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Introduction

Chairman Biggert and members of the Subcommittee, thank you for the opportunity to testify today on the role of new technologies in developing a more robust electric system.

America's electric system is facing serious problems: aging equipment and infrastructure, uncertain regulations and policies, difficulties attracting investment capital, and constrained supplies failing to meet rising demand. The National Academy of Sciences called America's electric system "…the supreme engineering achievement of the 20^{th} century." However, as currently configured, there are serious questions about the ability of this system to satisfy the increasingly complex electricity needs of the 21^{st} century.

The President is well aware of this problem. For example, on February 6^{th} 2003, President Bush reiterated the Administration's policy to modernize the electric grid, "It is a plan to modernize our electricity delivery system. It is a plan which is needed now. It is needed for economic security. It is needed for national security." The August blackout highlighted the economy's reliance on a secure and reliable electric system. Billions of dollars in goods and services, in productivity and food, were lost.

Implementing the President's plans for modernizing America's electricity infrastructure is one of the U.S. Department of Energy's top priorities. The President's National Energy Policy directed preparation of a detailed assessment of the major bottlenecks in our nation's transmission system, and in May 2002, Secretary Abraham issued the *National Transmission Grid Study*. This report made clear that without dramatic improvements and upgrades over the next decade our nation's transmission system will fall short of the reliability standards our economy requires, and will result in higher costs to consumers. The Department immediately began taking steps to implement the improvements that are needed to ensure continued growth and prosperity, working with Congress, States, and other stakeholders to promote innovation and enable entrepreneurs to develop a more advanced and robust transmission system. The mission of DOE's newly created Office of Electric Transmission and Distribution is focused on achieving this end.

Opportunities for Modernizing America's Electric System

Modernization includes the application of new and existing technologies to enhance the reliability and efficiency of the entire electric system. Electric reliability and efficiency are affected by all four segments of the electricity value chain: generation, transmission, distribution, and end-use. Investing in only one area will not necessarily stimulate performance improvements across other segments of the integrated system. Increasing supply without improving transmission and distribution infrastructure, for example, may actually lead to more serious reliability concerns. Thus, to improve the reliability and efficiency of electric power in America -- as called for in the President's energy plan – equipment upgrades as well as new technologies are needed throughout the electric system.

With electric generation, reliability is enhanced when additional supplies are added to ensure that peak demands are met. Reliability is also enhanced when sufficient reserve capacity is available for scheduled and unscheduled maintenance, and for emergency situations. Additional supplies can come from expansion of both central and distributed assets, representing a variety of technologies and fuel choices. Efficiency is enhanced when more fuel-efficient generation technologies are used, such as combined cycle combustion turbines and combined heat and power units. However, expanding supplies without balancing investment in transmission and distribution infrastructure will place additional cost burdens on consumers, both in terms of congestion and reliability. A reliable system requires balanced investment in supply, delivery, and demand management.

With respect to electric transmission, reliability is enhanced when additional lines are added to the grid, proper maintenance occurs in a timely manner, and when grid operators are able to make adjustments, in real-time, to address fluctuations in system conditions, particularly during periods of peak demand. Efficiency is enhanced when new transmission technologies are used that have reduced line losses, and that have the capability to carry more current for a given size of conductor. The Department is partnering today with industry to develop cost-effective transmission solutions, including advanced composite conductors, high temperature superconductors, and wide area measurement systems.

With respect to electric distribution, reliability is enhanced when additional lines are added, substation capabilities are expanded, proper maintenance occurs in a timely manner, communications and interconnections systems facilitate distributed energy development, and systems are protected better from natural disturbances. Efficiency is enhanced when new distribution technologies are deployed that reduce line losses, and information technologies optimize existing resources. The Department is working with States and industry to develop transformers, fault current limiters, cables, and power electronics that will revolutionize the distribution system.

With respect to electric end-use, reliability is enhanced when demand response programs manage electricity consumption in ways that result in lower overall peak demand and a better balance between on- and off-peak usages. Actions can include use of such technologies as real-time (or time-of-use) meters, and advanced energy storage. Efficiency is enhanced when new appliances and equipment require less electricity to produce equal (or greater) levels of service, such as advanced lighting, heating, cooling, refrigeration, and motor drive devices. Although peak load management offers significant benefits to utilities, electric consumption is controlled by the end-users. Their participation in a fully integrated energy system requires price transparency.

Barriers to Electric Grid Modernization

For more than two decades, America has been under-investing in the modernization of the electric system. The primary reason is uncertainty: technical uncertainty; regulatory uncertainty; and financial uncertainty. The consequences of this have been significant: greater numbers of congested transmission corridors, a higher likelihood of brownouts and blackouts, and more economic losses from outages when they do occur. Annual estimates of losses from outages and power quality disturbances range from $25 to $180 billion annually. Standard and Poor's estimates the economic losses from the August 14th blackout to be about $6 billion. Although some estimate it will take $100 billion to modernize the electric system, this should be compared against the scale of the existing electric industry: infrastructure worth approximately $800 billion (including generation), and revenues approaching $250 billion annually.

There are electricity technologies that are ready today to be used for grid modernization projects. However, electric assets are capital-intensive and long-lived, so the stock turnover process is relatively slow. Much of the nation's electric infrastructure of power lines, substations, switchyards, and transformers has been in service for 25 years, or longer.

The primary reason for the lack of investment in grid modernization is the financial uncertainty caused by the uneven process of restructuring of electric utility regulation, at both the federal and state levels. The electric power business currently is in and has for the last few years been in the midst of a difficult transition from a tightly regulated industry to one where competition and market forces play a greater role.

This transition has been slow and there have been missteps. For example, the unfortunate experience in California cost citizens billions of dollars, and has caused other states to re-think their approach to electric power regulation.

Regulatory uncertainty has affected other aspects of grid modernization. For example, there seems to have been a substantial decline in the level of spending recently by the electric power industry in research and development. The Electric Power Research Institute reports that its R&D funding from member utilities has fallen from about $600 million annually in 1994 to about $300 million annually in 2001. Federal spending on electric system research and development during that same time period did not rise to fill the gap. For example, for fiscal years 1996, 1997, and 1998, the funding for DOE's Transmission Reliability research and development program was zeroed out. This significant reduction in R&D investments has limited the flow of new technologies, tools, and techniques into the marketplace.

There are other barriers to the acceptance of new electric delivery technologies in the marketplace. Equipment must be introduced into the electric system in a manner that will ensure safe, reliable, and efficient operation. The electric industry is reluctant to use new technologies unless their functionality, and especially durability, is ensured. This slows down the process of moving technologies from the laboratory and into the "tool-kit" of electric system planners and operators. Some of the difficulties stem from problems in managing the risks associated with using new technologies, risks common to all industries. These technology transfer difficulties are exacerbated in the electric power sector by a regulatory framework that favors the status quo and does not typically reward managers for innovation, risk taking, or entrepreneurial activities. There is a need to work with State commissions to familiarize them with the new technologies and the extent to which their reliability has been demonstrated.

While this "re-thinking" proceeds, several states have implemented "price caps" as a way to protect consumers from price shocks while the markets adjust and policy makers identify next steps. While attractive to the regulator, price caps tend to hinder investment because they raise the uncertainty of cost recovery for new plant and equipment. For example, utilities subject to price caps cannot seek rate increases to recover reliability investment costs; they have to identify offsets from other aspects of their operation to maintain profitability.

Finally, public concern about the environmental, public health, and safety consequences of electric power has resulted in local or state siting and permitting processes that in many cases have impacted additional capacity. There are numerous instances over the past decade where projects to modernize the electric grid were stymied by siting and permitting delays caused by bureaucratic requirements or jurisdictional disputes among states and the Federal government. This has greatly hindered new investment despite the existence of a guaranteed rate of return for investors.. However, technologies such as advanced composite conductors that utilize existing transmission facilities may have a potential advantage over technologies that would require new rights-of-way.

Administration Action to Address Barriers

The Bush Administration, from the outset, has highlighted the importance of modernizing America's electric system. It is one of the most important policy objectives discussed in the President's National Energy Policy, which was issued in May 2001. One year later, the Department issued the *National Transmission Grid Study,* which contains 51 specific recommendations for modernizing the grid and increasing the reliability of America's transmission system. In September 2002, the Secretary's Energy Advisory Board issued the *Transmission Grid Solution Report* which outlines steps to streamline transmission siting and permitting and increase the level of investment in electric transmission facilities. In April 2003, the President's Council of Advisors on Science and Technology issued a report calling for expanded Federal investment in electric grid modernization technologies.

Also in April 2003, the Department held the National Electric System Vision meeting, which resulted in *Grid 2030 – a National Vision for Electricity's Second 100 Years*, a document that presents industry and DOE's views on the future of electric power in America. In July 2003, the Department followed up the "Grid 2030" vision with the National Electric Delivery Technologies Roadmap meeting, which will soon result in a document outlining the research, development, and technology transfer steps that government, industry, and others need to take to make the national vision for the future of the electric system into reality. The U.S. Department of Energy's website, www.energy.gov, provides access for downloading copies of these documents and reports.

"Grid 2030" – A National Vision for Electricity's Second 100 Years

The national vision calls for "Grid 2030" to energize a competitive North American marketplace for electricity. It will connect everyone to abundant, affordable, clean, efficient, and reliable electric power anytime, anywhere. It will provide the best and most secure electric services available in the world. Imagine the possibilities: electricity and information flowing together in real time, near-zero economic losses from outages and power quality disturbances, a wider array of customized energy choices, suppliers competing in open markets to provide the world's best electric services, and all of this supported by a new energy infrastructure built on superconductivity, distributed intelligence and resources, clean power, and the hydrogen economy.

Although the precise architecture of America's future electric system has yet to be designed, the "Grid 2030" concept has been envisioned to consist of three major elements:

- A national electricity "backbone"
- Regional interconnections which include Canada and Mexico
- Local distribution, mini- and micro-grids providing services to customers from generation resources anywhere on the continent

The backbone system will involve a variety of technologies. These include controllable, very-low-impedance superconducting cables and modular transformers operating within the synchronous AC environment; high voltage direct current devices forming connections between regions; and other types of advanced electricity conductors, as well as information, communications, and controls technologies for supporting real-time operations and national electricity transactions. Superconducting systems will be able to reduce line losses, assure stable voltage, and expand current carrying capacities in dense urbanized areas. They will be seamlessly integrated with high voltage direct current systems and other advanced conductors for transporting electric power over long distances.

Power from the backbone system will be distributed over regional networks. Long-distance transmission within these regions will be accomplished using upgraded, controllable AC facilities and, in some cases, expanded DC links. High-capacity DC interties will be employed far more extensively than they are today to link adjacent, asynchronous regions. Regional system planning and operations will benefit from real-time information on the status of power generation facilities (central-station and distributed) and loads. Expanded use of advanced electricity storage devices will address supply-demand imbalances caused by weather conditions and other factors. In this grid of the future, markets for bulk power exchanges will be able to operate more efficiently with oversight provided through mandatory reliability standards, multi-state entities, and voluntary industry entities.

In the "Grid 2030" distribution system, it is envisioned that customers will have the ability to tailor electricity supplies to suit their individual needs for power, including costs, environmental impacts, and levels of reliability and power quality. Sensors and control systems will be able to link appliances and equipment from inside buildings and factories to the electricity distribution system. Advances in distributed power generation systems and hydrogen energy technologies could enable the dual use of transportation vehicles for stationary power generation. For example, hydrogen fuel cell powered vehicles could be able to provide electricity to the local distribution system when in the garage at home or parking lot at work.

<u>National Electric Delivery Technologies Roadmap</u>

The Roadmap, which is still being finalized by DOE, will call for the collaborative implementation by government and industry of a five-part "action agenda" to modernize the grid and achieve the "Grid 2030" vision. The action agenda includes:

- Designing the "Grid 2030" Architecture – Conceptual framework that guides development of the electric system from the generation busbar to the customer's meter
- Developing the Critical Technologies – Advanced conductors, electric storage, high-temperature superconductors, distributed intelligence/smart controls, and power electronics that become the building blocks for the "Grid 2030" concept
- Accelerating Technology Acceptance – Field testing and demonstrations that move the advanced technologies from the laboratory and into the "tool kit" of transmission and distribution system planners and operators
- Strengthening Market Operations – Assessing markets, planning, and operations; improving siting and permitting; and addressing regulatory barriers bring greater certainty and lower financial risks to electric transactions and investment
- Building Partnerships – Leveraging stakeholder involvement through multi-year, public-private partnerships; working with States, FERC, and NERC to address shared concerns

Technologies for Modernizing the Electric Grid

There is a portfolio of technologies that have the capabilities to enhance the reliability and efficiency of the electric grid. Many of these will require further research, development, field testing, and demonstration to lower costs, improve reliability and durability, and demonstrate effective performance. The Appendix, taken from the National Transmission Grid Study, provides additional details on a wide range of grid modernization technologies.

Advanced Conductors and New Materials. Desirable properties of new material for electricity conductors include greater current-carrying capacity, lower electrical resistance, lighter weight, greater durability, greater controllability, and lower cost. Advances in semiconductor-based power electronics have given rise to new solutions that allow more power flow through existing assets, while respecting local land use concerns. Advanced composite materials and alloys are also making an impact and are being used in new designs for conductors and cables. Diamond technology could replace silicon and achieve dramatic increases in current density. In addition, scientific discoveries in advanced materials are resulting in new concepts for conductors of electric power. For example, nanoscience is opening new frontiers in the design and manufacture of machines at the molecular level for fabricating new classes of metals, ceramics, and organic compounds (such as carbon nanotubes) that have potential electric power applications.

High Temperature Superconductors. High temperature superconductors are a good example of advanced materials that have the potential to revolutionize electric power delivery in America. The prospect of transmitting large amounts of power through compact underground corridors, even over long distances, with minimal electrical losses and voltage drop, could significantly enhance the overall energy efficiency and reliability of the electric system, while reducing fuel use, air emissions, and physical footprint. Superconducting technologies can be used in generators, cables, transformers, storage devices, synchronous condensers, and motors – equipment that crosscuts the entire electric power value chain.

Electricity Storage. Breakthroughs that dramatically reduce the costs of electricity storage systems could drive revolutionary changes in the design and operation of the electric power system. Peak load problems could be reduced, electrical stability could be improved, and power quality disturbances could be eliminated. Storage can be applied at the power plant, in support of the transmission system, at various points in the distribution system, and on particular appliances and equipment on the customer's side of the meter.

Communications, Controls and Information Technologies. Information technologies (IT) have already revolutionized telecommunications, banking, and certain manufacturing industries. Similarly, the electric power system represents an enormous market for the application of IT to automate various functions such as meter reading, billing, transmission and distribution operations, outage restoration, pricing, and status reporting. The ability to monitor real-time operations and implement automated control algorithms in response to changing system conditions is just beginning to be used in electricity. Visualization tools are just beginning to be used by electric grid operators to process real-time information and accelerate response times to problems in system voltage and frequency levels. Distributed intelligence, including "smart" appliances, could drive the co-development of the future architecture for both telecommunications and electric power networks, and determines how these systems are operated and controlled. Data access and data management will become increasingly important business functions.

Advanced Power Electronics. High-voltage power electronics allow precise and rapid switching of electrical power. Power electronics are at the heart of the interface between energy storage and the electrical grid. This power conversion interface—necessary to integrate direct current or asynchronous sources with the alternating current grid—is a significant cost component of energy storage systems. Additionally, power electronics are the key technology for power flow controllers (e.g. Flexible Alternating Current Transmission Systems - FACTS) that improve power system control, and help increase power transfer levels. New power electronics advances are needed to lower the costs of these systems, and accelerate their application on the network.

Distributed Energy Technologies. Developments to improve the performance and economics of distributed energy generation and combined heat and power systems could expand the number of installations by industrial, commercial, residential, and community users of electricity. Devices such as fuel cells, reciprocating engines, distributed gas turbines and microturbines can be installed by users to increase their power quality and reliability, and to control their energy costs. They can lead to reduced "upstream" needs for electric generation, transmission, and distribution equipment by reducing peak demand.

Potential Benefits of Grid Modernization

An expanded and modernized grid will virtually eliminate electric system constraints as an impediment to economic growth and in fact will promote and encourage economic growth. As stated in the National Transmission Grid Study, wholesale markets save consumers $13 billion annually, but constraints cost billions more. Robust national markets for electric power will encourage growth and open avenues for attracting capital to support infrastructure development and investment in new plant and equipment. New business models will emerge for both small and large companies for the provision of a wide variety of new products and services for electricity customers, distributors, transmitters, and generators.

More energy efficient transmission and distribution will reduce line losses and lhelp avoid emission of air pollution and greenhouse gases. More economically efficient system operations and the expanded use of demand-side management techniques will reduce the need for spinning reserves, which could also lower environmental impacts. A modernized national electric grid will facilitate the delivery of electricity from renewable technologies such as wind, hydro, and geothermal that have to be located where the resources are located, which is often remote from load centers.

Faster detection of outages, automatic responses to them, and rapid restoration systems will improve the security of the grid, and make the grid less vulnerable to physical attacks from terrorists. Greater integration of information and electric technologies will involve strengthened cyber-security protections. Expanded use of distributed energy resources will provide reliable power to military facilities, police stations, hospitals, and emergency response centers. This will help ensure that "first-responders" have the ability to continue operations even during worst-case conditions. Greater use of distributed generation will lessen the percentage of generated power that must flow through transmission and distribution systems, reducing strain on the grid. Higher levels of interconnection with Canada, Mexico, and ultimately other trading partners will strengthen America's ties with these nations and boost security through greater economic cooperation and interdependence.

Conclusion

The electric grid is an essential part of American life. America has under-invested in maintenance of the national electric grid and in the development and deployment of advanced electric delivery technologies. Most of today's existing infrastructure of wires, transformers, substations, and switchyards has been in use for 25 years, or more. The aging of this infrastructure, and the increasing requirements placed on it, have contributed to market inefficiencies and electricity congestion in several regions. These conditions could lead to higher prices, more outages, more power quality disturbances, and the less efficient use of resources. Jobs, environmental protection, public health and safety, and national security are at risk. We must act now or risk even greater problems in the future.

In recognition of this, President Bush has asked the U.S. Department of Energy to lead a national effort to modernize the electric grid. The newly formed Office of Electric Transmission and Distribution has been given the assignment to do just that. The Office will work in partnership with the electric industry, states, and other stakeholders to develop a national vision of the future for America's electric grid, and a national roadmap of collaborative activities to achieve the vision. The Office's activities will include research and development, technology transfer, modeling and data analysis, and policy analysis.

Modernizing the grid will involve time, resources, and unprecedented levels of cooperation among the electric power industry's many and diverse stakeholders. Neither government nor industry can shoulder these responsibilities alone. The Office of Electric Transmission and Distribution stands ready to lead this transformation.

Appendix: List of Technology Options for Grid Modernization

This appendix, taken from the National Transmission Grid Study, contains a list of some of the technologies that are being researched and deployed to modernize the electric grid. The range of potential technologies is enormous and the list presented is not exhaustive.

- *Advanced Composite Conductors:* Usually, transmission lines contain steel-core cables that support strands of aluminum wires, which are the primary conductors of electricity. New cores developed from composite materials are proposed to replace the steel core.
  Objective: Allow more power through new or existing transmission rights of way.
  Benefits: A new core consisting of composite fiber materials shows promise as stronger than steel-core aluminum conductors while 50 percent lighter in weight with up to 2.5 times less sag. The reduced weight and higher strength equate to greater current carrying capability as more current-carrying aluminum can be added to the line. This fact along with manufacturing advances, such as trapezoidal shaping of the aluminum strands, can reduce resistance by 10 percent, enable more compact designs with up to 50 percent reduction in magnetic fields, and reduce ice buildup compared to standard wire conductors. This technology can be integrated in the field by most existing reconductoring equipment.
  Barriers: More experience is needed with the new composite cores to reduce total life-cycle costs.
  Commercial Status: Research projects and test systems are in progress.

- *High-Temperature Super-Conducting (HTSC) Technology:* The conductors in HTSC devices operate at extremely low resistances. They require refrigeration (generally liquid nitrogen) to super-cool ceramic superconducting material.
  Objective: Transmit more power in existing or smaller rights of way. Used for transmission lines, transformers, reactors, capacitors, and current limiters.
  Benefits: Cable occupies less space (AC transmission lines bundle three phase together; transformers and other equipment occupy smaller footprint for same level of capacity). Cables can be buried to reduce exposure to electric and magnetic field effects and counteract visual pollution issues. Transformers can reduce or eliminate cooling oils that, if spilled, can damage the environment. The HTSC itself can have a long lifetime, sharing the properties noted for surface cables below.
  Barriers: Maintenance costs are high (refrigeration equipment is required and this demands trained technicians with new skills; the complexity of system can result in a larger number of failure scenarios than for current equipment; power surges can quench (terminate superconducting properties) equipment requiring more advanced protection schemes).
  Commercial Status: A demonstration project is under way at Detroit Edison's Frisbie substation. Four-hundred-foot cables are being installed in the substation. Self-contained devices, such as current limiters, may be added to address areas where space is at a premium and to simplify cooling.

- *Below-Surface Cables:* The state of the art in underground cables includes fluid-filled polypropylene paper laminate (PPL) and extruded dielectric polyethylene (XLPE) cables. Other approaches, such as gas-insulated transmission lines (GIL), are being researched and hold promise for future applications.
  Objective: Transmit power in areas where overhead transmission is impractical or unpopular.
  Benefits: The benefits compared with overhead transmission lines include protection of cable from weather, generally longer lifetimes, and reduced maintenance. These cables address environmental issues associated with EMFs and visual pollution associated with transmission lines.
  Barriers: Drawbacks include costs that are five to 10 times those of overhead transmission and challenges in repairing and replacing these cables when problems arise. Nonetheless,

these cables represent have made great technical advances; the typical cost ratio a decade ago was 20 to one.
Commercial Status: PPL cable technology is more mature than XLPE. EHV (extra high voltage) VAC and HVDC applications exist throughout the world. XLPE is gaining quickly and has advantages: low dielectric losses, simple maintenance, no insulating fluid to affect the environment in the event of system failure, and ever-smaller insulation thicknesses. GILs feature a relatively large-diameter tubular conductor sized for the gas insulation surrounded by a solid metal sleeve. This configuration translates to lower resistive and capacitive losses, no external EMFs, good cooling properties, and reduced total life-cycle costs compared with other types of cables. This type of transmission line is installed in segments joined with orbital welders and run through tunnels. This line is less flexible than the PPL or XLPE cables and is, thus far, experimental and significantly more expensive than those two alternatives.

Underwater application of electric cable technology has a long history. Installations are numerous between mainland Europe, Scandinavia, and Great Britain. This technology is also well suited to the electricity systems linking islands and peninsulas, such as in Southeast Asia. The Neptune Project consists of a network of underwater cables proposed to link Maine and Canada Maritime generation with the rest of New England, New York, and the mid-Atlantic areas.

- *Tower Design Tools:* A set of tools is being perfected to analyze upgrades to existing transmission facilities or the installation of new facilities to increase their power-transfer capacity and reduce maintenance.
  Objective: Ease of use and greater application of visualization techniques make the process more efficient and accurate when compared to traditional tools. Traditionally, lines have been rated conservatively. Careful analysis can discover the unused potential of existing facilities. Visualization tools can show the public the anticipated visual impact of a project prior to commencement.
  Benefits: Avoids new right-of-way issues. The cost of upgrading the thermal rating has been estimated at approximately $7,000 per circuit mile, but reconductoring a 230-kV circuit costs on the order of $120,000 per mile compared with $230,000 per mile for a new steel-pole circuit (Lionberger and Duke 2001).
  Barriers: This technology is making good inroads.
  Commercial Status: Several companies offer commercial products and services.
  Six-Phase and 12-Phase Transmission Line Configurations: The use of more than three phases for electric power transmission has been studied for many years. Using six or even 12 phases allows for greater power transfer capability within a particular right of way, and reduced EMFs because of greater phase cancellation. The key technical challenge is the cost and complexity of integrating such high-phase-order lines into the existing three-phase grid.

- *Modular Equipment:* One way to gain flexibility for changing market and operational situations is to develop standards for the manufacture and integration of modular equipment.
  Objective: Develop substation designs and specifications for equipment manufacturers to meet that facilitate the movement and reconfiguration of equipment in a substation to meet changing needs.
  Benefits: Reduces overall the time and expense for transmission systems to adapt to the changing economic and reliability landscape.
  Barriers: Requires transmission planners and substation designers to consider a broad range of operating scenarios.
  Also, developing industry standards can take a significant period, and manufacturers would need to offer conforming products.
  Commercial Status: Utilities have looked for a certain amount of standardization and flexibility in this area for some time; however, further work remains to be done. National Grid (UK) has configured a number of voltage-support devices that use modular construction methods. As the system evolves, the equipment can be moved to locations where support is needed (PA Consulting Group 2001).

Ultra-High Voltage Levels: Because power is equal to the product of voltage times current, a highly effective approach to increasing the amount of power transmitted on a transmission line is to increase its operating voltage. Since 1969, the highest transmission voltage levels in North America have been 765 kV, (voltage levels up to 1,000 kV are in service elsewhere). Difficulties with utilizing higher voltages include the need for larger towers and larger rights of way to get the necessary phase separation, the ionization of air near the surface of the conductors because of high electric fields, the high reactive power generation of the lines, and public concerns about electric and magnetic field effects.

- *HVDC:* With active control of real and reactive power transfer, HVDC can be modulated to damp oscillations or provide power-flow dispatch independent of voltage magnitudes or angles (unlike conventional AC transmission).
  Objective: HVDC is used for long-distance power transport, linking asynchronous control areas, and real-time control of power flow.
  Benefits: Stable transport of power over long distances where AC transmission lines need series compensation that can lead to stability problems. HVDC can run independent of system frequency and can control the amount of power sent through the line. This latter benefit is the same as for FACTS devices discussed below.
  Barriers: Drawbacks include the high cost of converter equipment and the need for specially trained technicians to maintain the devices.
  Commercial Status: Many long-distance HVDC links are in place around the world. Back-to-back converters link Texas, WSCC, and the Eastern Interconnection in the US. More installations are being planned.

- *FACTS Compensators:* Flexible AC Transmission System (FACTS) devices use power electronics to adjust the apparent impedance of the system. Capacitor banks are applied at loads and substations to provide capacitive reactive power to offset the inductive reactive power typical of most power system loads and transmission lines. With long inter-tie transmission lines, series capacitors are used to reduce the effective impedance of the line. By adding thyristors to both of these types of capacitors, actively controlled reactive power are available using SVCs and TCSC devices, which are shunt- and series-controlled capacitors, respectively. The thyristors are used to adjust the total impedance of the device by switching individual modules. Unified power-flow controllers (UPFCs) also fall into this category.
  Objective: FACTS devices are designed to control the flow of power through the transmission grid.
  Benefits: These devices can increase the transfer capacity of the transmission system, support bus voltages by providing reactive power, or be used to enhance dynamic or transient stability.
  Barriers: As with HVDC, the power electronics are expensive and specially trained technicians are needed to maintain them. In addition, experience is needed to fully understand the coordinated control strategy of these devices as they penetrate the system.
  Commercial Status: As mentioned above, the viability of HVDC systems has already been demonstrated. American Electric Power (AEP) has installed a FACTS device in its system, and a new device was recently commissioned by the New York Power Authority (NYPA) to regulate flows in the northeast.

- *FACTS Phase-Shifting Transformers:* Phase shifters are transformers configured to change the phase angle between buses; they are particularly useful for controlling the power flow on the transmission network. Adding thyristor control to the various tap settings of the phase-shifting transformer permits continuous control of the effective phase angle (and thus control of power flow).
  Objective: Adjust power flow in the system.
  Benefits: The key advantage of adding power electronics to what is currently a non-electronic technology is faster response time (less then one second vs. about one minute). However,

traditional phase shifters still permit redirection of flows and thereby increase transmission system capacity.
Barriers: Traditional phase shifters are deployed today. The addition of the power electronics to these devices is relatively straightforward but increases expense and involves barriers similar to those noted for FACTS compensators.
Commercial Status: Tap-changing phase shifters are available today. Use of thyristor controls is emerging.

- *FACTS Dynamic Brakes:* A dynamic brake is used to rapidly extract energy from a system by inserting a shunt resistance into the network. Adding thyristor controls to the brake permits addition of control functions, such as on-line damping of unstable oscillations.
  Objective: Dynamic brakes enhance power system stability.
  Benefits: This device can damp unstable oscillations triggered by equipment outages or system configuration changes.
  Barriers: In addition the power electronics issues mentioned earlier, siting a dynamic brake and tuning the device in response to specific contingencies requires careful study.
  Commercial Status: BPA has installed a dynamic brake on their system.

- *Battery Storage Devices:* Batteries use converters to transform the DC in the storage device to the AC of the power grid. Converters also operate in the opposite direction to recharge the batteries.
  Objective: Store energy generated in off-peak hours to be used for emergencies or on-peak needs.
  Benefits: Battery converters use thyristors that, by the virtue of their ability to rapidly change the power exchange, can be utilized for a variety of real-time control applications ranging from enhancing transient to preconditioning the area control error for automatic generator control enhancement. During their operational lifetime, batteries have a small impact on the environment. For distributed resources, batteries do not need to be as large as for large-scale generation, and they become important components for regulating micro-grid power and allowing interconnection with the rest of the system.
  Barriers: The expense of manufacturing and maintaining batteries has limited their impact in the industry.
  Commercial Status: Several materials are used to manufacture batteries though large arrays of lead-acid batteries continue to be the most popular for utility installations. Interest is also growing in so-called “flow batteries” that charge and discharge a working fluid exchanged between two tanks. The emergence of the distributed energy business has increased the interest in deploying batteries for regional energy storage. One of the early battery installations that demonstrated grid benefit was a joint project between EPRI and Southern California Edison at the Chino substation in southern California.

- *Super-conducting Magnetic Energy Storage (SMES):* SMES uses cryogenic technology to store energy by circulating current in a super-conducting coil.
  Objective: Store energy generated in off-peak hours to be used for emergencies or on-peak needs.
  Benefits: The benefits are similar to those for batteries. SMES devices are efficient because of their super-conductive properties. They are also very compact for the amount of energy stored.
  Barriers: As with the super-conducting equipment mentioned in the passive equipment section above, SMES entails costs for the cooling system, the special protection needed in the event the super-conducting device quenches, and the specialized skills required to maintain the device.
  Commercial Status: Several SMES units have been commissioned in North America. They have been deployed at Owens Corning to protect plant processes, and at Wisconsin Public Service to address low-voltage and grid instability issues.

- *Pumped Hydro and Compressed-Air Storage:* Pumped hydro consists of large ponds with turbines that can be run in either pump or generation modes. During periods of light load (e.g., night) excess, inexpensive capacity drives the pumps to fill the upper pond. During heavy load periods, the water generates electricity into the grid. Compressed air storage uses the same principle except that large, natural underground vaults are used to store air under pressure during light-load periods.
  Objective: This technology helps shave peak and can help in light-load, high-voltage situations.
  Benefits: These storage systems behave like conventional generation and have the benefit of producing additional generation sources that can be dispatched to meet various energy and power needs of the system. Air emission issues can be mitigated when base generation is used in off-peak periods as an alternative to potentially high-polluting peaking units during high use periods.
  Barriers: Pumped hydro, like any hydro generation project, requires significant space and has corresponding ecological impact. The loss of efficiency between pumping and generation as well as the installation and maintenance costs must be outweighed by the benefits.
  Commercial Status: Pumped hydro projects are sprinkled across North America. A compressed-air storage plant was built in Alabama, and a proposed facility in Ohio may become the world's largest.

- *Flywheels:* Flywheels spin at high velocity to store energy. As with pumped hydro or compressed-air storage, the flywheel is connected to a motor that either accelerates the flywheel to store energy or draws energy to generate electricity. The flywheel rotors are specially designed to significantly reduce losses. Super conductivity technology has also been deployed to increase efficiency.
  Objective: Shave peak energy demand and help in light-load, high-voltage situations. As a distributed resource, flywheels enhance power quality and reliability.
  Benefits: Flywheel technology has reached low-loss, high-efficiency levels using rotors made of composite materials running in vacuum spaces. Emissions are not an issue for flywheels, except those related to the energy expended to accelerate and maintain the flywheel system.
  Barriers: The use of super-conductivity technology faces the same barriers as noted above under super-conducting cables and SMES. High-energy-storage flywheels require significant space and the high-speed spinning mass can be dangerous if the equipment fails.
  Commercial Status: Flywheel systems coupled with batteries are making inroads for small systems (e.g., computer UPS, local loads, electric vehicles). Flywheels rated in the 100 to 200 kW range are proposed for development in the near term.

- *Price-Responsive Load:* Fast-acting load control is an important element in active measures for enhancing the transmission grid. Automatic load shedding (under-frequency, under-voltage), operator-initiated interruptible load, demand-side management programs, voltage reduction, and other load-curtailment strategies have long been an integral part of coping with unforeseen contingencies as a last resort, and/or as a means of assisting the system during high stress, overloaded conditions. The electricity industry has been characterized by relatively long-term contracts for electricity use. As the industry restructures to be more market-driven, adjusting demand based on market signals will become an important tool for grid operators.
  Objective: Inform energy users of system conditions though price signals that nudge consumption into positions that make the system more reliable and economic.
  Benefits: The approach reduces the need for new transmission and siting of new generation. Providing incentives to change load in appropriate regions of the system can stabilize energy markets and enhance system reliability. Shifting load from peak periods to less polluting off-peak periods can reduce emissions.
  Barriers: The vast number of loads in the system makes communication and coordination difficult. Also, using economic signals in real time or near-real time to affect demand usage has not been part of the control structure that has been used by the industry for decades. A

common vision and interface standards are needed to coordinate the information exchange required.
Commercial Status: Demand-management programs have been implemented in various areas of the country. These have relied on centralized control. With the advent of the Internet and new distributed information technology approaches, firms are emerging to take advantage of this technology with a more distributed control strategy.

- *Intelligent Building Systems:* Energy can be saved through increasing the efficient operation of buildings and factories. Coordinated utilization of cooling, heating, and electricity in these establishments can significantly reduce energy consumption. Operated in a system that supports price-responsive load, intelligent building systems can benefit system operations. Note: these systems may have their own, local generation. Such systems have the option of selling power to the grid as well as buying power.
  Objective: Reduce energy costs and provide energy management resources to stabilize energy markets and enhance system reliability.
  Benefits: Such systems optimize energy consumption for the building operators and may provide system operators with energy by reducing load or increasing local generation based on market conditions.
  Barriers: These systems require a greater number of sensors and more complex control schemes than are common today. Should energy market access become available at the building level, the price incentives would increase.
  Commercial Status: Pilot projects have been implemented throughout the country.

- *Distributed Generation (DG):* Fuel cells, micro-turbines, diesel generators, and other technologies are being integrated using power electronics. As these distributed resources increase in number, they can become a significant resource for reliable system operations. Their vast numbers and teaming with local load put them in a similar category to the controllable load discussed above.
  Objective: Address local demand cost-effectively.
  Benefits: DG is generally easier to site, entails smaller individual financial outlay, and can be more rapidly installed than large-scale generation. DG can supply local load or sell into the system and offers owners self-determination. Recovery and use of waste heat from some DG greatly increases energy efficiency.
  Barriers: Volatility of fuel costs and dependence on the fuel delivery infrastructure creates financial and reliability risks. DG units require maintenance and operations expertise, and utilities can set up discouraging rules for interconnection. System operators have so far had difficulty coordinating the impact of DG.
  Commercial Status: Deployment of DG units continues to increase. As with controllable load, system operations are recognizing the potential positive implications of DG to stabilize market prices and enhance system reliability though this requires a different way of thinking from the traditional, hierarchical control paradigm.

- *Power-System Device Sensors:* The operation of most of the individual devices in a power system (such as transmission lines, cables, transformers, and circuit breakers) is limited by each device’s thermal characteristics. In short, trying to put too much power through a device will cause it to heat excessively and eventually fail. Because the limits are thermal, their actual values are highly dependent upon each device’s heat dissipation, which is related to ambient conditions. The actual flow of power through most power-system devices is already adequately measured. The need is for improved sensors to dynamically determine the limits by directly or indirectly measuring temperature.

- *Direct Measurement of Conductor Sag:* For overhead transmission lines the ultimate limiting factor is usually conductor sag. As wires heat, they expand, causing the line to sag. Too much sag will eventually result in a short circuit because of arcing from the line to whatever is underneath.

Objective: Dynamically determine line capacity by directly measuring the sag on critical line segments.
Benefits: Dynamically determined line ratings allow for increased power capacity under most operating conditions.
Barriers: Requires continuous monitoring of critical spans. Cost depends on the number of critical spans that must be monitored, the cost of the associated sensor technology, and ongoing cost of communication.
Commercial Status: Pre-commercial units are currently being tested. Approaches include either video or the use of differential GPS. EPRI currently is testing a video-based "sagometer." An alternative is to use differential GPS to directly measure sag. Differential GPS has been demonstrated to be accurate significantly below half a meter.
Indirect Measurement of Conductor Sag: Transmission line sag can also be estimated by physically measuring the conductor temperature using an instrument directly mounted on the line and/or a second instrument that measures conductor tension at the insulator supports.
Objective: Dynamically determine the line capacity.
Benefits: Dynamically determined line ratings allow for increased power capacity under most operating conditions.
Barriers: Requires continuous monitoring of critical spans. Cost depends upon the number of critical spans that must be monitored, the cost of the associated sensor technology, and ongoing costs of communication.
Commercial Status: Commercial units are available.

- *Indirect Measurement of Transformer Coil Temperature:* Similar to transmission line operation, transformer operation is limited by thermal constraints. However, transformers constraints are localized hot spots on the windings that result in breakdown of insulation.
  Objective: Dynamically determine transformer capacity.
  Benefits: Dynamically determined transformer ratings allow for increased power capacity under most operating conditions.
  Barriers: The simple use of oil temperature measurements is usually considered to be unreliable.
  Commercial Status: Sophisticated monitoring tools are now commercially available that combine several different temperature and current measurements to dynamically determine temperature hot spots.

- *Underground/Submarine Cable Monitoring/Diagnostics:* The below-surface cable systems described above require real-time monitoring to maximize their use and warn of potential failure.
  Objective: Incorporate real-time sensing equipment to detect potentially hazardous operating situations as well as dynamic limits for safe flow of energy.
  Benefits: Monitoring equipment maximizes the use of the transmission asset, mitigates the risk of failure and the ensuing expense of repair, and supports preventive maintenance procedures. The basic sensing and monitoring technology is available today.
  Barriers: The level of sophistication of the sensing and monitoring equipment adds to the cost of the cable system. The use of dynamic limits must also be integrated into system operation procedures and the associated tools of existing control facilities.
  Commercial Status: Newer cable systems are being designed with monitoring/diagnostics in mind. Cable temperature, dynamic thermal rating calculations, partial discharge detection, moisture ingress, cable damage, hydraulic condition (as appropriate), and loss detection are some of the sensing functions being put in place. Multifunctional cables are also being designed and deployed (particularly submarine cables) that include communications capabilities. Monitoring is being integrated directly into the manufacturing process of these cables.

- *Direct System-State Sensors:* In some situations, transmission capability is not limited by individual devices but rather by region-wide dynamic loadability constraints. These include transient stability limitations, oscillatory stability limitations, and voltage stability limitations.

Because the time frame associated with these phenomena is much shorter than that associated with thermal overloads, predicting, detecting and responding to these events requires much faster real-time state sensors than for thermal conditions. The system state is characterized ultimately by the voltage magnitudes and angles at all the system buses. The goal of these sensors is to provide these data at a high sampling rate.

- *Power-System Monitors*
  Objective: Collect essential signals (key power flows, bus voltages, alarms, etc.) from local monitors available to site operators, selectively forwarding to the control center or to system analysts.
  Benefits: Provides regional surveillance over important parts of the control system to verify system performance in real time.
  Barriers: Existing SCADA and Energy Management Systems provide low-speed data access for the utility's infrastructure. Building a network of high-speed data monitors with intra-regional breadth requires collaboration among utilities within the interconnected power system.
  Commercial Status: BPA has developed a network of dynamic monitors collecting high-speed data, first with the power system analysis monitor (PSAM), and later with the portable power system monitor (PPSM), both early examples of WAMS products.

- *Phasor Measurement Units (PMUs)*
  Objective: PMUs are synchronized digital transducers that can stream data, in real time, to phasor data concentrator (PDC) units. The general functions and topology for this network resemble those for dynamic monitor networks. Data quality for phasor technology appears to be very high, and secondary processing of the acquired phasors can provide a broad range of signal types.
  Benefits: Phasor networks have best value in applications that are mission critical and that involve truly wide-area measurements.
  Barriers: Establishing PMU networks is straightforward and has already been done. The primary impediment is cost and assuring value for the investment (making best use of the data collected).
  Commercial Status: PMU networks have been deployed at several utilities across the country.