note that achieving the grid performance, security, and reliability are a profitable national investment, not a cost burden on the taxpayer. The economic payback is three to seven times greater than the money invested. Further, the payback starts with the completion of each sequence of grid improvement. The issue is not merely who invests money, because that is ultimately the public, but whether it's invested through taxes or kilowatt-hour rates. Considering the impact of regulatory agencies, they should be capable of inducing the electricity producers to plan and fund the process; this may be the most efficient way to get it in operation. The current absence of a coordinated national decision-making body is a major obstacle. State's rights and state PUC regulators have removed the individual state's utility motivation for a national plan. Investor utilities face either collaboration on a national level or a forced nationalization of the industry.

Given economic, societal, and quality-of-life issues and the ever-increasing interdependencies among infrastructures, a key challenge before us is whether the electricity infrastructure will evolve to become the primary support for the 21st century's digital society—a smart grid with self-healing capabilities—or be left behind as a 20th century industrial relic?

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For Further Reading

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Biography

S. Massoud Amin is a professor of electrical and computer engineering at the University of Minnesota. p&e