The Galvin Electricity Initiative: Task 3—Technology Scanning, Mapping, and Foresight

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Galvin Electricity Initiative

The Galvin Electricity Initiative seeks to identify opportunities for technological innovation in the electric power system (broadly defined) that will best serve the changing needs of consumers and businesses over at least the next 20 years. Of paramount importance will be insuring that the electricity system provides absolutely reliable and robust electric energy service in the context of changing consumer needs.

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INTRODUCTION

This report summarizes the results of Task 3 of the Galvin Electricity Initiative aimed at developing Technology Scanning, Mapping, and Foresight and laying the foundation for broader application of science and technology innovations by the Initiative. It particularly focuses on technologies that may exist outside of the traditional electricity industry.

Executive Summary, Macro-Level Insights, and Recommendations

The existing electricity infrastructure evolved to its technology composition today from the conjunction of several major forces, only one of which was technologically based. The Task 3 Workshop and the process used to scan technology has 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" vs. MAC models, respectively, for personal computing.[1] Windows and Intel were the major driving forces for the existing personal computer (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.

Technology Gaps

To identify broader science and technology innovations, the following technology capability gaps were identified in the Task 3 workshop. We shall briefly summarize them here as they are presented in more detail on p. 2-6. 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; alternating current (AC) and direct current (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 (PHEV), and technologies and systems that enable "hardened" end-use devices.

Additional Innovation Opportunities

A summary of further insights gained in Task 3 and at its corresponding workshop, are:

- The need for unconventional standards and benchmarking; e.g., Xerox did not use their competitors, but instead used companies like LL Bean—to avoid reinventing what others have done and to learn the positive lessons from others.
- Consumer-centered design: Not only services to end users, but also end users as producers must be accounted for. This is as much an attitude as it is an architecture.

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[1] "Wintel" refers to the Windows operating system running on Intel microprocessors; a term often used to indicate the close alliance between Intel and Microsoft.

- To achieve perfection will in fact require extraordinary, outside-of-the-box thinking.

> *The lowest cost option is perfection, and anything less reliable is more expensive from the consumer perspective*
>
> —Bob Galvin

- Include both personal and power system security as a design criterion and build it in to the architecture rather than as an afterthought.
- To get to perfect power, a "large" percentage of improvement (to be determined) may need to come from the consumer side. Some focus needs to remain on improving the power delivery system and central power production but much greater consideration needs to be given to end-use devices, appliances, and digital handhelds, for example.
- Include and address minority consumer/contrarian views: For example, what does electrification mean to rural Americans? A Navajo woman, for example, would think of things differently from the assembled experts at the Galvin workshops. Some have a hard time affording power. Emerging countries are not going to be constrained by a hundred-year history as they build their infrastructure. Of particular importance is the service perspective of younger consumers who are growing up in the Digital Age.
- Address soft sciences, regulation, and economic issues, including the role of innovation, climate for enabling this transformation to a perfect system, economics, policy, and the related "soft" sciences; for example:
    - How do macro portions or components of major systems advance. How do these technologies play out in a high oil price world?
    - Consider further fertile intersections between the power industry and other sectors that are in technological transition, such as the transportation sector.
    - Consider billing as a component of the infrastructure. Include financial institutions and how they may affect the relationship between provider and end user.
    - Consider what can be learned from the successful cases of transformative innovation (e.g., hand calculators) as applied to the various source and technology areas.
    - Consider the impact of energy efficiency and demand response (consumer response to various electricity price signals)—factors in a distributed power system that will have huge impacts up the line.

In addition, several illustrative examples are incorporated into this report, including: 1) a granular semi-autonomous architecture, 2) a consumer-centered, configuration, not central-station- and macro-grid-focused, and 3) A bio-fuel system combined with distributed generation and storage and integrated with advanced information capabilities for network management.

Outcomes

Key outcomes of Task 3 along with selected examples and technology R&D results are summarized in this report. The expectations and anticipated outcomes for Task 3, as described below, were met.

Discover the science and technology strengths in the current technology profile, as they relate to future trends. The teams involved in Task 3 identified and mapped those key science and technologies that are essential to the Consumer Needs, Technology Potential, and Technology Scanning tracks (see pp. 2-3 through 2-7 and 3-3 through 3-5).

Target major new growth platforms. The teams sorted existing science and technology strengths and new opportunities to characterize platforms (see pp. 2-7 through 2-20).

Identify emerging consumer needs and technology development opportunities. These opportunities can be applicable to core electricity stakeholders or involve new ventures based on science and technology strengths (see pp. 2-17 through 2-20).

Gain insight for R&D prioritization and strategy. Prioritization is a key problem for most R&D organizations. There are always too many paths to take and jobs to do within resource allocation (see pp. 3-5 through 3-8).

Integrate input for the strategic planning and optimization process. The results of the foresight process provide a business view of science and technology developments and opportunities that can be integrated into the strategic plan, rather than tacked on as the “contribution” from R&D (see pp. 3-5 through 3-10).

Leverage existing technology strengths. The process can lead to clearer insight on current science and technology assets when looked at from a future perspective, rather than just incremental contributions to today’s system and products (see pp. 3-3 through 3-5 and examples 1-4 on pp. 3-11 through 3-18).

Drive innovation through interconnecting the science and technology community. By using the expertise of technical and business professionals in the process, new relationships across disciplines and businesses are created. These can be a major source of innovation for years to come. We have also seen the re-energizing of key sectors and technical personnel through participation in these activities with their peers. An example of such an alliance on the development of foundation and feeder technologies appears below.

Alliances and Partnerships

In order to address many of the areas discussed in this report and to achieve most of the milestones, the industry and pertinent public and private sectors will need to collaborate with other stakeholders. Specifically, for foundation and feeder technologies shown in Figures 3-3, 3-4, and 3-5 on pp. 3-9 and 3-10, consideration should be given to forming alliances where scientific, technical, policy experts, and business leaders integrate the resulting Technology

Foresight into the R&D strategy with other planning inputs, to actionable programs, new R&D, new product development projects, and new business development activities supporting the overall strategy.

In particular regarding these foundation and feeder technology areas, partnerships with agencies such as the U.S. National Science Foundation (NSF) are recommended. We are honored to have received constructive feedback on this report along with the following quotation from Dr. Arden Bement at the NSF:

> *I am impressed with the quality and readability of the report. The identification of technology gaps, and the mapping of technology space maps and technology interaction plots, provide important graphical tools to help the reader grasp the significance of current industry strengths and investment opportunities.*
>
> *The role of the National Science Foundation is especially important at the apices of your triangle: physical science, the bio side of bio-and life sciences, and information science. We are strongly invested in most of the critical technologies identified in the report, especially in advanced materials, nanotechnology, information technology, and sensors. Therefore, I believe that NSF has been, and will continue to be, a key provider of new concepts at the forefront of the electricity industry's innovation system.*
>
> —Dr. Arden L. Bement, Jr., Director, National Science Foundation
> January 4, 2006

A Recommended Path Forward

The next steps beyond Phase One of the Galvin Electricity Initiative include more carefully analyzing alternatives and identifying demonstration testing requirements via the use of advanced simulation with sub-system 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 towards 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 including the Task 3 Workshop. These efforts could result in the ultimate development of a “system” (or a meta-system 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.

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, DG, storage, etc.). In this sense it is an emergent system. It could be a complement or supplement to the existing macro grid 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 sub-system 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 towards the design and development a of a potential real world alpha site test.

2

GOALS OF THE GALVIN ELECTRICITY INITIATIVE AND CONTEXT FOR TASK 3

The Galvin Electricity Initiative seeks to define the most confident systemic solution for achieving and maintaining an absolutely reliable and robust electric energy service capability most perfectly meeting 21st century consumer needs and expectations. This capability will consider, and utilize to best advantage, an optimal combination of the traditional electricity infrastructure plus advanced power generation, storage, and delivery technologies; as well as a transformed electrical interface with the consumer incorporating innovative energy consuming processes, devices, and appliances. The Initiative also examines the opportunities for the marriage of this transformed electric energy service capability and innovative electro-technologies to advance productivity and quality of life for all consumers. In the context of this Initiative, electric energy service is defined as the end-use service ultimately provided by electricity. This extends beyond today's consumer interface (e.g., presently the meter) between consumers and service providers to the energy consuming device or appliance, and includes all elements in the chain of technologies that ultimately enable electricity to be transformed into such services as motive power; lumens of visual quality applied to the work surface, or digitized processes.

The goal of Task 3 and the corresponding workshop, held on September 28–29, 2005 in Chicago, was to investigate whether there are leading applications of science and technology (S&T) outside the traditional electric energy industry that may apply in meeting and shaping consumer needs. These applications may include entirely new technologies, not part of the portfolio of traditional electricity solutions and not identified in other tasks, which could potentially facilitate reaching the goal of system perfection.

In this context, outside the traditional sources means outside of electric utilities, laboratories and electrical apparatus, appliance and device manufacturers, etc. who typically conduct research, design, demonstration, and commercialization of energy utilization, distributed resources, power quality and/or power electronic technologies. These applications will possibly derive from the following areas at the frontiers of potentially disruptive science and technology; as part of this investigation, researchers provided a comprehensive analysis through a systematic process of technology scanning, mapping, and foresight, described below.

The objective is to anticipate the introduction of new science and technology into opportunities for: the benefit of society; consumer aspirations for perfect electric energy services in North America; for new innovations that meet changing consumers' demands or may shape their desires; and to identify and address performance roadblocks. In this context, "new" is based on identifying areas in the science and technology space, depicted here as a triangle (see Figure 2-1) and discussed in more detail on pp. 2-17 through 2-20, beyond the current strengths. The purpose of this report is to offer a summary of findings and recommendations resulting from this task. It also contains a brief background on the Initiative, a definition of what a power system is (Appendix B), and some details on the technical gaps in today's power system.

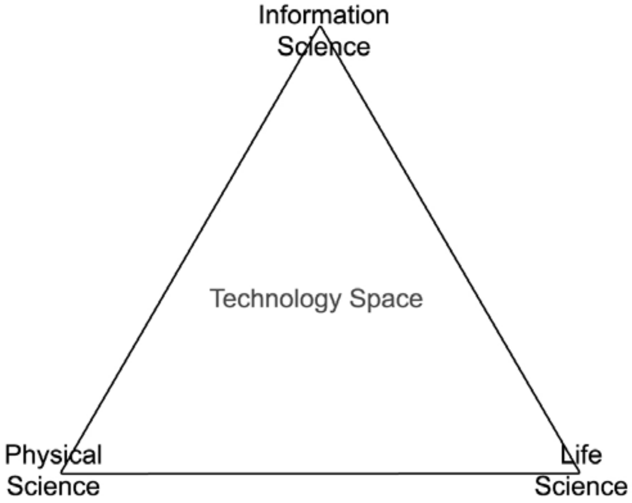

Figure 2-1
The Science and Technology Space

Although the Galvin Electricity Initiative is ultimately responsible for the content of this report, the scenarios described, the key drivers that shape them, and their implications for electricity service requirements reflect the insights and collaboration of many individuals. A complete list of contributors is provided in Appendix A.

Existing Strengths (the "PowerZone"): Discover the Science & Technology Strengths in the Current Technology Profile, as They Relate to Future Trends

The Task 3 Workshop teams initially identified and mapped those key science and technologies that are essential to the Consumer Needs, Technology Potential, and Technology Scanning tracks. These were later refined and modified by the researchers and leaders of the Task 3 efforts. For example, some of the most prominent current and emerging "PowerZone technologies" already **within** the power industry are described in Table 2-1.[2]

While the emerging technologies listed in the table could also be considered as the basis of today's industry; they are within the existing industry "PowerZone" and several ongoing thrusts are underway; however, their application is rather limited and should be considered as a part of future opportunities.

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[2] Technology PowerZone™ and Technology Foresight Dynamics™ are trademarks of Lockwood Carlson, the Carlson Consulting Group and are used here with permission.

Table 2-1
Current and Emerging PowerZone Technologies

Technologies That Form The Basis of Today's Electricity Industry	Technologies That Are Already Emerging
Central Generation (coal, nuclear, gas turbines)	Automation
Transformers	Monitoring
Circuit Breakers	Sensors
Conductors & Cables	Fault Current Limiters
Capacitors	Power Electronics
Metering & Billing	Power Quality Devices
Relays	Wind Generation
Insulators	Distributed Generation
Surge Arrestors	
Electrotechnologies	
Lighting	
Motors	
Refrigeration	
Energy Management Systems	
Network Protectors	

Attributes of the Future "Perfect" System

In order to move beyond these core technologies and existing strengths to achieve objectives/vision articulated by the Galvin Electricity Initiative, the key challenge is how to plan for a "perfect power system" to ensure absolute and universal availability of energy in the quantity and quality necessary to meet every consumer's needs.

"Perfect" means meeting every consumer's expectation for electric energy quantity and quality. At first glance this may seem **unattainable** for all consumers, but that is not required: the point is that different consumers have different requirements. Therefore, the "perfect" supply is required by **some** consumers, and perhaps a variety of levels of attainment by others. The perfect system has one or more configurations. Key questions are:

- What are these configurations?
- At what cost?
- How will a system that attains these objectives look?

An extreme case of power quality “indifference” is a large electric arc furnace. Without proper design, most networks that include a consumer device like this will not receive power satisfying the “perfect” conditions defined above. However, the arc furnace operator **absolutely requires** the power to be there when he/she hits the button, but can communicate with the supplier ahead of time to ensure that this will be so and delivered at a reasonable cost.

Extreme cases of “perfect” requirements are a large semiconductor manufacturer and high-end server farms, where perfection means absolute reliability and power quality at value-based competitive cost.

In an intermediate case, power quality is of limited importance, but availability is very important, and the timing is not foreseeable—for example, water or waste-water facilities, or some emergency services that may not rely on high-end electronic devices.

There is, at the moment, a large sector of consumers for electric power whose needs are much less demanding. Fluctuations in voltage or frequency, within the currently permissible ranges, are irrelevant, and even brief blackouts, while irritating, are not tremendously important for most in our current global society. The implication of this is that the power delivery system of the future may in fact need to have **completely separate** components, but there may also be more than one system—perhaps interconnected, interdependent or perhaps not. These entire possible future configurations must be considered in this context.

Within the 20-year time span specified in our discussions, a large fraction of the U.S. electric power system may continue to look much like it does now. However, in order to effectively move towards the system required to meet escalating demands for improved quality, reliability, and consumer services, construction of the new components (retrofitting) or pilot demonstrations of new configurations must begin to be introduced right now. As these are introduced, compatibility for integration with the existing system must be considered, and this will continue for some time so that the existing (~ $800 billion) electricity infrastructure (including generation, transmission, and distribution) investment can be economically transformed.

There is an understandable existing bias toward large central generation plants. Coal and nuclear generation, combined, account for over 70% of today’s electricity production. At present, there is no other efficient means of exploiting these two abundant resources without large central plants. As long as the conversion of these resources to electricity in large central plants remains by far the most economic source of electricity, these plants will need to be part of a modern power system. The electrification of the U.S. economy continues to increase accordingly, and the total generation needs will continue to increase. It seems certain that a considerable fraction of this will continue to be supplied by central generating plants, with units typically in the 300 MW – 500 MW scale; sites may contain more than one such unit.

Interconnection through a system of wires will almost certainly continue, but it may be possible to relax this limitation. Originally the high-voltage transmission system (commonly called the grid) was intended to link units, with relatively modest amounts of power running between the service areas of the large generating plants, as the only way to ensure efficiently/economically and environmentally safe operation of current coal and nuclear generators, but deregulation has changed that. How the national power system will look in the future is not clear. If the functionality required of the grid continues to increase, changes will have to be made because the current grid was not designed for this and failures will continue to increase. If the Galvin Electricity Initiative concludes that tomorrow's needs are indeed to be met by a largely central system-solution, then researchers will need to identify how the power production and delivery system will evolve, and what new technology opportunities exist that can contribute to the realization of this.

The most important market component for the new system is what can be called the "digital ready" component. This component currently represents approximately 10% of the market, but it can be expected to increase to perhaps 30%, or more, over the next 20 years. In other words, current estimates indicate that as much as 10 – 12 % of current electricity consumption is either by digital devices or controlled by digital devices. These devices require digital grade power. The proliferation of these devices is expected to continue, increasing to 30% or more. This results in a corresponding increase in the need for the power system to supply digital-grade power.

The problem appears to be mainly the short-term fluctuations in power quality, but the absolute requirements of this market component need to be well defined. In a number of cases, their power quality problems **appear** to be dealt with by conversion at the user facility wall from the alternating current (AC) supplied to direct current (DC), and the power quality of the "in-house" DC dealt with by the usual post-AD/DC circuitry or a new DC microgrid. However, as the market fraction of this user component increases, it may be in everyone's interest to have the utility supply the "perfect" power, or alternatively have a distributed (grid independent) or a granular semi-autonomous architecture.[3]

It is important to note that large generating plants will not—and should not—provide electricity at this level of "cleanliness". This argues for an additional generating component capable of providing the higher-quality electricity. If a central system architecture is chosen for the perfect system then it may be worth reviewing the extent of the interconnection needed between these generating plants to protect against a plant going down and mitigating the risk of a cascading failure, or to cover for scheduled generating plant outages for periodic maintenance. It may be that DC generation would be the path to follow. This would define the permissible distance between the generating plants, and hence their size, distances, and locations. It is also possible that users requiring this level of supply might concentrate round the generating plant. Issues related to switching and to the impact of a large user coming on and off line will need to be addressed. New technologies may be needed to address these.

Design Criteria

The design criteria that would be employed to meet the performance specifications of a "perfect" power system may include the following:

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[3] Some illustrations of these are highlighted briefly in Examples 1-4, pp.3-11 through 3-18 in this report.

- **End-use Energy Service Devices**—design the simplest possible end-use devices that provide the ultimate energy services required with the lowest reasonable overall energy requirements incorporating local storage, connectivity, and power conditioning, as necessary.
- **System Configurations and Asset Management**—design energy delivery systems that allow optimal use of assets while minimizing environmental impact and assuring redundancy to supply reliable, safe, secure, high-quality energy at a reasonable cost.
- **System Monitoring and Control**—enable the energy system to be monitored and controlled in real time with minimal human intervention. Facilitate the use of "intervention" (automatic or with humans in the loop) where it is needed. This may also highlight that several configurations could yield perfection.
- **Resource Adequacy**—assure sufficient electric generation, storage and demand response with fuel and technology diversity distributed to assure reliability through competitive markets.
- **Operations**—organize a "six sigma" quality operational paradigm for electric system operations including training, standardization, system-wide coordination, and management.
- **Portability**—increase the ability to operate portable electric appliances and devices.
- **Connectivity**—enable integration of the electric energy system with communications to increase choice of smart energy services.

Technology Gaps

The following key technology gaps were identified in Task 2; and they were presented earlier in this report on pp. 1-2 and 1-3 to highlight opportunities where science and technology from other industries could possibly be identified to fill these gaps:

- Ubiquitous, hierarchical computational ability with perfect software integrated into the power system, which enables dynamic control through fast simulation and modeling with complete system visualization
- Low-cost, practical electric and thermal (heating and cooling) energy storage
- Microgrids—AC and DC, both self-contained, cellular, and universal energy systems and larger building or campus-sized systems with potential connectivity and compatibility with larger systems.
- Advanced power electronics (advanced silicon or post-silicon) devices (valves) to be embedded into flexible AC and DC transmission and distribution circuit breakers, short-circuit current limiters, and power electronics-based transformers
- Power electronic-based distribution network devices with integrated sensors and communications
- Fail-safe communications that are transparent and integrated into the power system
- Cost-competitive fuel cells

- Low-cost sensors to monitor system components and to provide the basis for state estimation in real time
- Thermal appliances that provide “plug-and-play” capability with distributed generation devices
- High-efficiency lighting, refrigeration equipment, motors, and space conditioning.
- Enhanced portability by improving storage devices, control, display efficiency, and power conversion devices
- Efficient, reliable, cost effective plug-in hybrid electric vehicles (PHEV)
- Technologies and systems that enable “hardened” end-use devices so as to minimize the need for external perfect power supply
- Conductors that enable greatly increased power flow capability
- Smart, green, zero-energy buildings
- Thermoelectric devices that convert heat directly to electricity

Enabling Technologies

The goal of Task 3 and the corresponding workshop was to investigate whether there are leading applications of science and technology (S&T) outside the traditional electric energy industry that may apply in meeting and shaping consumer needs. These applications may include entirely new technologies, not part of the portfolio of traditional electricity solutions and not identified in other tasks, which could be potentially available as well.

In this context, outside the traditional sources means outside of electric utilities, laboratories and electrical apparatus, appliance and device manufacturers, etc. who typically conduct research, design, demonstration, and commercialization of energy utilization, distributed resources, power quality and/or power electronic technologies. These applications will possibly derive from the following areas at the frontiers of potentially disruptive science and technology and were discussed in the Task 3 Primer, a document with background informational that was sent to workshop participants prior to the Task 3 workshop.[4] Specific technology areas were addressed along with those indicated in the Task 3 Primer (not intended to be an exhaustive list), including the following categories:

- Materials and devices—including nanotechnology, microfabrication, advanced materials and smart devices
- Meso- and Micro- scale devices and sensors and networks
- Advances in information science: algorithms, AI, systems dynamics, network theory, complexity theory

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[4] The *Task 3 Primer* included the *Galvin Project Work Plan Summary*; background on the Task 3 goals and the process for Technology Scanning, Mapping & Foresight; reference material on the existing power delivery system and infrastructure; some details on the technical gaps in today’s power system; examples of emerging science and technology areas (not intended to be an exhaustive list), and workshop participants’ biographies.

- Bioinformatics, biomimetics, biomechatronics, systems biology
- Enviromatics
- Other industries— moving to a wireless world—transportation, telecommunications, digital technologies, sensing and control
- Markets, economics, policy and environment
- End-to-end infrastructure-- from fuel supply to end use
- Other areas

For a related discussion of exciting emerging technologies (Table 2-2), see the May 2005 issue of MIT Technology Review for details on each.[5]

Table 2-2
Examples of Emerging Technologies (MIT *Technology Review*, May 2005)

Airborne Networks	**Quantum Wires**	**Silicon Photonics**	**Metabolomics**	**Magnetic-Resonance Force Microscopy**
Universal Memory	**Bacterial Factories**	**Enviromatics**	**Cell-Phone Viruses**	**Biomechatronics**

We discussed several inter-related enabling science and technology areas, including those identified in the Electric Power Research Institute’s (EPRI) Difficult Challenge Number 9 “Advances in Enabling Technology Platforms.” In what follows, we briefly highlight examples of six technology platforms:

- Sensors
- Biotechnology
- Smart Materials
- Nanotechnology
- Fullerenes
- Information Technology

These six platforms have been selected on the basis of past technology road mapping efforts to identify key underlying technologies, and the emphasis is primarily on long-term, limit-breaking developments. Higher-temperature alloys for turbines and steam generator components, for example, are certainly important, but their development is likely to follow from conventional, near-term refinement work and are not discussed here. On the other hand, more-innovative solutions to heat-based turbine problems—and much larger improvements—may result from

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[5] http://www.technologyreview.com/articles/05/05/issue/feature_emerging.1.asp

longer-term research on biomimetic ceramics or fullerene composite materials. The outlook and future possibilities for some of these technology platforms are summarized below:

Sensors

Industry has always been dependent on measurement instruments to ensure safe, efficient processes and operations, and today almost every engineering system incorporates sophisticated sensor technology to achieve these goals. But an increased focus on cost and efficiency, along with the growing complexity of industrial processes and systems, has placed new demands on measurement and monitoring technology: operators are asking for more-accurate data on more variables from more system locations in real time. The power industry, with its large capital investment in expensive machinery and its complicated, extremely dynamic delivery system, has an especially pressing need for advanced sensors that are small enough to be used in distributed applications throughout the power system. These sensors must be low cost, easy to install, and be combined with data management systems that can intelligently and securely handle the increased measurement data that will result. Continued development of digital control systems to replace far-less-accurate analog and pneumatic controls is a key research focus. Sensors that can accurately detect and measure a wide range of chemical species are needed, as are sensors and gauges robust enough to withstand the harsh temperatures and chemical environments characteristic of power plants. In addition, sensors must be configured so as to be easily powered. This seems an easy task—after all it is an electrical system. But it is not easy to power a sensor on a 345,000 volt transformer simply by running a wire. Advanced fiber optic sensors—devices based on sapphire fibers or fiber Bragg gratings, for instance—are especially important because of their versatility, small size, and freedom from magnetic interference. Overcoming today’s limitations on temperature, robustness, versatility, and size will facilitate attainment of a number of long-standing power system needs, including real-time characterization of plant emissions and waste streams, distributed measurement of transformer winding temperatures, and online monitoring of pH in steam plant circulation water.

In addition, sensors will monitor the electrical characteristics of the system (voltage, current, frequency, harmonics, etc.) as well as the condition of critical components such as transformers, feeders, circuit breakers, etc. The system will self-diagnose and reconfigure to achieve an optimal state. When a potential problem is detected and identified, its severity and the resulting consequences will be assessed and corrective actions taken. Examples of such potential problems would be a transformer with unusual gassing activity or a cable termination with higher than normal partial discharge.

In the context of distributed sensing and control systems, each individual local controller, will be comprised of one or more sensors and/or actuators, a microprocessor with some memory, and two-way communications. This configuration could be created by adding some computational power to what would otherwise be a simple regulator or a Proportional/Integral/Derivative (PID) controller with remotely adjustable bias, set point and/or gain. Conceptually, the added sensing and computational power would come from the distribution of the sensors, processors, and the memory in a central computer made up of parallel processors. For a system complex enough to require a powerful, parallel computer for real-time control, such a distributed configuration is only marginally more expensive and has the added potential for reducing the communication burden and providing greater resiliency to equipment failures.

The individual agents, represented by the software in each of the distributed processors, could, of course be “hard wired” as a complicated algorithm comprising what its designer believed to be all the possible eventualities that agent might have to handle. But this only increases the difficulty of the design process and leaves no margin for the unexpected, no possibility for improvement from experience under actual operation, nor any way to adapt to aging and temporary component failures in the plant. For any plant or system complex enough to warrant the distribution of computation along with control, it is computationally intractable to handle all possible combinations of capabilities, requirements, errors, and failure modes. It is better to design a control system that can adapt its own behavior reasonably and safely, if not always optimally. Given the time to act, experienced human operators do this remarkably well. Distributed intelligent control with adaptive agents can provide the same robust response to a fast-changing process in real-time.

Proof-of-concept generic models of electric power grid (including generation, transmission, distribution, and loads) coupled with communication, transportation, and financial networks, based on multiple adaptive, intelligent agents, were developed by EPRI during 1997-2002 as part of the EPRI/DOD Complex Interactive Networks/Systems Initiative (CIN/SI).

These experiments used in part complex adaptive systems (CAS) modeling and simulation which addressed two essentially different applications—distributed sensing and control, and the simulation of evolving business strategies. On the one hand, CAS were used to model the computational intelligence required to automate the distributed control of a geographically dispersed but globally interconnected power network. Intelligent agent-based distributed control may be the only practical way to achieve true real-time, dynamic control while getting full advantage from Flexible AC Transmission System (FACTS) and other high power, electronic devices, making maximum use of the intelligent sensors and wide area measurement systems (WAMS), and maintaining overall system security in a completely competitive economic environment. At the same time, the multiple agents-based model and simulation being developed will also serve as a “scenario-free” test bed for “what if” studies and computer experiments to provide insight into the evolution of the electric enterprise in response to various economic pressures and technological advances. Modeling the electric power industry in a control theory context is especially pertinent since the current movement toward deregulation and competition will ultimately be limited only by the physics of electricity and the topology of the grid. The CAS simulation will test whether any central authority is required, or even desirable, and whether free economic cooperation and competition can, by itself, optimize the efficiency and security of network operation for the mutual benefit of all.

During the next two decades, alternative infrastructure configurations using FACTS, sensors, and other WAMS equipment will be developed and introduced into service, these models can then be extended to agent-based models of the individual components of the grid at the level required to design and implement a real-time distributed control system operated by autonomous agents representing each of those components and physically embodied in the computational parts of the sensors and controllers at each location.

Biotechnology

Biotechnology has already proved extremely valuable in agricultural applications, with genetic optimization of food strains boosting crop yields considerably. Work on environmental biotechnology, such as the development of microbes that can process and destroy toxic chemicals, has also proved valuable. The results of industrial bioengineering research, ranging from corrosion-preventing biofilms to ethanol-based petroleum substitutes to biodegradable plastics, also hold great promise. Biomimetic materials—man-made substances that imitate the characteristics of natural substances or systems—are the subject of much research, as these materials often promise superior properties, functionality, and adaptability. Biomimetic materials may be used as direct substitutes for existing technologies, enabling technologies for which existing materials are inadequate, or as the basis for new applications. It is hoped that biomimetic catalysis will provide an economic alternative to costly enzymes needed for conversion of biomass or other cellulosic materials to ethanol. New, protein-based adhesives modeled on those produced by mussels and barnacles may form stronger bonds with slick materials in wet industrial environments.

Photovoltaic cells may be improved using light-gathering and self-assembly mechanisms suggested by plant photosynthesis. Hydrogen production and the desalinization of seawater are possibilities for a biomimetic process based on light-induced decomposition of water. Miming the ability of some biological systems to pump protons across cellular membranes may allow the development of advanced fuel cells that operate at room temperature. Realization of these biomimetic applications will generally require a better understanding of the natural processes being copied and substantial research on how similar functions can be engineered in a man-made system.

Smart Materials

Smart materials and structures (SMSs) have the unique capability to sense and physically respond to changes in their environments—to changes in temperature, pH, or magnetic field, for example. Generally consisting of a sensor, an actuator, and a processor, SMS devices based on such materials as piezoelectric polymers, shape-memory alloys, hydrogels, and fiber optics can function autonomously in an almost biological manner. Smart materials have already shown up in a number of consumer products and are being studied extensively for aircraft, aerospace, automotive, electronics, and medical applications. In the electric power field, SMSs hold promise for real-time condition assessment of critical power plant components, allowing continuous monitoring of remaining life and timely maintenance and component replacement. Control of power plant cycle chemistry could be done rapidly and automatically with smart systems to inject chemicals that counter pollutants or chemical imbalances. Control of NOx creation in boilers could be accomplished by adjusting the combustion process with sensor and activation devices distributed at different boiler locations. On the wires side of the business, smart materials could be utilized to monitor the condition of conductors, breakers, and transformer to avoid outages. Smart materials could also be used to avoid potentially catastrophic subsynchronous resonance in generating units and to adjust transmission line loads according to real-time thermal measurements. Critical capability gaps relate to integrating smart materials into sensors, actuators, and processors; embedding the SMS components into the structure to be controlled;

and facilitating communication between smart structure components and the external world. One exciting new development involves the application of shape-changing materials to overhead conductors. These materials could actually bend under heat in the opposite direction from the ground. As a result the sag of conductors under heavy current flow would not cause the conductors to sag into trees.

The growing list of smart materials includes materials that encompass a number of different physical forms and respond to a wide variety of stimuli:

- **Piezoelectric ceramics and polymers:** Materials, such as lead zirconate titanate ceramics and polyvinylidene fluoride polymers, that react to physical pressure. They can be used as either sensors or actuators, depending on their polarity.
- **Shape-memory alloys**: Metal alloys, such as nitinol, that can serve as actuators by undergoing a phase transition at a specific temperature and reverting to their original, undeformed shape.
- **Shape-memory polymers**: Elastomers, such as polyurethane, that actuate by relaxing to their undeformed shape when heated above their glass transition temperatures.
- **Conductive polymers**: Polymers that undergo dimensional changes on exposure to an electric field. These versatile materials can be used not only as sensors and actuators but also as conductors, insulators, and shields against electromagnetic interference.
- **Electrorheological fluids**: Actuator materials containing polarized particles in a nonconducting fluid that stiffens when exposed to an electric field.
- **Magnetorestrictive materials:** Molecular ferromagnetic materials and other metallic alloys that change dimensions when exposed to a magnetic field.
- **Polymeric biomaterials:** Synthetic, muscle-like fibers, such as polypeptides, that contract and expand in response to temperature or chemical changes in their environment.
- **Hydrogels:** Cross-linked polymer networks that change shape in response to electric fields, light, electromagnetic radiation, temperature, or pH.
- **Fiber optics:** Fine glass fibers that signal environmental change through analysis of light transmitted through them. Perhaps the most versatile sensor material, optical fiber can indicate changes in force, pressure, density, temperature, radiation, magnetic field, and electric current.

These materials, when matched to an appropriate application, provide the base functionality for simple as well as higher-level smart structures and systems. Sensory structures, such as optical fibers embedded in concrete bridge support pillars, only furnish information about system states; with no actuator, they are able to monitor the health of the structure but cannot physically respond to improve the situation. Adaptive structures contain actuators that enable controlled alteration of system states or characteristics; electrorheological materials, for example, can damp out vibrations in rotating mechanical systems when an electric field is applied. Controlled structures provide feedback between sensors and actuators, allowing the structure to be fine-tuned continuously and in real time; for example, aircraft wings instrumented with piezoelectric sensors and actuators can be programmed to subtly change shape to avoid flutter under problematic wind conditions.

In the future, smart materials and structures are expected to show up in applications that span the entire electric power system, from power plant to end user. Smart materials, in their versatility, could be used to monitor the integrity of overhead conductor splices, suppress noise from transformers and large power plant cooling fans, reduce cavitation erosion in pumps and hydroturbines, or allow nuclear plants to better handle structural loads during earthquakes. The following applications address broad areas where SMS capabilities are expected to produce important improvements for long-term gain.

Nanotechnology

The miniaturization push, led primarily by the makers of integrated circuits, is now being ratcheted from the micro-scale to the nano-scale, a size a thousand times smaller. Nanotechnology operates on the level of individual molecules and atoms—the basic building blocks of matter. By learning how to handle and assemble these blocks appropriately, researchers hope to develop materials and functional devices unlike any that presently exist. Biomedical applications include the use of nanocrystals as biological tags for DNA testing and for tracking the activities of organic molecules. Artificial molecules or other nano-scale structures may be used as miniature delivery vehicles to get drugs safely to just those tissues needing treatment. Nano-based improvements have also been conceived for biocompatibility, diagnostic imaging, and implant technology. Materials science is another fertile application area. Nanoparticles have a tremendous commercial future and are already being used in paints, scratch- and graffiti-resistant coatings, and industrial catalysts. Such materials are likely to see use in power plant applications, along with corrosion-resistant nanoparticle composites, less-brittle ceramics, and superstrong metal alloys. Hybrid photovoltaic cells based on conducting polymers and semiconductor nanorods have demonstrated good efficiencies in the laboratory and could dramatically reduce the cost of solar cells. Nano-scale electronics are the only hope for making circuits smaller than they are now. Basic transistors have already been created from organic molecules, but the feasibility of building complicated nano-scale electronic or mechanical devices is likely to be stymied for some time by fabrication problems, quantum effects, and communication difficulties.

The theme of the development of nano-technology in energy application technology is geared toward two main directions, "Nano-materials for Energy Storage" and "Nanotechnology for Energy Saving". Owing to the advantages of high reactivity, large surface area (200-2000 mO/g), self-assembly (1~3 nm active catalyst), super crystal characteristics (10~30nm nano-structures), and special opto-electronic effects of nano-materials for energy saving, advanced countries are heavily engaged in the development of energy related nano-materials.

There is an expectation that with nanotechnologies we will be able to develop power storage systems with higher energy density than current batteries by at least several times. Due to the small dimensions (5-20nm) and high specific surface area and special optical properties of nano-materials, nanotechnology for energy saving is expected to increase in the contact area of the medium. The will shorten response time, and improve thermal conductivity by a factor of two.

Nano-technology applications for energy storage include using nano-particles and nanotubes for batteries and fuel cells. Nano-technology is being used to better the performance of rechargeable batteries through the study of molecular electrochemical behavior. Newly patented lithium ion batteries that use nano-sized lithium titanate can provide 10-100 times greater charging / discharging rates in comparison with the current conventional batteries. Other new batteries that apply nano-technology could provide added power and storage capabilities by applying a concept based on mechanical resonance using a single MEMS device. Micro- Electromechanical Systems (MEMS) are devices that use the combined technology of computers and mechanical devices. This combined device improves the power density, offering significant benefits for portable equipment.

Several teams are currently working on hydrogen storage possibilities in carbon nano-tubes or nano-crystalline magnesium, which could be applied to the fuel cell sector. However, some experts believe that the expectations for carbon nano-tubes as a hydrogen storage material are not likely to be fulfilled. However, other nano-structured materials such as nano-Magnesium or nano-Magnesium-Alanate with nano-Titanium as a catalyst are very promising candidates for a storage material.

Many of the most important automobile and aircraft companies (Daimler-Chrysler, General Motors, Opel, Boeing, etc.) have scientific groups dedicated to the research of fuel cells. However, the fuel cell catalyst has drawbacks: they are both expensive and have limited efficiency. To solve these issues, research work is being done using honeycomb nano-structures mounted on carbon electrodes to reduce the use of noble metals and therefore increase the catalyst performance.

Current Status

Micro Fuel Cell: develop catalytic nano-particles for electrode (1~3nm), proton conductive nano-composite membrane (1~5nm channel), simulation and computation, and system miniaturization design.

High-Efficiency Energy Storage Device: develops high-energy density lithium battery and high power nano-structured materials for energy storage and devices (250 Wh/kg).

Photochemical Energy Conversion System: develop products related to battery raw materials, battery module system, and nano-materials for energy saving, and applications to power supply system.

Nano Heat Transfer Technology: establish measurement equipments, data simulation technology, a nano-fluid property databank and design technology for micro heat exchange systems.

Nano-crystal Application Technology: establish technologies for porous nanostructured electrode, oxidation and reduction chromophore, and dye molecule design technology for solar energy.

Fullerenes

A newly discovered type of carbon molecule, fullerenes exhibit extraordinary properties, including high strength, toughness, and both metallic and semiconducting electrical characteristics. The soccerball-patterned C60 and the cylindrical carbon nanotube have been considered by many to be the ultimate materials, and while only small amounts of fullerenes have yet been produced, researchers have suggested many potential applications. Most of these involve the carbon nanotube, a long, hollow string with tremendous tensile strength that could be wound into the strongest structural cable ever made. Use of shorter nanotube strings in metal, ceramic, or polymer composites would create stronger, lighter, more versatile materials than are currently available in any form. Structural beams, struts, and cables for airplanes, bridges, and buildings are envisioned, along with uses in rocket nozzles, body armor, and rotating machinery such as flywheels or generators. Electrical applications range from highly conductive (and perhaps superconductive) wires and cables to electron emitters in flat panel displays to magnetic recording media for data storage. Because nanotubes are incredibly thin and have such versatile electrical properties, they are seen as ideal building blocks for nanoscale electronic devices. Realization of such possibilities is highly dependent on developing processes for producing high-quality fullerenes in industrial quantities at reasonable cost and in finding ways to manipulate and orient nanotubes into regular arrays. Cost will almost certainly determine whether fullerenes will become a true universally used material or an esoteric, high-cost/high-value option for specialized applications.

Information Technology

Information technology (IT) —hardware and software that enable the effective collection and processing of data—have been a cornerstone of efficiency and business productivity for the last decade. Led by the computer, semiconductor, and telecommunications industries, IT has brought incredible improvements in the speed and effectiveness of communications, computations, transactions, and record keeping. Trends in business and personal technology—expanded interconnection, distributed systems, and automated control, for example—will place significant new demands on IT capabilities in future systems, especially the nation’s electric power infrastructure. Monitoring and controlling the highly dynamic power grid requires the application of data mining techniques to recognize patterns of healthy and problematic system operation. Data mining based on cutting-edge artificial intelligence concepts—neural networks, fuzzy logic, and rough sets, for instance—are the best bet for extracting usable knowledge from such complex networks. Improved interface displays that help operators visualize the state of the system are also needed to ensure that important information is not masked by a glut of irrelevant details. Virtual reality technology is expected to be of help in operations planning and maintenance training. Other IT applications involve improvement of such human aspects as internal knowledge retention and routing and the upgrading of information security and privacy protection.

IT and the Future

Technology must always be developed with the future in mind—a difficult task, since nearly all we know about the future is that change will be relentless. Still, analysis of fast-moving sectors—particularly communications, computers, and the Internet—tell us that certain trends in are in the ascendance for nearly all technical aspects of our business and personal lives. These trends will place significant demands on IT capabilities in future systems and infrastructures.

- **Expanded interconnection**. Large systems such as the Internet, satellite networks, and telephone and power grids will become larger, more complicated, and even more extensively interconnected. This will require not only more computing power but more-complicated operations software as well.
- **Data overload**. The easy availability of so much detailed information from so many sources has left users overloaded with a glut of unstructured data. Advanced techniques for sifting out the pertinent data and assembling it into useful information will be critical to keeping systems truly efficient.
- **Distributed systems**. Large systems such as the power grid will increasingly require data collection and device activation at “nodes” widely distributed across the system. This need will require the embedding of specialized sensors throughout the network, with communications connections to control centers or activation devices.
- **Automated control**. Real-time monitoring and control of large dynamic systems will be facilitated by embedded sensors and switches. However, the variables involved in such systems can be so large in number and their interactions so complicated that conventional analysis methods may be inadequate. Real automated and adaptive control systems will need to incorporate advanced concepts based on artificial intelligence techniques.
- **Interface issues**. For effective control and avoidance of errors, system operators need to be able to maintain a general awareness of many variables while focusing sharply on a few crucial or problematic situations. Man-machine interfaces that promote good, selective system visualization will be important, as will other human performance and training advances.
- **Information security and privacy**. The controlled sharing and security of critical information is essential to virtually all business operations. Widespread use of the Internet and other “open” communication pathways puts the security of businesses—especially those employing highly distributed, intelligent management networks—at risk to cyber threats and terrorist attacks.

A very pertinent area is the need for secure communication and in particular cyber security (Appendix B). The electric power grid is an essential enabler for the physical security of the nation. It is important to note that currently most stakeholders including the local and federal agencies more concerned with a physical attack such as the 9/11 attack than a cyber attack and have somewhat dismissed the effect of cyber attack on the grid. Yet in a complex system of systems it is easy for unanticipated interaction between particularly critical infrastructures to have significant impact. As an example, in the 9/11 flaws observed in the transportation system specifically the airlines were exploited for physical attack. The loss of power over a region even the size of a city such as New York City would significantly impact physical security starting with disorienting the society, significantly reducing situational awareness. It could essentially reduce or eliminate many sensors currently in place and cause a redeployment of security personnel that would be advantageous to attackers. Such a cyber attack is not as difficult as some imagine considering the move to Internet standard OS's and protocols. While there is a definite trend for many individual sites to install backup generators and for many sensors to have battery capability this will never completely replace the power grid and the local impact of a power outage.

Extend and or Move the "PowerZone": New Opportunities from Other Technical Areas and Enabling Technologies

The goal of researchers in the Galvin Electricity Initiative has been to target major new growth platforms. The teams involved in Task 3 Workshop sorted existing science and technology strengths and new opportunities to characterize platforms. Meeting the energy requirements of society will require the application of a combination of advanced technologies. Some of these can be identified, others are not yet known. The following list of critical enabling technologies that are needed to move toward realizing the vision of the power delivery infrastructure and electricity markets were developed as part of the Galvin Electricity Initiative:

- Automation: the heart of a "smart power delivery system"
- Communication architecture: the foundation of the power delivery system of the future
- Distributed energy resources and storage development and integration
- Power electronics-based controllers
- Power market tools
- Technology innovation in electricity utilization

These technologies, which are a subset of those discussed in this report, are synergistic (i.e., they support realization of multiple aspects of the vision). Aspects of some of these enabling technologies are under development today. However, a primary conclusion of this report is that each of these technologies calls for either continued emphasis or initiation of efforts soon in order to meet the energy needs of society in the next 20 years and beyond.

Automation: The Heart of a "Smart Power Delivery System. Automation will play a key role in providing high levels of security, quality, reliability, and availability (SQRA) performance throughout the electricity value chain of the near future. To a consumer, automation may mean receiving hourly electricity price signals, which can automatically adjust home thermostat settings via a smart consumer portal. To a distribution system operator, automation may mean automatic "islanding" of a distribution feeder with local distributed energy resources in an emergency. To a power delivery system operator, automation means a self-healing, self-optimizing smart power delivery system that automatically anticipates and quickly responds to disturbances to minimize their impact, minimizing or eliminating power disruptions altogether. This smart power delivery system will also enable a revolution in consumer services via sophisticated retail markets. Through a two-way consumer portal that replaces today's electric meter, consumers will tie into this smart power delivery system. This will allow price signals, decisions, communications, and network intelligence to efficiently flow back and forth between consumer and service provider in real time. The resulting fully functioning retail marketplace will offer consumers a wide range of services, including premium power options, real-time power quality monitoring, home automation services, and much more.

Communication Architecture. To realize the vision of the smart power delivery system, a standardized communications architecture must first be developed and overlaid on today's power delivery system. This "architecture" will be an open standards-based systems architecture for a data communications and distributed computing infrastructure. Several technical elements will constitute this infrastructure including, but not limited to, data networking, communications over a wide variety of physical media, and embedded computing technologies. This architecture will enable the automated monitoring and control of power delivery systems in real time, support deployment of technologies that increase the control and capacity of power delivery systems, enhance the performance of end-use digital devices that consumers employ, and enable consumer connectivity, thereby revolutionizing the value of consumer services.

Distributed Energy Resources and Storage Development and Integration. Small power generation and storage devices distributed throughout – and seamlessly integrated with – the power delivery system ("distributed energy resources") and bulk storage technologies offer potential solutions to several challenges that the electric power industry currently faces. These challenges include the need to strengthen the power delivery infrastructure, provide high quality power, facilitate provision of a range of services to consumers, and provide consumers lower cost, higher quality power. However, various impediments stand in the way of widespread realization of these benefits. A key challenge for distributed generation and storage technologies, for example, is to develop ways of seamlessly integrating these devices into the power delivery system, and then dispatching them so that they can contribute to overall reliability and power quality. The initial challenge for bulk storage technologies is to identify ways of effectively demonstrating the value proposition for these systems in a restructured industry. Both distributed storage and bulk storage technologies address the inefficiencies inherent in the fact that, unlike other commodities, almost all electricity today must be used at the instant it is produced.

Power Electronics-Based Controllers. Power electronics-based controllers, based on solid-state devices, offer control of the power delivery system with the speed and accuracy of a microprocessor, but at a power level 500 million times higher. These controllers allow utilities and power system operators to direct power along specific corridors – meaning that the physical flow of power can be aligned with commercial power transactions. In many instances, power electronics-based controllers can increase power transfer capacity by up to 50 percent and, by eliminating power bottlenecks, extend the market reach of competitive power generation. On distribution systems, converter-based power electronics technology can also help solve power quality problems such as voltage sags, voltage flicker, and harmonics. However, fully realizing these benefits requires advances in silicon-based voltage-sourced converters, devices based on materials other than silicon, and integrated control of multiple controller devices.

Power Market Tools. To accommodate changes in retail power markets worldwide, market-based mechanisms are needed that offer incentives to market participants in ways that benefit all stakeholders, facilitate efficient planning for expansion of the power delivery infrastructure, effectively allocate risk, and connect consumers to markets. For example, service providers need a new methodology for the design of retail service programs for electricity consumers. At the same time, consumers need help devising ways they can participate profitably in markets by providing dispatchable or curtailable electric loads, especially by providing reserves. And in the absence of long-held regulatory compacts, market participants critically need new ways to manage financial risk. To enable the efficient operation of both wholesale and retail markets, rapid, open access to data is essential. Hence, development of data and communications standards for emerging markets is needed. Further, to test the viability of various wholesale and retail power market design options before they are put into practice, power market simulation tools are needed to help stakeholders establish equitable power markets.

Technology Innovation in Electricity Utilization. Technology innovation in electricity utilization is a cornerstone of global economic progress. In the U.S., for example, the growth in GDP over the past 50 years has been accompanied by improvements in energy intensity and labor productivity. Improved energy-use efficiencies also provide environmental benefits. Development and adoption of technologies in the following areas are needed:

- Industrial electrotechnologies and motor systems
- Improvement in indoor air quality
- Advanced lighting
- Automated electronic equipment recycling processes
- Advanced refrigeration

In addition, widespread use of electric transportation solutions—including hybrid and fuel cell vehicles—will reduce petroleum consumption, reduce the U.S. trade deficit, enhance U.S. GDP, reduce emissions, and provide other benefits.

These technologies, which are a subset of those discussed in the Task 3 primer report, are synergistic (i.e., they support realization of multiple aspects of the vision). Aspects of some of these enabling technologies are under development today. However, a primary conclusion of this report is that each of these technologies calls for either continued emphasis or initiation of efforts soon in order to meet the energy needs of society in the next 20 years and beyond. Non-utility areas where teams investigated for other technologies that could be mined for application to build a better system for the future included but were not limited to the following:

- Information and network technologies
- Software and simulation technologies
- Nanoscience and Nanotechnology
- Superconductivity
- Advanced materials including aerospace composites

- Bioscience and Biotechnology
- Environmatics
- Biomimesis

Examples of New Technology Opportunities

In addition to areas summarized in the Task 3 Workshop Primer and those indicated above, several more areas were identified during the Task 3 workshop. To show how these relate to their underlying science and engineering content we map them onto a “Technology Space Map,” each vertex of which represents one of three fundamental science areas, namely Physical Science, Life and Bio-Science, and Information Science (see Figure 2-1).

The careful choice of these three areas aims to represent the technology landscape in the context of objectives for the Galvin Electricity Initiative. Informed by the consumer-centered strategy, the first part of the process is to understand—in depth and strategic importance—the current technology strengths of the power industry sector. These are extrapolated along both future consumer needs, scenarios (identified in Task 1) and business and technology lines. They lead to identifying the sector’s technology PowerZone in a three dimensional technology space, akin to a phase diagram in metallurgy. Here we used dimensions of 1) physical sciences and engineering, 2) information and system science, and 3) biotechnology and bio/life sciences. For other applications outside of this context researchers have employed dimensions of materials science, manufacturing and process engineering, and information sciences. These can, of course, be changed to suit the industry or business; for example, in the biotechnology industry applications researchers replaced manufacturing with life sciences. These area depicted in the triangle was identified as the most pertinent in defining the technology space for the future power system.

The electricity enterprise technologies are largely based on inventions of Edison, Tesla, Westinghouse and others around the turn of the century. These evolved through history with regulations, dominant suppliers, and the grid itself. The technologies in place as legacies and the platform used to make incremental improvements were located in the physical science corner with a very slow diffusion upwards towards information science. The technologies that can create the 21st century “meta-system” to meet all of the consumer needs, range all across the science and engineering landscape.

3

TECHNOLOGY MAPPING AND ASSESSMENT

Identifying new science and technology-based opportunities are critical activities to meet the needs and aspirations of today's consumers and the broader society. From incremental improvements to existing core technologies to long-term threats and opportunities, society and businesses need to understand and manage more science and technology options than ever before. In order to address these for this Initiative, the next stages in Task 3 were: 1) strategic enhancement of the PowerZone—extrapolation of current needs, followed by 2) extension of the PowerZone— building for the strategic future based on today's foundation, and 3) identification of New Technology Opportunities.

To achieve this, we utilized the Technology Foresight Dynamics™ (TFD), a perspective and process that sorts the options, identifies new science and technology opportunities, and develops coherence between short- and longer-term R&D opportunities (see Figure 3-1). The process leverages the insight of experts to identify current science and technology strengths and, with outside information, develops foresight from the interaction of industry, society and technology trends. These yield enhancement and extension of the current technology structure and new technology-based opportunities.

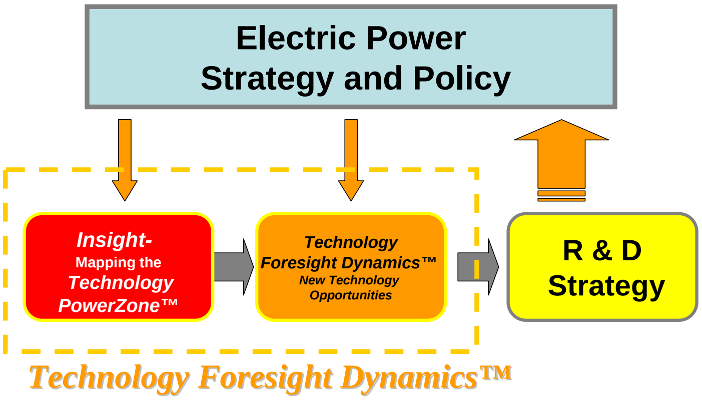


Figure 3-1
Technology Foresight Dynamics^{TM}

The process starts with, and returns to, the overall identification of consumer needs, which are resident in applicable non-traditional electric industry science and technology. The results are inherently strategic. Within this context, the process has two distinct parts with different perspectives – insight and foresight. Informed by our assessment of future consumer needs to be developed in other tasks, the first part of the process is to understand, in depth and by strategic importance, the current electricity technology strengths and trends; these are extrapolated along both business and technology lines. These define the electricity service technology PowerZone.

The next stage is the TFD process itself. This process takes a very different perspective by looking into the future (10 to 20 years out) in Technology areas totally outside of the electricity sector. The process is illustrated in the accompanying figure. Once the key questions and issues were defined and the scope of the process determined, the workshop participants were divided into small teams (4–5 people) by electricity service function. Breakout sessions focused on the above steps. Using examples of technology opportunities drawn directly from the energy sector, participants were divided into parallel breakout sessions where they will systematically address each step.

In the Task 3 Workshop, a broad range of stakeholders were engaged to identify a few (less than 10) critically important highest priority innovation nodes. While not an exhaustive list of the challenges that must be overcome, these are crucial to success, and thus, may ultimately become the focus of the Phase Two efforts. The highest priority nodes will create a unified picture of critical goals and challenges for meeting 21^{st} century service expectations. At the Task 3 workshop, participants:

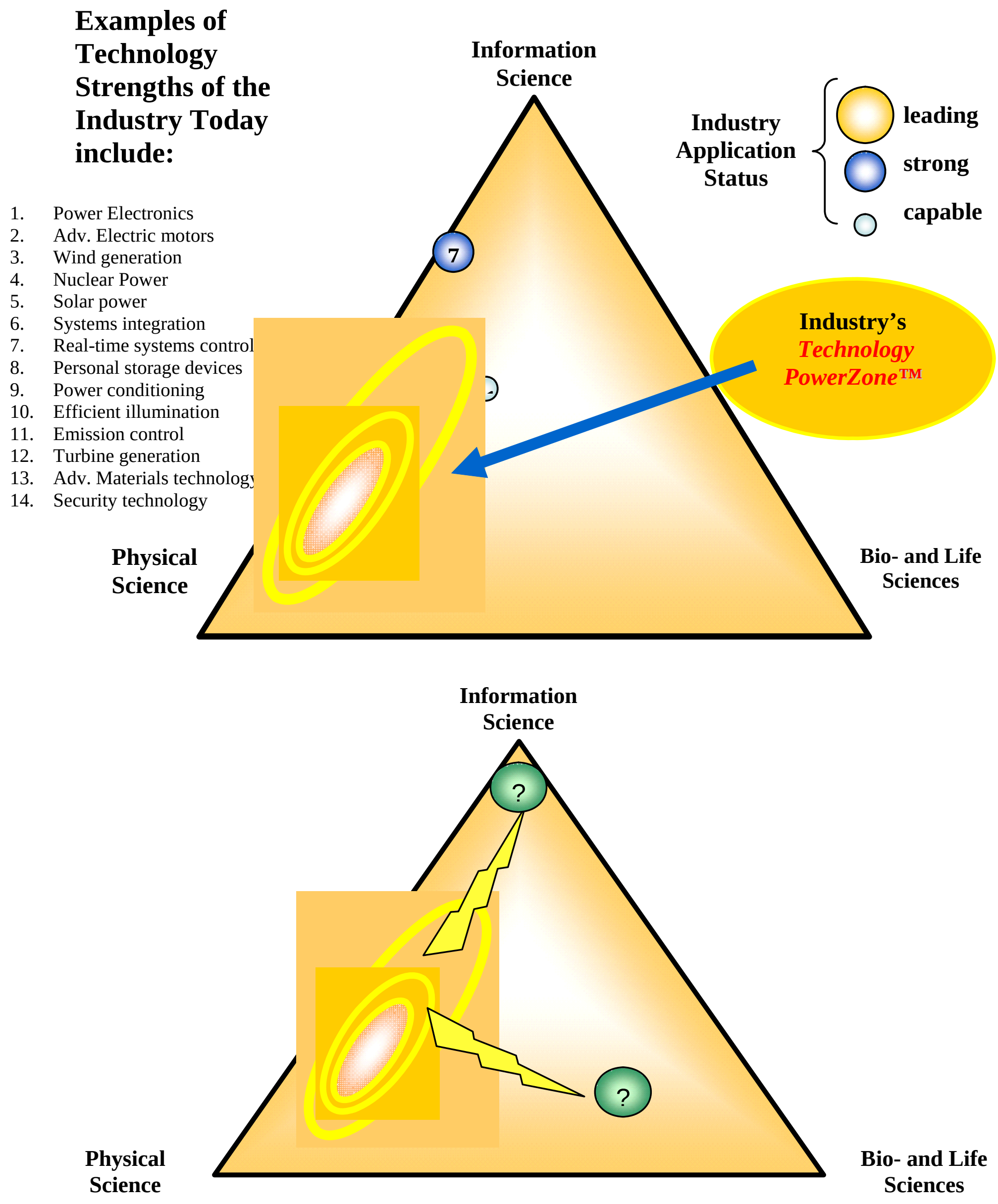
1. Formed groups of 4–5 as indicated above; mixed organizations and areas of expertise represented
2. Identified a few (5–7) key technologies per group that make the highest impact.
3. Expanded the key technology list (12+) with related technologies that drive, use, or synergize with these.
4. Mapped these onto the Technology Space Map™
5. Circle size for impact potential: leading (large), strong (medium), or capable (small)
6. Shaped the Technology PowerZone™
7. Described where the market, policy and technology trends are likely to move the PowerZone in the next 5–7, 10, and 20 years.
8. Shared results with all participants.

The specific enabling science and technology areas addressed are indicated above. The teams then looked for interactions between electricity energy service trends and technology dynamics to develop a portfolio of science and technology opportunities in various categories pertinent to the Galvin Electricity Project. The whole group then reconvened to share, integrate, and analyze the outputs of the sector teams. These overall opportunities were then mapped against the assets of the system (taken in the broadest sense). The outputs of this step were then mapped back to the current technology strengths from the insight phase. This overlay yields three types of opportunities and actions:

1. Strategic enhancement of the Technology PowerZone™. This extrapolates current S&T and business needs reflecting incremental opportunities.
2. Extension of the Technology PowerZone™. The extension describes the strategic future based on today’s foundation.
3. New Technology Opportunities. Developed within current units, this identifies new development or alliance partnering prospects not currently within the planning horizon.

PowerZone: Technology Mapping and Assessment of Current Strengths

Researchers first identified the key technologies employed by the industry today; those that make it effective and innovative. With this ensemble, they performed "static" and "dynamic" technology analyses. For the former they mapped the technologies on a technology "phase diagram," mapping each technology on the diagram based on its use of the underlying science and engineering of physical science, bio- and life science, and information science. The centroid of these on the diagram is the industry's current Technology PowerZone™ as illustrated in Figure 3-2.



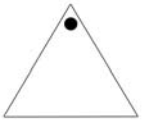
Examples of Technology Strengths of the Industry Today include:

1. Power Electronics
2. Adv. Electric motors
3. Wind generation
4. Nuclear Power
5. Solar power
6. Systems integration
7. Real-time systems control
8. Personal storage devices
9. Power conditioning
10. Efficient illumination
11. Emission control
12. Turbine generation
13. Adv. Materials technology
14. Security technology

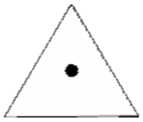
Figure 3-2
Extending or Moving the Technology PowerZone: The Key Strategic Technological Innovation Questions for the Electricity Enterprise

Extending the PowerZone

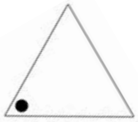
Next, a list was generated of emerging and new technologies that might possibly help drive innovation for the future of the industry and extend or move the PowerZone. The technologies identified, together with their location on the map, as most important to reaching the goals of this project, are illustrated below:



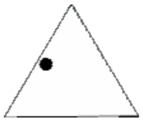
Information and Network Technologies. This has been identified as the most significant area to mine for enabling technologies and should be considered as a technological imperative. It includes use of data mining and knowledge management, advanced algorithms, systems dynamics, complexity theory, cognitive modeling, and simulation technologies. In particular with regard to power systems it involves employing sensors, communications and computational ability. These synergize with all of the other technologies, such as being combined with distributed sensors, including embedded nanosensors for measuring local currents, fields, etc. Technology developed in recent years for warehousing, and non-intrusive inspection of containers at seaports (for example) have shown how data can be collected and processed over significant areas.



Nanoscience and nanotechnology (NSNT). Several recent workshops, (including a recent Electric Power Research Institute (EPRI) workshop) have included considerations of the possible applications of NSNT in the utility industry. Applications identified include: photovoltaics, sensors of various kinds, including chemical detectors for pollutants, high strength-to-weight ratio materials. Perhaps it is appropriate to mention catalysis here: this is a pervasive field, with important (and pacing) applications in the development of an advanced electric utility system. Nanotechnology is not the only component in the identification and development of new catalysts, but there have been some notable successes.

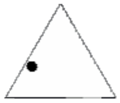


Superconductivity has been explored for some time, and the first model electricity transmission line was built at Brookhaven many years ago. The dependence on the liquid helium coolant was a major inhibitor. The appearance of the new class of superconductors with transition temperatures above the boiling point of liquid nitrogen excited the community, and there have been a number of large-scale demonstrations of the technology, specifically a transmission line in Detroit, and several Superconducting Magnetic Energy Storage (SMES) models. Superconductivity has potential application in conductors, storage, motors, generators, and current limiters. However, a variety of (mostly engineering) problems have resulted in a much slower progress towards general application than had been hoped. However, there are other possible directions, including for example Josephson Junctions. (Note: high field magnetic fields produced by superconducting magnets are widely applied in practice). The major opportunity in is the ability to transmit DC at high voltages over long distances with no losses.



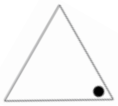
Advanced materials and aerospace composites have led the general field of high strength-to weight materials coupled with other optimized properties (corrosion resistance, impact resistance, fatigue resistance, and so forth). Some areas of this appear already: turbine blades, compressor blades, wind turbine blades, etc.

However, there are major opportunities in the application of this class of materials to overhead transmission lines (e.g., increased ampacity with existing tower infrastructure). Nanotechnology is leading to further advances in this class of materials.



New technologies of interest obviously include the new approaches to **photovoltaics** that have appeared recently, with the potential of producing low-cost cells and cell assemblies with modest but acceptable efficiencies (of the order of 12%). These hopefully can be used for applications such as large area roof-top assemblies. Also there are recent reports of higher efficiency semiconductor materials and improved optical systems for light gathering.

Biotechnology is, of course, a very large area. In relation to this area, there have been several studies of the production of liquid fuels through biotechnology routes. The new directions are concerned with the genetic modification of feed stocks to optimize the eventual product. Longer term and with more significance, systems biology and advanced bioinformatics can lead to models for complex multi-grids with multi-energy source modality, overlapping distribution networks, higher efficiency (biosystems are "solutions" to multivariable non-linear optimizations) and more robust performance with respect to exogenous and endogenous system failures and assaults. The mammalian immune system is an example of this class of systems.



Biomimetics means examining the ways in which biological systems achieve positive results, and then seeing how these might be translated into engineering approaches. Examples include the ability of biological systems to form components with specific mechanical applications – bones in vertebrates (hydroxyapatite in human beings); calcium carbonate as calcite or aragonite in marine shells. Analysis of these processes is well advanced, but only limited applications have appeared so far.

Technology Interaction Matrix™ (TIM)

Task 3 researchers performed a dynamic technology analysis on these new and emerging technologies through the use of the Technology Interaction Matrix™ (TIM). This is a matrix of all the technologies, from basic to product-ready, that the team identifies as potentially important to the future of the industry or market segment. The TIM and the rules for filling it out are shown, with the example technologies in Table 3-1. Once this was done, the column score totals are a semi-quantitative estimate of the strength of that technology to drive all of the others, yielding a "source technology score." Likewise, the row scores estimate the degree to which that technology utilizes other technologies to move forward—the "technology utilization score."

Table 3-1
Example Summary of the Combined Results of One of the Teams in Task 3 Workshop

Technology Utilization Score

Technology Source Score

	Advanced Materials	Nanotech	Meso & Micro-scale Dev.	Adv. Info. Science	Bioscience	Enviromatics	Advanced Sensors	Computing Systems	Economics	Policy	TOTAL
Advanced Materials	**0**	**3**	**3**	**10**	**3**	**0**	**0**	**3**	**3**	**0**	**25**
Nanotech	**10**	**10**	**3**	**10**	**3**	**0**	**0**	**3**	**3**	**3**	**45**
Meso- & Micro-scale Devices	**10**	**10**	**3**	**3**	**3**	**0**	**0**	**3**	**3**	**0**	**35**
Adv. Info. Science	**0**	**0**	**0**	**3**	**0**	**0**	**0**	**3**	**0**	**0**	**6**
Bio-Science	**3**	**10**	**10**	**10**	**0**	**3**	**3**	**3**	**0**	**3**	**45**
Enviromatics	**0**	**3**	**3**	**10**	**10**	**0**	**10**	**3**	**3**	**10**	**52**
Adv. Sensors	**3**	**10**	**10**	**3**	**3**	**0**	**0**	**0**	**0**	**0**	**29**
Computing Systems	**3**	**3**	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**9**
Economics	**3**	**3**	**0**	**3**	**3**	**3**	**0**	**3**	**3**	**3**	**24**
Policy	**0**	**0**	**0**	**3**	**3**	**10**	**0**	**0**	**10**	**0**	**26**
TOTALS	**32**	**52**	**32**	**58**	**28**	**16**	**13**	**21**	**25**	**19**	

This matrix captures the positive interactions among the ensemble of new technologies. It enables researchers to analyze which ones are the major drivers of the others and which ones utilize the others to move forward. The results of this evaluation of technology relationships are plotted on the Technology Interaction Matrix™, which is a map that resolves the type of technology (see the plot in Figure 3-4) and the intensity of its interaction in the ensemble.

Table 3-2
Summary of Results for Task 3 Combined with Those Obtained in Task 2

	Safety Products	Environ. Friendly	Hardened Appliances	Microgrids	Power Quality	Efficient Appliances	Electro-technologies	Increased Power Flow	Storage	Distributed Generation	Power Electronics	Grid Interf.	Control Hierarchy	DC Systems	Sensors	Comp. Ability	Comm.	Total
Safety Products	3													3	3			9
Environmentally Friendly Devices		10				3					3				3			19
Hardened Appliances			10		10	3	10		10	3	10			10				66
Microgrids				3	3		3	3	3	10	10	10	10		10	10	10	85
Power Quality Technologies			10	10	10		3		3	10	10	3	3	10	3		3	
Efficient Appliances		3			3	10	10				3							
Electrotechnologies						10	3		3	3	10			3				
Increased Power Flow				3				10	3	3	10	10	3	3	10	10	10	
Storage			3	10	3			3	10	10	10	3	3	10	3	3	10	
Distributed Generation								3	10	10	10	10	10	10	10	10	10	
Power Electronics				10	3	3	3	10		3	10	10	10	10	3	10	3	88
Grid Interface				3						3	3	10	3		3	10	10	45
Control Hierarchy								3		3	3	10	10		3	10	10	52
DC Systems			3	3	3	10	10		3	10	3	3	3	10			3	64
Sensors	3							3				10	10	3	10	3	10	52
Computational Ability				3				3				10	10		3	10	10	49
Communications						3		3				10	10		10	10	10	56
Total	6	13	26	45	35	42	42	41	45	68	95	99	85	72	74	86	99	

Table 3-3
Technology R&D Matrix Combing Results for Tasks 2 and 3 Summarizing the Results for the Interaction Matrix for Table 2

Pre-production	Application	Synergy	Feeder	Foundation
Safety Products	Micro Grids	Efficient Appliances	Storage	Sensors
Environmentally Friendly Devices	Power Quality	Electro-technologies	Distributed Generation	Communications
Hardened Appliances		Increased Power Flow	Power Electronics	Computational Ability
			Grid Interface	
			Control Hierarchy	
			DC Systems	

Technology Interaction Plots and R&D Strategies

A useful format for visualizing and understanding these estimates for “source technology score” and “technology utilization score” is to plot the two scores as shown in Figure 3-3 to Figure 3-5. This disperses the technology in several useful ways. The distance a technology is from the origin shows how interactive it is in the whole ensemble of technologies under consideration. A technology near the origin is isolated and should be dealt with on its own business merits. Technologies farther out from the origin are very important and disperse out from the foundation technologies in the lower right to product-ready technologies in the upper left of the X–Y plot.

The most interesting and strategically important technologies usually map between these two and are called “synergy” technologies (e.g., nanotechnology). We have found that this matrix approach helps sort different types of technologies and also brings out the most powerful technologies for the future of the industry or market sector.

The column and row scores from the Technology Interaction Matrix are these plotted in a scatter-type plot with the column scores, representing a technology’s capability to drive others, on the X-axis and the row scores, representing a technology’s utilization of others, on the Y-axis. A characterization of the different technologies is suggested by the labels shown.

The technologies then can be “typed” by how they are dynamically coupled to the others: foundation, feeder, synergy, application, and pre-product. This analysis can be used to identify actions and priorities for all of the technologies being evaluated.

For example, foundation and feeders are very basic and fundamental and usually are advanced in universities, national labs, industry centers, etc. Synergy technologies are very important and drive the industry's technological progress and innovation. These require commercial development, management, and investment.

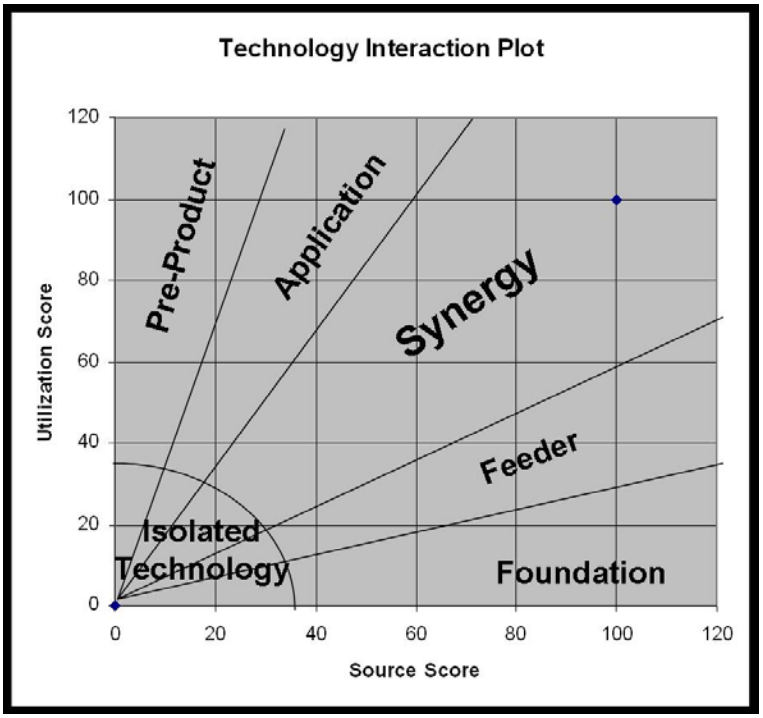


Figure 3-3
Technology Interaction Plot

Application and pre-product technologies are those that aggregate and use many other technologies and are usually ready for product concept development, demonstration projects, applications, etc. As an example, a summary of the results of Task 3 Workshop is shown in Figure 3-4.

The column and row scores show a strong dispersion of strategic types of technology with, for example, advanced information and systems sciences being a strong source technology and advanced sensor devices being a technology that depends on components of other technologies as it advances.

The final step was to rate the technologies against the industry's current strengths (the "Power Assets") and highlight those opportunities that can exert the greatest leverage on the current strengths. At this point, it is usually straightforward to identify several attractive technology opportunities. This is where technical, policy experts and business leaders integrate the resulting Technology Foresight into the R&D strategy (see Figure 4). The selected technologies, the future Technology Space Map and the overall TIM are background; they should lead, with other planning inputs, to actionable programs, new R&D, new product development projects, and new business development activities supporting the overall strategy.

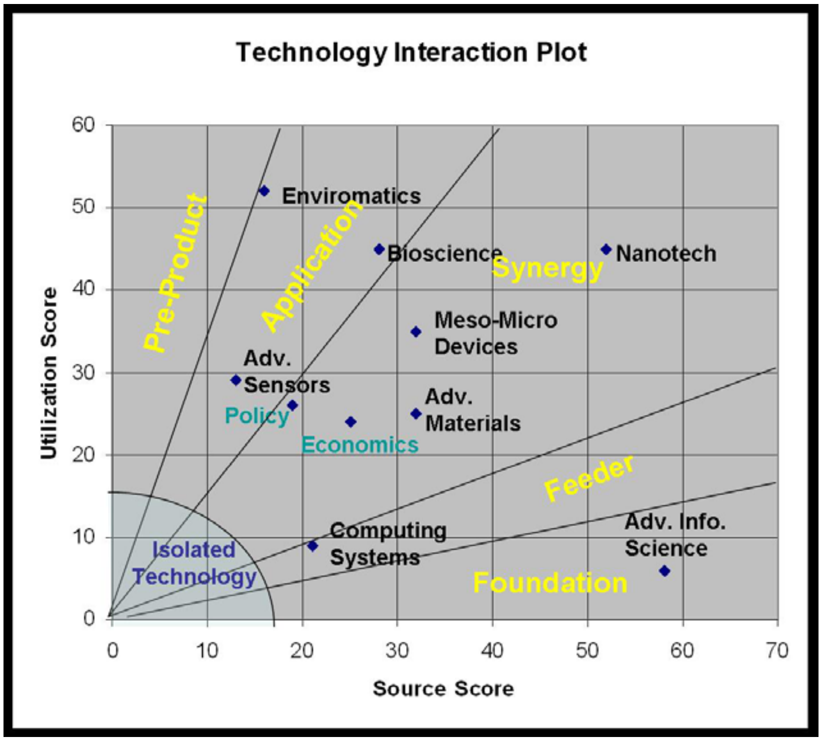


Figure 3-4
Example of the Technology Interaction Plot

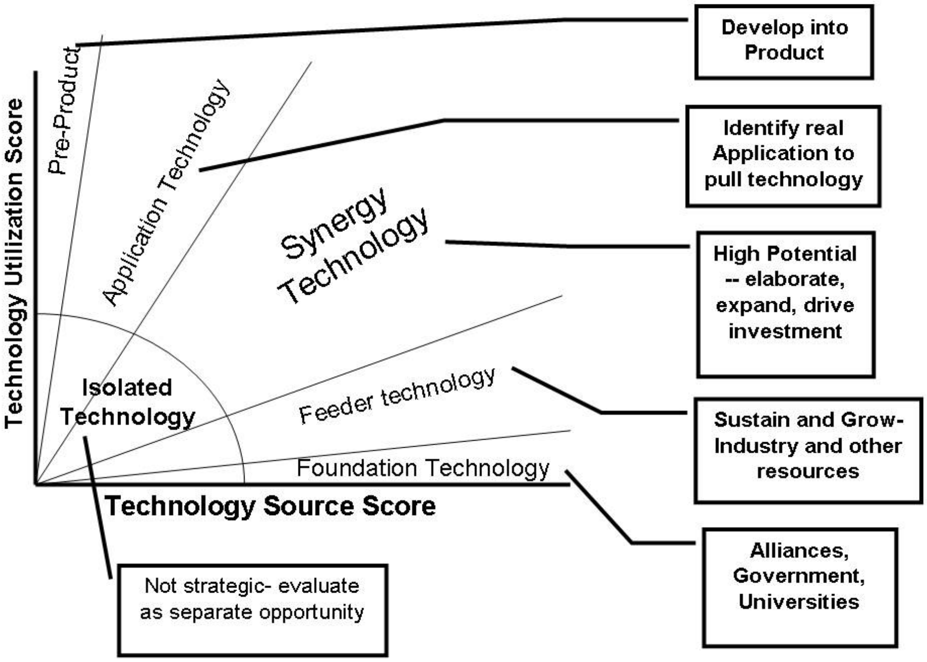


Figure 3-5
R&D Strategies

Examples of Selected Technologies

To highlight selected R&D areas, the workshop teams selected a few (under a dozen) technologies that it sees as most important to its sector and map these back onto the Technology Space to give a strategic picture of where the important future technology areas will be and how they map relative to the industry's PowerZone.

To highlight a few of these scenarios and R&D opportunities, consider the following four examples that may be achievable with in a decade as proof-of- concept pilot demonstrations:

Example 1: Limited supply of fossil fuels scenario

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:

- 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 persistent consumer demands are:

- Reliable, fail-safe energy system
- Affordable, efficient energy management
- Security and freedom
- Environment friendly

The teams mapped the following Solution/Technologies to extend the existing PowerZone (see Figure 3-6):

- Micro-grid Technology
- Generation—Nuclear Fusion
- Distribution—Carbon Nano Technology
- Storage—Advanced Battery Technology
- Energy Management—EM Software

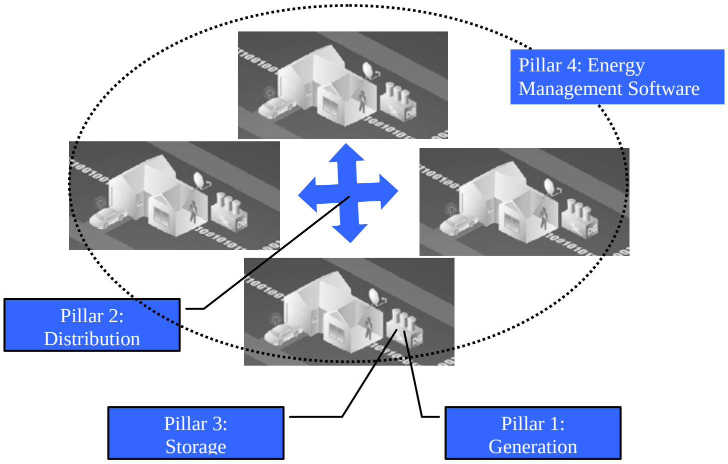


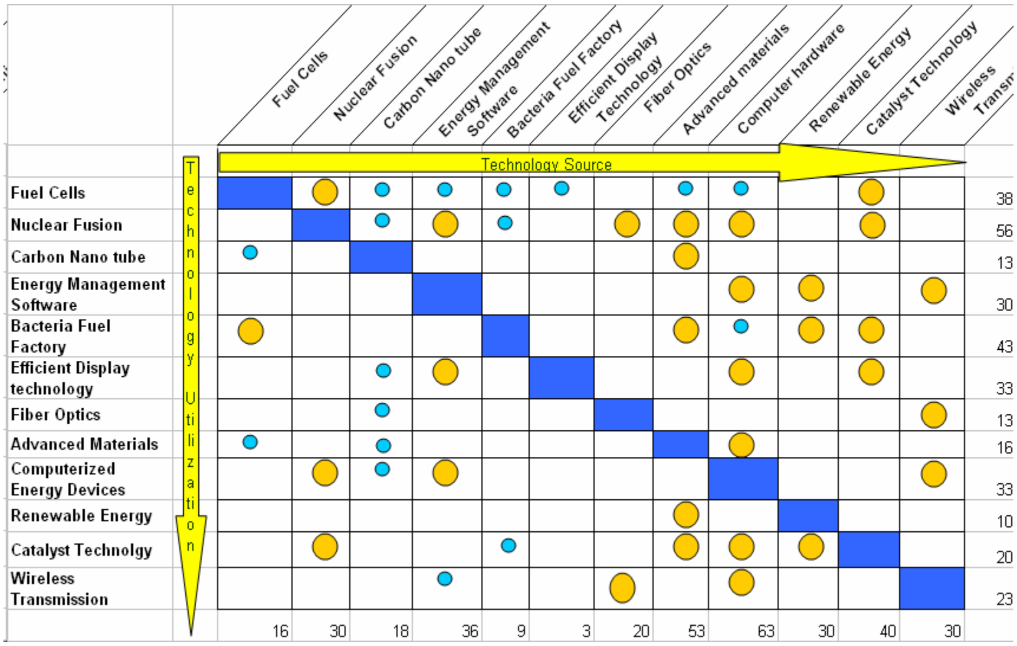
Figure 3-6
Solution/Technologies to Extend the Existing PowerZone (source: EPRI and Primen, 2001)

Technology opportunities that were identified include:

- Massive redundancy provides seamless responses to any energy disruption
- Reduction of demand from centralized power grid system
- Active consumer choices to optimize the performance of 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 3-7.

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.



	Fuel Cells	Nuclear Fusion	Carbon Nano tube	Energy Management Software	Bacteria Fuel Factory	Efficient Display Technology	Fiber Optics	Advanced materials	Computer hardware	Renewable Energy	Catalyst Technology	Wireless Transm	
Fuel Cells	■	●	•	•	•	•		•	•		●		38
Nuclear Fusion		■	•	●	•		●	●	●		●		56
Carbon Nano tube	•		■					●					13
Energy Management Software				■					●	●		●	30
Bacteria Fuel Factory	●				■			●	•	●	●		43
Efficient Display technology			•	●		■			●		●		33
Fiber Optics			•				■					●	13
Advanced Materials	•		•					■	●				16
Computerized Energy Devices		●	•	●					■			●	33
Renewable Energy								●		■			10
Catalyst Technolgy		●			•			●	●	●	■		20
Wireless Transmission				•			●		●			■	23
	16	30	18	36	9	3	20	53	63	30	40	30	

Figure 3-7
Technology Interaction Matrix and Ranking of the Various Technology Opportunities for Example 1

Example 2: Grid-Independent Community

The teams considered environmentally friendly and self-sustaining energy configurations, with the use of advanced communications and power networks; the system requirements are to be:

- Efficient and 100% Reliable
- Environmentally Friendly
- Ubiquitous

Consumer needs include local high-reliability energy and telecom nodes, along with common storage for nodes allow them to exist independently as needed. Other requirements are to connect with and leverage the energy and telecom grids as needed

Conclusions for Example 2 included the following solution/technologies:

- Move toward local power generation
    - Allow individual units (or groups of) to be energy generators
    - Allow groups to form Energy Co-ops
    - Focus on renewable and variable forms
- Use local power storage
    - Store cyclical power generation

  - Draw off grid when most cost effective
- Increased situational awareness, monitoring and detection:
  - Monitor the people energy and communication needs/usage and the overall environment
  - Detect and alert anomalies and changes
  - Based on ubiquitous telecommunication networks

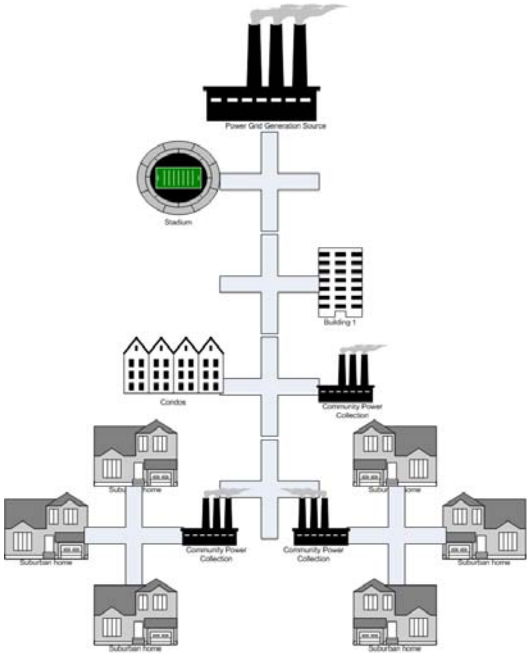


Figure 3-8
Grid-Independent Community

Example 3: Consumer-Centered, not Central-Station- and Macro-grid Focused

In this example, concentrating on local area networks and micro grids, 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 3-9. These technologies range from advanced power system control to fast multiresolution 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 3-10.

1. Advanced power system control
2. Intelligent load-shedding and demand-response
3. Green micropower generation
4. Storage devices (end-use)
5. Device-responsive power conditioning (end-use)
6. Price-sensitive appliance controller (end-use)
7. Standard power interface (end-use)
8. Willingness-to-pay market research
9. Closed-loop economics
10. Fast multiresolution modeling and simulation

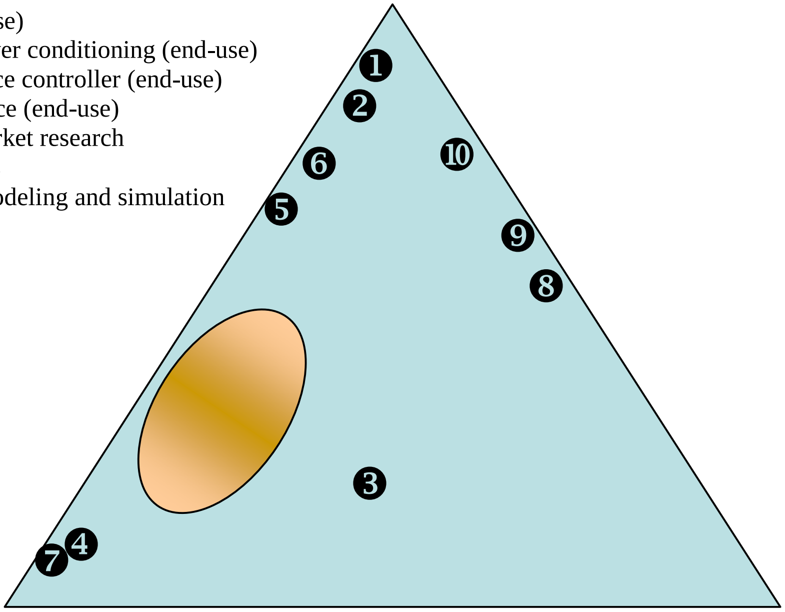


Figure 3-9
Transition to Consumer-centered, not Central Station and Macro-grid Focused (Example 3)

Isolated Technologies:
Standard power interface
Device-responsive power conditioning

	PowerZone	PowerZone Extension	New Technologies
Application		Storage devices (end use)	Intelligent load shedding and demand response Advanced power system control
Synergy		Alliances, Government, Universities	Price-sensitive appliance controller Closed-loop economics
Feeder			Willingness-to-pay market research Fast multiresolution modeling and simulation

Figure 3-10
R&D Strategy Matrix for Consumer-centered, not Central Station and Macro-grid Focused (Example 3)

Example 4: Granular Semi-Autonomous Architecture

This is a new system architecture with:

- Smaller and distributed “chunks” of the system
- DC Interconnects – 400kV, ~2.5kA
  - Less sensitive to power swings
  - Easier to add DER/Renewables
- Fault Tolerant - Looped Distribution Systems
- Migrate away from radial distribution with loops
  - Analogy with FPDs
- Fractal grid
  - Self similar at different scales
  - Modular sources – lego power bricks

    Blocks of fuel cells

    Self-configured

Interoperability

Standards without centralized control

- Plug & Play Smart Appliances/Devices
    - Information bus in the power plug
    - V to G self plugging
- Distributed Generation

    Vehicle to grid (V2G)

    Solar Energy

    Wind
- Distributed Storage
- Thermal

    Buildings as net producers of energy

    Building's high thermal inertia

    Water pumping
- Analogy: Cell model: mitochondria/saccharides => robustness

As indicated earlier, in Figures 3-2 and 3-9 we map the technology opportunities in the technology space, and then extend or move the Technology PowerZone:

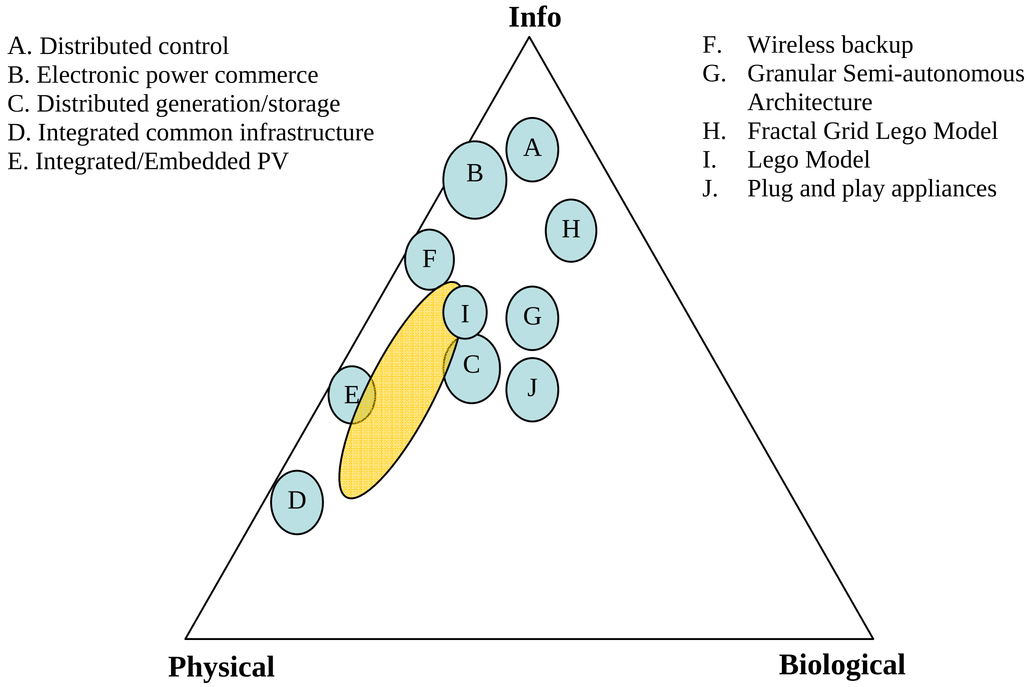


Figure 3-11
Technology Space Map for the Granular Semi-Autonomous Architecture

Example 4 highlights several pertinent areas including development of those technologies depicted in Figure 10 and judicious R&D strategy (from foundation to feeder to synergistic, etc.) for those technologies as shown in Figure 3-12.

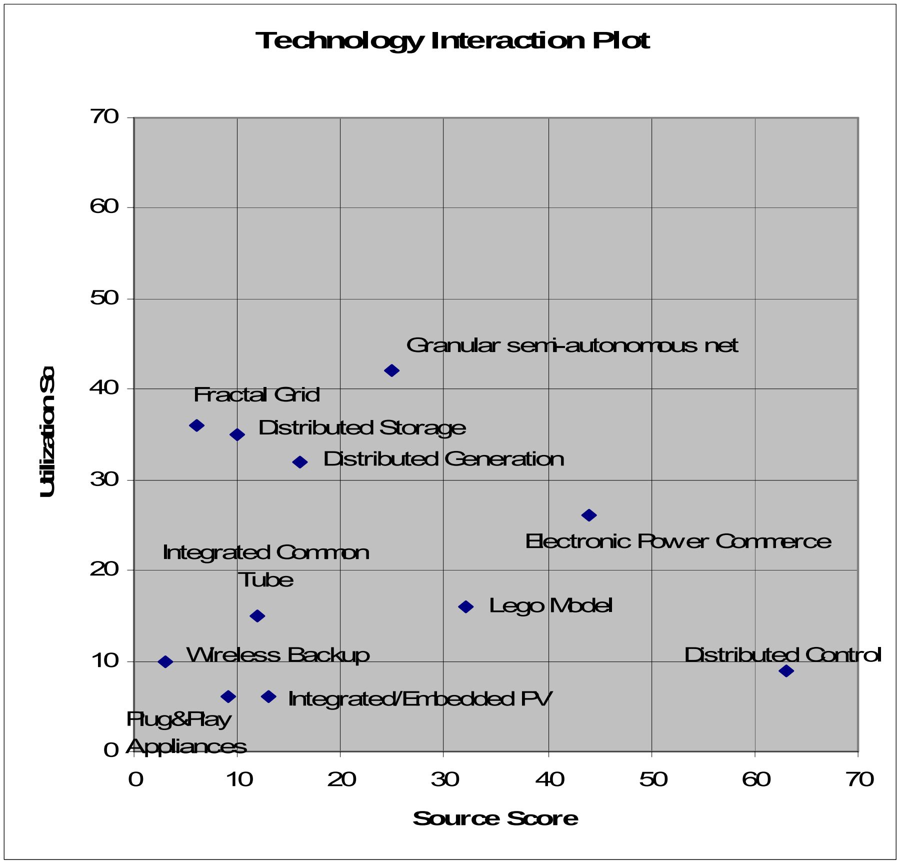


Figure 3-12
Technology Interaction Plot for the Granular Semi-Autonomous Architecture

Summary

The Task 3 Workshop and our process has led to clearer insight on current science and technology assets when looked at from a consumer-centered and future perspective, rather than just incremental contributions to today's system and products.

New opportunities applicable to core electricity stakeholders or those involving new ventures based on science and technology strengths were captured through the foresight process and are summarized in this report.

As shown in the four selected examples, additional innovative technologies using Bio-fuel Systems, Distributed Generation and Storage systems integrated with Advanced Information

Systems for Network management will allow further transitions from the current PowerZone for the following R&D Strategy Matrix.

Application		2. Adv Gen Systems 8. End-use Efficiency	6. Micro-grids
Synergy		3. Dist.Gen and Storage 5. AC/DC control/interface 7. Plug-in hybrid vehicles	
Feeder	4. Adv. Info Systems for network ops and mgt.		1. Biofuel systems
	PowerZone	PowerZoneExtension	New Tech Options

(Incl. 9. Benchmarking for Best Practices)

Figure 3-13
R&D Strategy Matrix for Bio-fuel Systems, Distributed Generation, and Storage Systems Integrated with Advanced Information Systems for Network Management

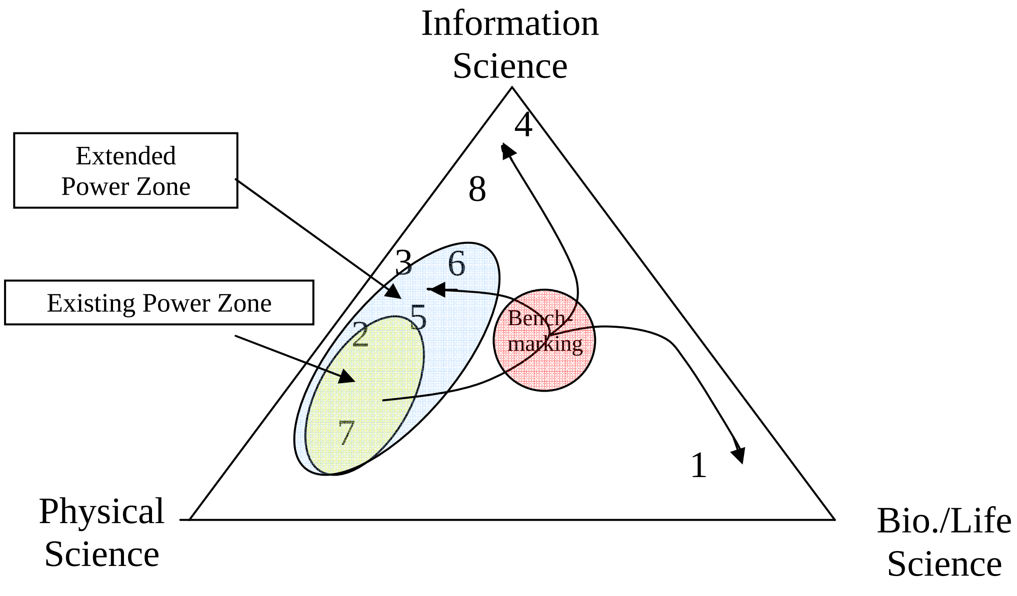


Figure 3-14
Technology Space Map for Bio-fuel Systems, Distributed Generation, and Storage Systems Integrated with Advanced Information Systems for Network Management

As indicated earlier, the next steps involve identifying requirements for an in-silico simulation testing via the use of advanced simulation with sub-system component functionalities from today's state of the art in distributed power sources, transmission modalities, conditioning technology, etc. Based on these outcomes, a small-scale breadboard demonstration (with a limited number of small-scale real world components) would be set up and used for testing with an aim towards the design and development a of a potential real world alpha site test. The next step would involve a "pre-alpha" off-line field testing and validation, setting up at a building level or neighborhood, or even a small town ("bread board").

A novel approach along the lines of examples 1-4, 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 (generation, translation, storage, transmission, conditioning, etc.). In this sense it is an emergent system. It could be a complement or supplement to the existing macro grid structures. Such a system will be very difficult to initiate but will become more effective as users are added, new technology is pulled in, and organizational patterns develop. These would then also be templates for more conventional top-down systems architectures and a broader base to enable a high-confidence and high-quality system adaptive to disturbances and price elasticity while providing consumer service choice.

A

APPENDIX: TASK 3 PROCESS AND CONTRIBUTORS

For Task 3 of the Galvin Electricity Initiative we began soliciting these contributions through interviews with a broad base of S&T leaders including academics, authors, technologists, and members of the business community with eclectic and diverse backgrounds on all the areas of science and technology indicated in this report. We were very pleased to have the participation of exceptionally creative technologists, who actively participated to best inform the evaluation process regarding emerging technology areas and to illuminate electric energy service opportunities. Expectations from the Task 3 contributors and workshop participants were to embrace the following principles as background for guiding their participation:

1. The ultimate success of this project depends on creative thinking "outside the box" of conventional wisdom. Workshops will be used extensively to engage the most insightful, boldly expansive, thinkers and doers who have the courage of their convictions but are equally open to better ideas. Divergent viewpoints will be sought out and encouraged throughout this quest, in the spirit of Six-Sigma, for the most consumer-perfect electric energy service system.
2. Electricity, in virtually every application, is the most efficient and effective energy form for the delivery of energy-related goods and services. It is also the unique "equal-opportunity" vehicle enabling the transformation of essentially all raw energy resources into those goods and services. Most importantly, electricity has proven to be the primary energizer of innovation and ultimate competitive advantage throughout the 20th century, and therefore of societal progress. The Initiative will seek to creatively exploit these advantages in the context of the 21st century U.S. economy and society.
3. Electricity must be made available to society in such quantities and qualities as necessary to satisfy its escalating needs and expectations. Specifically, efficiency at the point of end use can be improved and managed much more effectively, and the requirements for electricity reliability and quality must be met by coordinated advancements in both end-use devices and the power supply infrastructure. Thus, while the amount of electricity required is likely to continue to grow as a fraction of overall energy use, its overall value can be enhanced substantially.
4. Electrification progress depends on the continued invention and deployment of ever-more efficient and user-responsive end-use energy consuming processes, devices and appliances. This has been the primary engine of productivity progress; however the rate of advancement has slowed considerably as investment and innovation have stagnated in recent years.
5. The electricity infrastructure as we know it will likely change substantially into a multi-dimensional service capability incorporating an array of distributed, stored, and potentially even wireless power resources as system assets, some so small as to internally power appliances and other devices. At the same time, this infrastructure transformation will enable

the convergence of electricity, sensors and telecommunications into a mega infrastructure powering a universal digital society.

All the above expectations were met and exceeded in each category. We gratefully acknowledge the following colleagues who participated in the Task 3 Workshop:

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The teams were grouped together as shown in Table A-1.

Table A-1
Task 3 Workshop Teams

Team 1:
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Marty Cooper
Irving Mintzer
Bill Spencer
John Stringer

Team 2:
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James Buckman
Tom Keelin
Tariq Samad
John Kotowski

Team 3:
Walter Baer
John Elter
Roger Gale
Les Shephard
Kelly Parmenter

Team 4:
Steve Batsell
David Fork
Arnulf Grubler
Bruce Wollenberg
Gene Oatman

In addition to the individuals highlighted above, several members of the project team for the Galvin Electricity Initiative were present at the Task 3 workshop and made substantive contributions to the evolving scenarios. These included Kurt Yeager, Clark Gellings, John Kotowski, Kelly Parmenter, and Gene Oatman.

Finally, we were honored to have the sponsorship and vision of the Galvin Electricity Initiative, Bob Galvin, as well as Chris and Michael Galvin who participated in the Task 3 workshop. Their presence, insightful observations and contributions were invaluable, as were those of all of the Initiative's contributors. Final responsibility for the content and conclusions of this report, of course, rests with Massoud Amin, Lockwood Carlson and Clark Gellings the co-authors and the Task 3 team. The primary authors for this report are:

Professor Massoud Amin, University of Minnesota

Dr. Massoud Amin is professor of electrical and computer engineering, directs the Center for the Development of Technological Leadership (CDTL), and holds the H.W. Sweatt Chair in Technological Leadership at the University of Minnesota, Minneapolis. Before joining the University of Minnesota in March 2003, he was with the Electric Power Research Institute (EPRI), where he held positions of increased responsibility (including area manager of infrastructure security, grid operations/planning, markets, risk and policy assessment), developed the foundations of and coined the term self-healing grid, and led the development of more than 19 technologies being transferred to industry. After the events of 11 September 2001, he directed all security- related research and development.

Before October 2001, Dr. Amin served as manager of mathematics and information science at EPRI, where he led strategic research and development in modeling, simulation, optimization, and adaptive control of national infrastructures for energy, telecommunication, transportation, and finance. He twice received Chauncey Awards at EPRI, the institute's highest honor. Prior to joining EPRI in January 1998, he held positions of associate professor of systems science and mathematics and associate director of the Center for Optimization & Semantic Control at Washington University in St. Louis, Missouri. He is a member of several boards, including the Board on Infrastructure and the Constructed Environment (BICE) at the U.S. National Academy of Engineering, a member of the IEEE Computer Society's Task Force on Security and Privacy, chaired ASME's Energy security team of the ASME Critical Asset Protection Initiative and serves on its 6-member steering committee.

Dr. Amin is the author or co-author of more than 120 research papers and editor of six collections of manuscripts, became an unprecedented three-times Professor of the Year at Washington University (1992-95). Dr. Amin received his B.S. (cum laude) and M.S. degrees in electrical and computer engineering from the University of Massachusetts, Amherst and M.S. and D.Sc. degrees in systems science and mathematics from Washington University. For additional publications, see http://umn.edu/~amin.

Dr. Lockwood Carlson, University of Minnesota

Dr. Carlson is President of Carlson Consulting Group (dba), providing technology and business foresight and strategy development consulting to early stage as well as large companies. He has consulted with several Fortune 500 companies in medical devices, chemicals, materials, instrumentation, systems design, etc. He holds the James Renier Chair in Technological Leadership at the Center for the Development of Technological Leadership at the University of Minnesota, where he is on the faculty and teaches in the Management of Technology program.

Dr. Carlson received his PhD in Physics in 1971 from the University of Wyoming. He joined 3M Company and led research efforts in thin films, electrophotography, solid state materials, and electronic imaging. He then became Laboratory Manager of the Consumer Video and Audio Tape business and later Chief Scientist for a major Department of Defense program in 3M in electromagnetic materials and thin film deposition processes. As Corporate Scientist, in 1987 he formed and led the Theory and Modeling group for the company, which included efforts in optical polymer films, fiber optics, fuel cells, LCD display optics and data storage technology. In 1997 he helped form the Corporate Enterprise Development department that identified, developed, and incubated new business opportunities, from internal concepts as well as outside technology acquisitions. He also developed technology strategy for the corporation using “Foresight” processes to match emerging technology trends to high value business opportunities that aligned with corporate growth strategies. He provided the technical leadership for 3M’s Corporate Venture program. He is a member of the American Physical Society, IEEE, World Future Society, and the Association of Professional Futurists.

Clark W. Gellings, Vice President, Innovation, Electric Power Research Institute (EPRI)

Clark W. Gellings is Vice President – Innovation of EPRI, Palo Alto, California. EPRI is a national collaborative research and development organization for electric power. It has evolved to become a non-profit electric power research institute with an applications subsidiary encompassing collaborative and proprietary R&D as well as technical solution applications in the U.S. and over 40 other countries.

He joined EPRI in 1982 progressing through a series of technical management and executive positions including five previous VP positions and CEO and member of the Board of several of EPRI’s subsidiaries. Prior to joining EPRI, Mr. Gellings spent 14 years with Public Service Electric and Gas Company.

Mr. Gellings has received distinguished awards from a number of organizations, including The Illuminating Engineering Society, the Association of Energy Services Professionals and the South African Institute of Electrical Engineers. He is a 2003 recipient of CIGRE’s (International Council on Large Electric Systems) Attwood Award for notable contributions.

Mr. Gellings is a registered Professional Engineer, a Fellow in the Institute of Electrical and Electronics Engineers (IEEE), a Fellow in the Illuminating Engineering Society (IES), and President of the U.S. National Committee of CIGRE. He has degrees in Electrical Engineering, Mechanical Engineering, and Management Science and is a graduate of the Wesley J. Howe School of Technology Management at Stevens Institute of Technology.

B

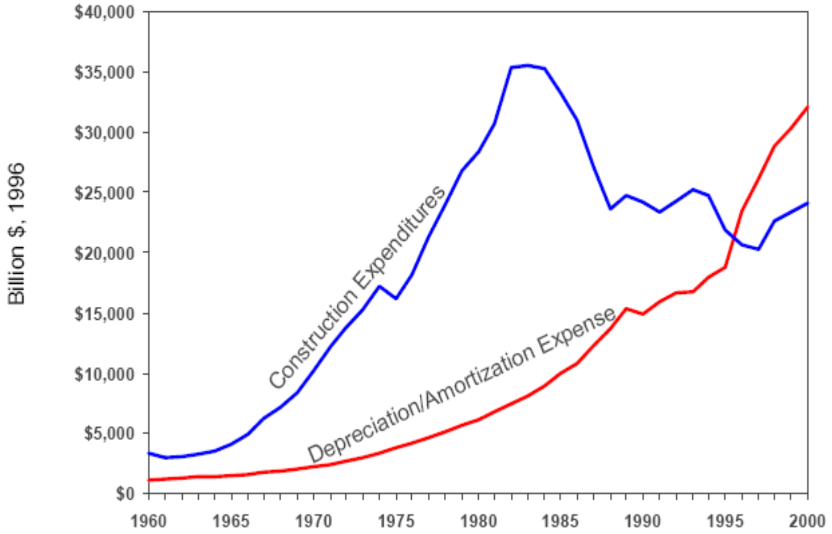
APPENDIX: ELECTRICITY INFRASTRUCTURE AND POWER MARKETS

This Appendix summarizes references 1-25 and briefly explains how the infrastructure that provides electricity is becoming increasingly vulnerable due to a variety of stresses. For detailed information, please see section "Further Readings and References," at the end of this Appendix.

The electric power grid was historically operated by separate utilities; each independent in its own control area and regulated by local bodies, to deliver bulk power from generation to load areas reliably and economically-- as a non-competitive, regulated monopoly, emphasis was on reliability (and security) at the expense of economy. Competition and deregulation have created multiple energy producers that must share the same regulated energy delivery network. Traditionally, new delivery capacity would be added to handle load increases, but because of the current difficulty in obtaining permits and the uncertainty about achieving an adequate rate of return on investment, total circuit miles added annually are declining while total demand for delivery resources continues to grow. In recent years, the "shock absorbers" have been shrinking; e.g., during the 1990s actual demand in the U.S. increased some 35%, while capacity has increased only 18%. The most visible parts of a larger and growing U.S. energy crisis are the result of years of inadequate investments in the infrastructure. According to EPRI analyses, since 1995 to the present the amortization/depreciation rate exceeds utility construction expenditures (Figure B-1).

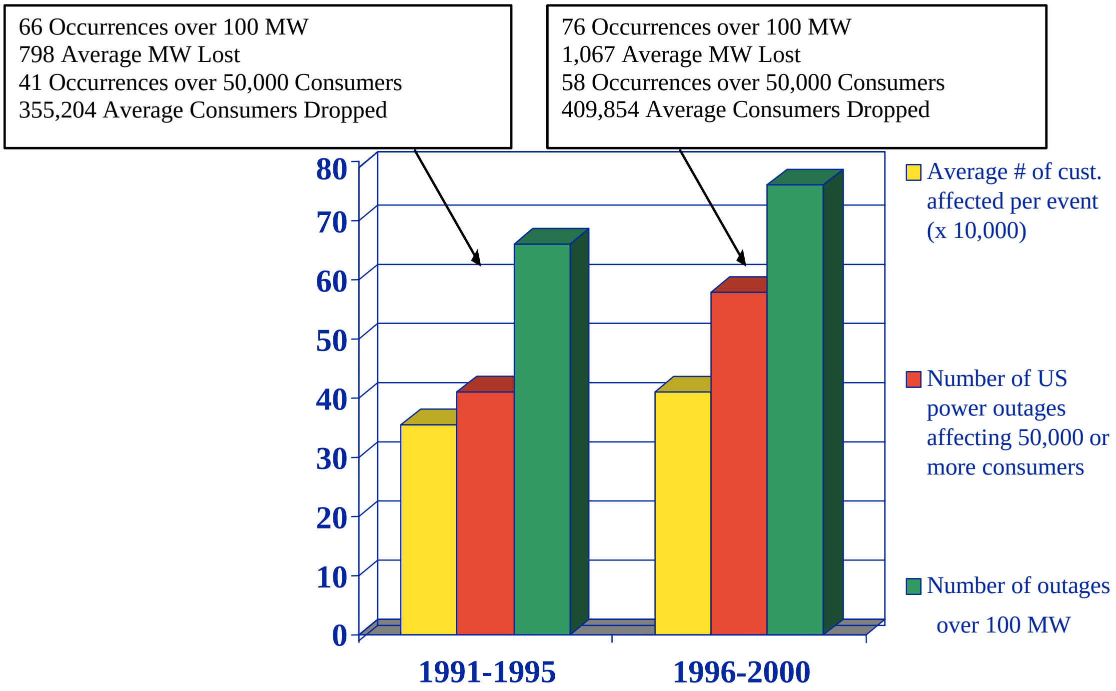
As a result of these "diminished shock absorbers," the network is becoming increasingly stressed, and whether the carrying capacity or safety margin will exist to support anticipated demand is in question. The complex systems used to relieve bottlenecks and clear disturbances during periods of peak demand are at great risk to serious disruption, creating a critical need for technological improvements. 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. Widespread outages and huge price spikes during the past few years raised a public concern about grid reliability at the national level. According to data from the North American Electric Reliability Council (NERC) and analyses from the Electric Power Research Institute (EPRI), average outages from 1984 to the present have affected nearly 700,000 consumers per event annually. Smaller outages occur much more frequently and affect tens to hundreds of thousands of consumers every few weeks or months, while larger outages occur every two to nine years and affect millions. Much larger outages affect seven million or more consumers per event each decade.

These analyses are based on data collected for the U.S. Department of Energy (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.



Source: "Historical Statistics of the Electric Utility Industry" and "EEI Statistical Yearbook" - EEI

Figure B-1
Since the "cross over" point in about 1995 utility construction expenditures have lagged behind asset depreciation. This has resulted in a mode of operation of the system analogous to "harvesting the farm far more rapidly than planting new seeds" (data provided by EEI and graph courtesy of EPRI).



66 Occurrences over 100 MW
798 Average MW Lost
41 Occurrences over 50,000 Consumers
355,204 Average Consumers Dropped

76 Occurrences over 100 MW
1,067 Average MW Lost
58 Occurrences over 50,000 Consumers
409,854 Average Consumers Dropped

Figure B-2
Increasing frequency and size of U.S. power outages 100 MW or more (1991-1995 versus

1996-2000), affecting 50,000 or more consumers per event. Generally, a relatively small number of U.S. consumers experience a large number of outages; conversely, outages that affect a large number of consumers are quite rare. However, this plot could also indicate that the number of larger outages could be rising (data courtesy NERC's Disturbance Analysis Working Group database).

Coupling these analyses with diminished infrastructure investments, and noting that the cross-over point for the utility construction investment vs. depreciation occurred in 1995 (Figure B-1), we analyzed the number and frequency of major outages along with the number of consumers affected during the decade 1991-2000; splitting it into the two time periods 1991-1995 and 1996-2000 (Figure B-2). Based on EPRI's analyses of data in NERC's Disturbance Analysis Working Group (DAWG) database. 41 % more outages affected 50,000 or more consumers in the second half of the 1990s than in the first half (58 outages in 1996-2000 versus 41 outages in 1991-1995). The average outage affected 15 % more consumers from 1996 to 2000 than from 1991 to 1995 (average size per event was 409,854 consumers affected in the second half of the decade versus 355,204 in the first half of the decade). In addition, there were 76 outages of size 100 megawatts (MW) or more in the second half of the decade, compared to 66 such occurrences in the first half. During the same period, the average lost load caused by an outage increased by 34 %, from 798 MW from 1991 to 1995 to 1067 MW from 1996 to 2000 (Figure B-2).

North American electricity infrastructure vulnerabilities and cost of cascading failures

Attention to the grid has gradually increased after several cascading failures. The August 10, 1996 blackout cost was over $1.5 billion and included all aspects of interconnected infrastructures and even the environment. Most recently, the August 13, 2003 outage was estimated to have a cost in the range of $6-$10 billions. Past disturbances in both the power grid give you some idea of how cascading failures work:

- November 1965—A cascaded system collapse blackout in 10 states in the Northeast US affected about 30 million people
- 1967—The Pennsylvania-New Jersey-Maryland (PJM) blackout occurred.
- May 1977—15,000 square miles and 1 million consumers in Miami lost electricity.
- July 1977—In New York's suburbs, lightning caused over voltages and faulty protection devices, which caused 10 million people to lose power for over 24 hours, resulting in wide-spread looting, over 4,000 arrests, and ultimately, the ouster of New York City's mayor.
- December 1978—Blackout in part of France due to voltage collapse.
- January 1981—1.5 million consumers in Idaho, Utah, and Wyoming were without power for 7 hours.
- March 1982—Over 900,000 lost power for 1.5 hours due to high-voltage line failure in Oregon.
- December 1994—2 million consumers from Arizona to Washington state lost power.
- July 1996—A high-voltage line touched a tree branch in Idaho and fell. The resulting short circuit caused blackouts for 2 million consumers in 14 states for approximately 6 hours
- August 1996—Following the 2 July blackout, two high-voltage lines fell in Oregon and caused cascading outages affecting over 7 million consumers in 11 Western states and two Canadian provinces.
- January 1998—Ice storms caused over 3 million people to lose power in Canada, New York, and New England.
- December 1998—San Francisco, California Bay Area blackout.
- July 1999—New York City blackout caused 300,000 people to be without power for 19 hours.
- 1998–2001—Summer price spikes affect consumers (infrastructure's inadequacy affecting markets).
- Industry-wide Y2K readiness program identified telecommunication failure as the biggest source of risk of the lights going out on rollover to 2000.
- Western states' suffered power crises in summer 2001 and its aftermath.
- Eastern United States and Canada face cascading outages on 14 August 2003.

Electricity Infrastructure: Interdependencies with Cyber and Digital Infrastructures

Electric power utilities typically own and operate at least parts of their own telecommunications systems, which often consist of backbone fiber optic or microwave connecting major substations, with spurs to smaller sites. Increased use of electronic automation raises significant issues regarding the adequacy of operational security. As is true of other critical infrastructures, increased use of automated technologies raises significant security issues, however:

- Reduced personnel at remote sites makes the sites more vulnerable to hostile threats;
- Interconnecting automation and control systems with public data networks makes them accessible to individuals and organizations, from any worldwide location using an inexpensive computer and a modem; and
- Use of networked electronic systems for metering, scheduling, trading or e-commerce imposes numerous financial risks associated with network failures.

In what follows we shall provide a brief overview of some key areas and present selected security aspects of operational systems, without discussing potentially sensitive material; these aspects include:

- Operational Systems rely very heavily on the exchange of information amongst disparate systems
- Utilities rely on very extensive private and leased telecommunication systems
- Networking of these systems is expanding rapidly
- This networking is expanding beyond utility doors, to encompass other utilities, corporations, and consumers
- Standard communication protocols and integration techniques are a **must**, despite the increased security risks
- Increased security concerns in the aftermath of tragic events of 11 September 2001
- Deregulation is increasing the incentives for unauthorized access to information

Increasingly Stressed Infrastructure

The North American power delivery system is vulnerable to increasing stresses from a variety of sources. One such stress is caused by an imbalance between growth in the demand for electric power and enhancement of the power delivery system to support this growth. From 1988 to 1998, total electricity demand in the U.S. rose by nearly 30 percent, but the capacity of the nation’s transmission network grew by only 15 percent. This disparity is anticipated to increase from 1999 to 2009: demand is expected to grow by 20 percent, while planned transmission system grows by only 3.5 percent (see Figure B-3).

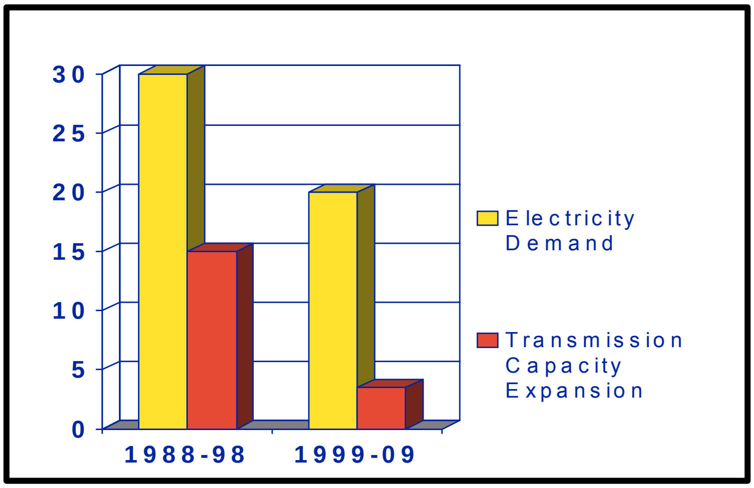


Figure B-3
U.S. Electricity Demand vs. Transmission Capacity Expansion (historical and projected)

Over the decade of the 1990s, the capital expenditures of the electricity sector, both regulated and deregulated, as a fraction of its electricity revenues was about 12 percent in the U.S. Moreover, power generation, rather than power delivery infrastructure improvements, accounted for a large share of this reduced investment. This low level of investment compared to revenue was only approached during the depths of the Great Depression and World War II when private investment was generally at its lowest. Even after accounting for intervening changes in demand and technology, this is a dangerously low and unsustainable level of investment. The consequent investment gap amounts to about $25 billion per year (U.S. dollars) and is already resulting in average additional service reliability cost nationally of at least 50 cents for every dollar of electricity purchased. The limited construction of new transmission systems is due largely to the inadequate and/or uncertain investment return from such systems and difficulty in obtaining new rights-of-way. No one wants new construction in their backyard, a problem that affects not only power delivery system equipment but also freeways, dams, and airports.

The Wholesale Power Market

The North American power delivery system was initially designed to reliably supply native load. Portions of this power system were designed regionally or locally to account for the locations of load centers (where power was needed) and the most reasonable locations to site power production facilities (often dictated by the availability of water and fuel). These load centers and power production facilities were then connected together by a power delivery grid. These networks became “cohesive electrical zones” that were designed to optimize local generation with local loads.

Regulatory changes have led to functional shifts in the structure of electric power industries worldwide, which in turn affect this power delivery system. In the United States, for example, a series of three federal initiatives have transformed and restructured the electric power industry. The most recent of these, the U.S. Federal Energy Regulatory Commission’s (FERC) August

2002 Notice of Proposed Rulemaking (NOPR) aimed to establish a “standard market design” (SMD) that standardizes transmission service and wholesale electricity market design.

The advent of competition in wholesale electricity markets in the United States increases stress on the North American power delivery system. Low-cost power generators in one area are incented to sell power in another not-too-distant area to meet electric demand, and can do so by virtue of the interconnected nature of the power delivery system. The desire to obtain the lowest-cost power generation leads to an increase in the number of power transactions, which are carried over the power transmission system. During the last decade, there was a dramatic increase in the number of wholesale transactions. However, the North American power delivery system was not designed to also support a thriving power market in which gigawatts of power are bought and sold every day. The large number of wholesale transactions breaks down the “cohesiveness” of the power delivery system, creating stress. Figure 7 illustrates the number of level two or higher calls for Transmission Loading Relief in North America. This illustrates the increasing inability of the transmission system to handle open markets.

Without construction of power delivery system equipment, this situation is expected to worsen. A 2002 reliability study recently concluded that “If there is no new transmission capacity built in the Eastern Interconnection in the next five years, during half of the summer period, operators will face congestion that may result in curtailments of the wholesale power market.”

Vulnerabilities to Natural Disaster and Attack (Security)

In addition to these stresses, economic effects, and power market impacts, the existing power delivery system is vulnerable to natural disasters and intentional attack. Regarding the latter, a successful terrorist attempt to disrupt the power delivery system could have adverse effects on national security, the economy, and the lives of every citizen. A recent EPRI assessment developed in response to the September 11, 2001 attacks highlights the following three different kinds of potential threats to the U.S. electricity infrastructure:

- Attacks on the power system, in which the infrastructure itself is the primary target.
- Attacks by power system components as weapons to attack the population.
- Attacks through the power system take advantage of power system networks to affect other infrastructure systems, such as telecommunications.

Complicating the protection of the power delivery system from a determined attack is the dispersed nature of the system’s equipment and facilities. Presenting another complexity, both physical vulnerabilities and susceptibility of power delivery systems to disruptions in computer networks and communication systems must be considered. For example, terrorists might exploit the increasingly centralized control of the power delivery system to magnify the effects of a localized attack. Because many consumers have become more dependent on electronic systems that are sensitive to power disturbances, an attack that leads to even a momentary interruption of power can be costly. A 20-minute outage at an integrated circuit fabrication plant, for example, can cost $30 million (U.S. dollars).

In summary, the power delivery and markets system have to overcome the following barriers and vulnerabilities:

- The present electric power delivery infrastructure was not designed to meet, and is unable to meet, the needs of a digital society – a society that relies on microprocessor-based devices in homes, offices, commercial buildings, industrial facilities, and vehicles.
- Investment in expansion and maintenance of this infrastructure is lagging, while electricity demand grows and will continue to grow.
- This infrastructure is not being expanded or enhanced to meet the demands of wholesale competition in the electric power industry, and does not facilitate connectivity between consumers and markets.
- Under continued stress, the present infrastructure cannot support levels of power security, quality, reliability, and availability (SQRA) needed for economic prosperity.
- The existing power delivery infrastructure is vulnerable to human error, natural disasters, and intentional physical and cyber attack.
- The infrastructure does not adequately accommodate emerging beneficial technologies, including distributed energy resources and energy storage, nor does it facilitate enormous business opportunities in retail electricity/information services.

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