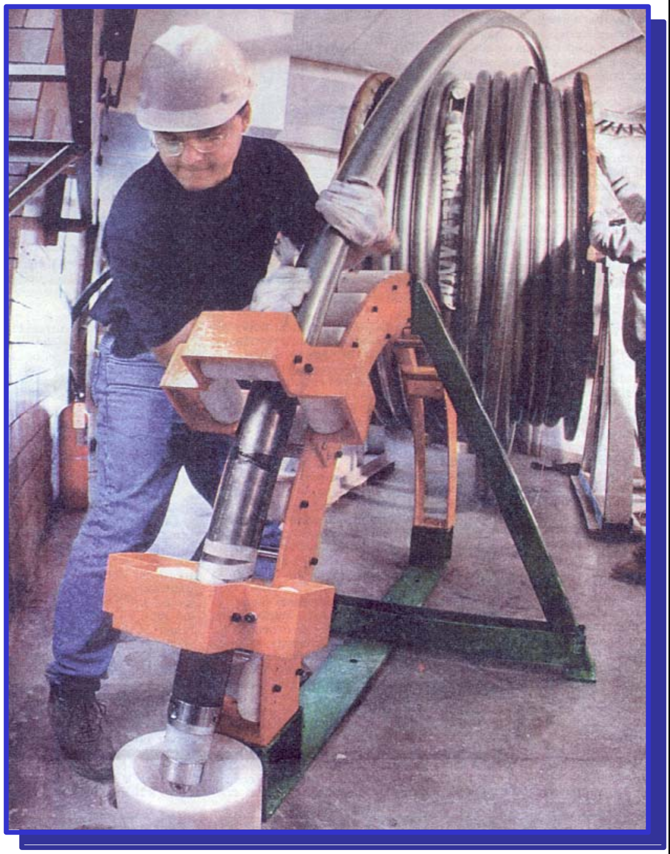
1.3 INFRASTRUCTURE

1.3.1 HIGH-TEMPERATURE SUPERCONDUCTIVITY

Technology Description



The United States' ongoing appetite for clean, reliable, and affordable electricity has increased at a rate that seriously threatens to exceed current capacity. Demand is estimated to increase by an average rate of 1.8% per year for the next 20 years, yet investments in transmission and distribution infrastructure have not kept pace with those in generation. Furthermore, a majority of the new gas-fired generation is not optimally sited where existing transmission assets are located. Witnessing the regional outages being experienced throughout the country – and those most recently highlighted in the northeast blackout of August 2003 – the inadequacies of the investment in infrastructure have, in effect, issued a wake-up call for modernizing and expanding grid capacity. High-temperature superconducting (HTS) wires can carry many more times the amount of electricity of ordinary aluminum or copper wires. HTS materials were first discovered in the mid-1980s and are brittle oxide, or ceramic-like materials, that can carry electricity with virtually no resistance losses. Through years of Federal research in partnership with companies throughout the nation, technology has developed to bond these HTS materials to various metals, providing the flexibility to fashion these ceramics into wires for use in transmission cables and for coils for power transformers, motors, generators, and the like. Superconducting technologies make possible electric power equipment that is half the size of conventional alternatives, with half the energy losses. When HTS equipment becomes pervasive, up to 50% of the energy now lost in transmission and distribution will become available for customer use. HTS also will reduce the impact of power delivery on the environment and is helping create a new high-tech industry to help meet industry challenges due to delays in electric utility restructuring. Other benefits of superconducting electric power systems include improved grid stability, reliability, power quality, and deferred generation expansion. Affordability of capacity expansion is also enhanced, because underground superconducting cables require only 10% of the rights-of-way of conventional overhead transmission; and because HTS cables may be installed in conventional underground ducts without extensive street excavation.

System Concepts

- HTS cables have almost no resistance losses and can transport three-five times as much power as a conventional cable in the same size conduit.
- HTS power transformers have about 30% reduction in total losses, can be 50% smaller and lighter than conventional units, have a total ownership cost that is about 20% lower, are nonflammable, and do not contain oil or any other potential pollutant. In addition, there are electrical performance benefits associated with current limiting capacity and reduced impedance that will yield cost savings to power companies.
- HTS Fault Current Limiters can provide power companies with surge protection within the transmission and distribution system. They are reusable, require minimal maintenance, and do not need replacement after being activated.

- HTS motors with more than 750 kW would save enough energy over their lifetime to pay for the motor. Replacement of all U.S. motors greater than 750-kW with HTS motors would save consumers $2 billion per year in electricity costs. The motors are 50% smaller and lighter than conventional motors, as well.
- HTS generators with more than 100 MVA output will be more energy efficient, compact, and lighter than the conventional generator. The generator has characteristics that may help stabilize the transmission grid.

System Components

- HTS cables consist of large numbers of wires containing HTS materials operating at 65-77 K, insulated thermally and electrically from the environment. A cryogenic refrigerating system maintains the temperature of the cable, at the desired operating temperature, regardless of the load on the cable.
- HTS transformers use the same types of HTS materials as cables, formed into coils and mounted on conventional transformer cores. Electrical insulation is accomplished by means other than conventional oil-and-paper, and typically involves a combination of solid materials, liquid cryogens, and vacuum. HTS transformers may be overloaded for periods of time without loss of transformer life.
- HTS motors, generators, magnetic separators, and current limiters use HTS wires and tapes in a coil form. Rotating cryogenic seals provide cooling for the rotating machines.
- HTS flywheel systems use nearly frictionless bearings made from superconducting "discs," cooled below the transition temperature of the HTS materials.

Technology Status/Applications

- HTS wires: First generation "BSCCO" wires are available today in kilometer lengths at about $200/kA-m. Prototype, pre-commercial, second-generation "coated conductors" have been made in 10-100 m lengths by industry and are to be scaled up in 2006-2008 to 1,000-m lengths. The 100-m tapes carry approximately 100 amperes of current in nitrogen.
- HTS cables: Under the DOE Superconductivity Partnership Initiative (SPI), a team led by Southwire Company has installed and successfully tested a 30-m prototype cable that has been powering three manufacturing plants in Carrollton, Georgia, since February 2000. Three new HTS cable demonstration projects are planned with partial DOE funding from the SPI for 2006. A 600-m cable to be operated at 138-kV will be installed on Long Island, New York; and a 350-m distribution cable will be installed in downtown Albany, New York. A section of the 350-m cable will also be manufactured using second-generation "coated conductors." A 200-m HTS distribution cable carrying 3,000 amperes will be installed at a suburban substation in Columbus, Ohio.
- HTS transformers: Waukesha Electric Systems, with partial DOE funding, demonstrated a 1-MVA single-phase prototype transformer in 1999 and is leading a team developing technology needed for electrical insulation that would be used for a pre-commercial, three-phase prototype transformer.
- HTS motors: Rockwell Automation successfully demonstrated a prototype 750-kW motor in 2000 and is designing a motor with improved performance characteristics.

Current Research, Development, and Demonstration

RD&D Goals

- Performance: HTS wires with 100 times the capacity of conventional copper/aluminum wires. More broadly, the program aims to develop and demonstrate a diverse portfolio of electric equipment based on HTS, such that the equipment can achieve a 50% reduction in energy losses compared to conventional equipment and a 50% size reduction compared to conventional equipment with the same rating. Low-cost, high-performance, second-generation coated conductors are expected to become available in 2008 in kilometer-scale lengths.
- Cost: (a) for the conducting wire, the aim for $0.01/ampere-meter; (b) equipment premium cost payback (efficiency savings) to be achieved in two-five years of operation; and (c) equipment total cost payback to be achieved during the operating lifetime. For coated conductor goals for applications in liquid nitrogen, the wire cost goal is to be less than $50/kA-m; while for applications requiring cooling to temperatures of 20-60 degrees K, the cost goal is to less than $30/kA-m. By 2010, the cost-performance ratio will have improved by at least a factor of 2.

RD&D Challenges

- The manufacture of promising HTS materials in long lengths with minimum defects and low loss, all at low cost, remains a key program challenge.
- Materials for cryogenic insulation and standardized, high-efficiency refrigerators (approaching 30% of Carnot efficiency) are required.
- Improved dielectric materials used to insulate electric power equipment at cryogenic temperatures are required.
- Scale-up of national laboratory discoveries for "coated conductors" requires the use of film industry or semiconductor industry processing expertise and equipment to make kilometer-long electric wires and is a key activity for the labs and their industry partners. Fashioning these long wires into commercially viable forms needed to wind low-loss coils is also a key challenge.

RD&D Activities

- DOE funding is used for three key program activities: Second Generation Wire Research, the Superconductivity Partnership Initiative, and Strategic Research. Performers include national laboratories, industry, academia, and other Federal agencies.

Recent Progress

- The development at the national laboratories of ion-beam assisted deposition and rolling-assisted, biaxially textured substrate (RABiTS™) technologies for producing high-performance HTS film conductors suitable for cables and transformers, and the involvement of four unique industry-led teams to capitalize on it, was a major success story for FY 1997.
- The world's first HTS cable to power industrial plants exceeded 28,000 hours of trouble-free operation in Carrollton, Georgia, (Southwire Company) in early 2005, and is the world's longest-running superconducting cable. The 30-m cable system has been operating unattended since June 2001.
- Short lengths of coated conductors made under stringent laboratory conditions exceeded the DOE goal of 1,000 A/cm width.
- SuperPower verified greater than 80% current limiting performance of proof-of-concept Fault Current Limiter at up to 8,660 volts.
- Rockwell Automation demonstrated a prototype 1000-HP synchronous motor that exceeded design specifications by 60%, and is now designing a motor that would use second-generation coated conductors with enhanced performance-to-cost ratio for the industrial marketplace.

Commercialization and Deployment Activities

- High-temperature superconducting cables and equipment: Commercialization and market introduction requires development of inexpensive wires for transmission and distribution, and end uses such as electric motors. These wires are now under development under a government-industry partnership but are still years from wide-scale use. In addition, there is an international race underway to develop and deploy the new second-generation coated conductors. Numerous companies in Europe, Japan, Korea and China are pursuing the technologies first demonstrated by the national labs. Using high-temperature superconductivity wires to replace existing electric wires and cables may be analogous to the market penetration that occurred when the United States moved from copper wire to fiber optics in communications. Some pre-commercial demonstrations using commercial BSCCO wires are underway, but the Superconductivity Partnerships with Industry and the Second-Generation Wire Initiative could be expanded to include additional U.S. companies.

1.3.2 TRANSMISSION AND DISTRIBUTION TECHNOLOGIES

Technology Description

The electric utility industry is restructuring itself from a regulated environment to operation under competitive wholesale electricity markets. However, the electric transmission and distribution (T&D) systems remain regulated entities that connect in many regions deregulated generation to the end-use customer. Construction of U.S. transmission above 230 kV is expected to increase by only 6% (in line-miles) during the next 10 years, while demand is expected to increase more than 20%. The resulting increase in the intensity of use of existing facilities will increase energy losses and transmission congestion, and is likely to cause grid reliability problems and threaten the continued growth of wholesale electricity trade.

Energy losses in the U.S. T&D system were 7.2% in 1995, accounting for 2.5 quads of primary energy and 36.5 MtC. Losses are divided such that about 60% are from lines and 40% are from transformers (most of which are for distribution). Technologies that can improve efficiency and reduce carbon emissions are high-voltage DC (HVDC) transmission, high-strength composite overhead conductors, and power transformers and underground cables that use high-temperature superconductors (see related technology profile). High-efficiency conventional transformers also could have significant impacts on reducing distribution system losses. In addition, energy storage and real-time system monitoring and control systems could improve system reliability and customer access to competitive generation, including renewable power producers. There is no active U.S. program for HVDC development or improved distribution transformer technologies.

System Concepts

- Composite-core, low-sag transmission conductors can transport two to three times as much power as conventional conductors over the same rights-of-way and with no tower modifications.
- Energy storage will facilitate more optimal use of existing infrastructure and increase the dispatchability of renewable resources.
- Real-time grid operations using measured data and automatic, intelligent controllers can improve T&D reliability – and lead to a smart, switchable future network that can anticipate and respond automatically to system contingencies.

System Components

- One advanced composite overhead transmission line conductor consists of an aluminum metal matrix composite core (replacing the steel core of a conventional conductor) surrounded by temperature-resistant aluminum alloy wires.
- Several large- and medium-scale energy-storage systems, using different electrochemistries, have been developed.
- Real-time control uses wide-area measurement systems, synchronized by global positioning system (GPS) satellite clocks that feed system information to intelligent electronic controllers. The controllers reconfigure the system in real time, preventing outages and allowing maximum use of available transmission capacity.

Technology Status/Applications

- Aluminum composite-core conductors, terminations, and suspensions have been developed by 3M Company and demonstrated in the field by leading U.S. and European utilities. Successful field trials in the United States and accelerated thermal cycling tests occurred in 2003-2005. This extensive mechanical and electrical testing is required to predict the 40-year life responses of this new conductor technology. Niche applications including long-span river crossings and short lead-time reconductoring over congested existing rights-of-way are now cost-effective. In addition, the conductor's core has 25% lower electrical resistances than steel, enabling higher transmission efficiencies. The first commercial sale of composite-core conductors was installed on a 10-mile (16 km) Minnesota transmission line in 2005.

- Large-scale energy-storage systems are entering field demonstrations.
- Wide-area grid measurement systems used for monitoring, event analysis, and system model studies have been deployed in the western United States power grid to help analyze system disturbances, particularly those that threaten grid collapse and blackout..

Current Research, Development, and Demonstration

RD&D Goals

- By 2010, demonstrated reliability of energy-storage systems; reduced cost of advanced conductors systems by 30%; and operation of a prototype smart, switchable grid on a region on the U.S. transmission grid.

RD&D Challenges

- Development of large-diameter composite conductors for high-voltage transmission lines that are both low-cost and high capacity, so as to yield the highest payoffs in grid reliability and competitive market efficiency.
- Energy-storage systems with reduced costs that can meet several applications while using a single system.
- Neural net and intelligent agent networks that can be trained in parallel to perform control functions in real-time control systems.
- A regulatory framework that will allow investors to make credible projections of the return on investment in new transmission capacity.

RD&D Activities

- For composite conductors, 3M Company cost-shared on a DOE effort in FY2002 and FY2003 to perform field tests and accelerated, controlled thermal tests on several conductor sizes.
- DOE is cost-sharing an energy-storage effort with industry. EPRI has a newly reformed energy storage target.
- DOE is leading a large working group to address software, hardware, communications, data management, performance, and business issues needed to deploy a real-time phasor measurement (early-warning) network in the Eastern Interconnection of the U.S. grid.

Recent Successes

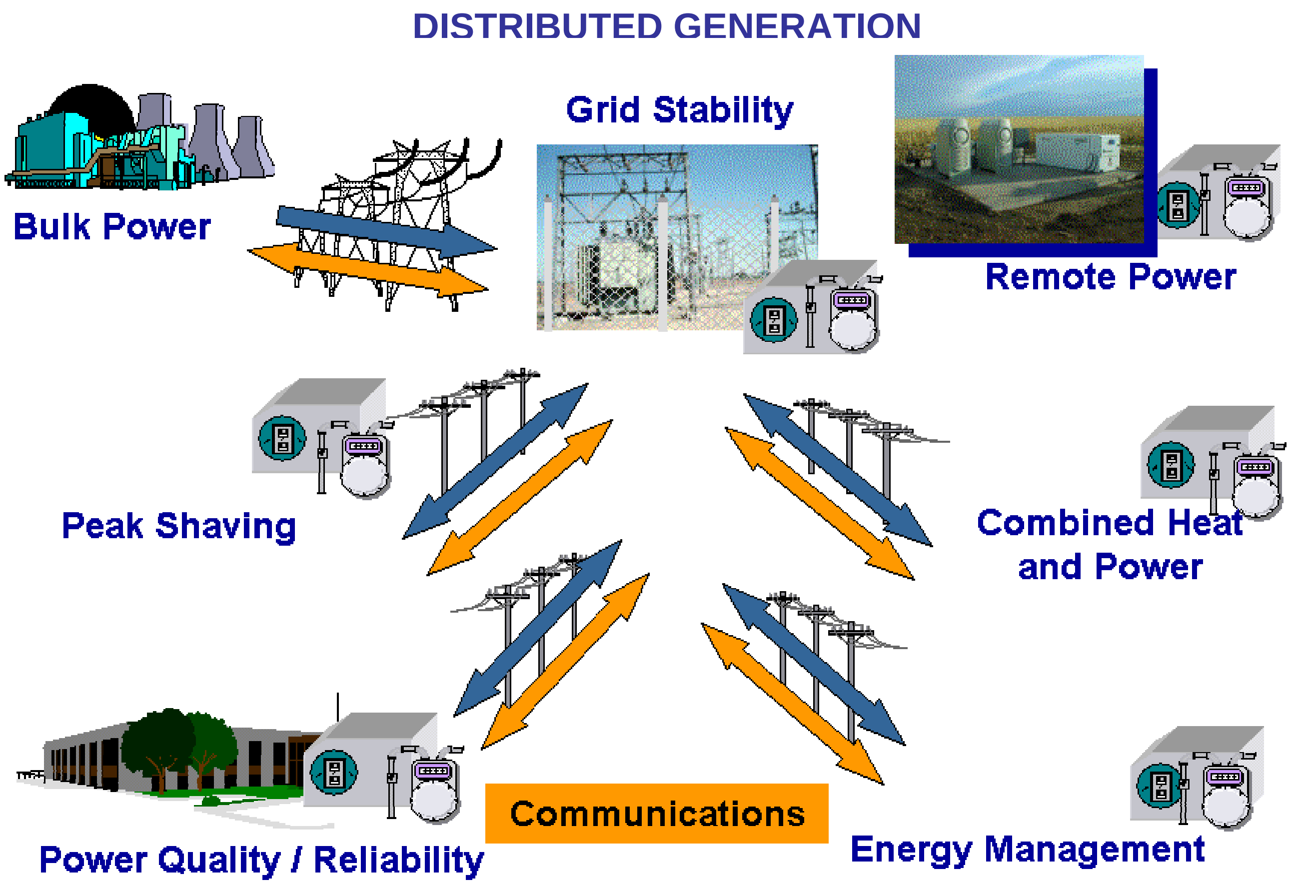
- DOE's *National Transmission Grid Study*, released in May 2002, examined issues surrounding U.S. transmission system upgrades and expansion, and contains 51 recommendations for actions to remove constraints on the U.S. transmission grid.
- Real-time grid early-warning monitoring tools have been developed by DOE and installed in California with funding by the California Energy Commission, and at the North American Electric Reliability Council (NERC) to monitor and display voltage and frequency over wide areas of the Western Interconnection of the U.S. grid.
- Various DOE demand response (DR) projects are assisting independent transmission system operators (ISOs) with DR program design and evaluation to better bring customers into wholesale markets, thus allowing load to be better used as a resource.

Commercialization and Deployment Activities

- Commercial deployment of high-current composite conductors awaits U.S. field trial results, and manufacturing cost reductions for all but high-value niche applications.

1.3.3 DISTRIBUTED GENERATION AND COMBINED HEAT AND POWER

Technology Description



Distributed generation, including combined heat and power (CHP), can be distinguished from central energy resources in several respects. These distributed energy resources are small, modular, and come in a range of capacities from kilowatts to megawatts. They comprise a portfolio of technologies that can be located onsite or nearby the location where the energy is used. They provide the consumer with a greater choice, local control, and more efficient waste utilization to boost efficiency and lower emissions.

System Concepts

- The portfolio of distributed generation technologies includes, for example, photovoltaic systems, fuel cells, natural gas engines, industrial turbines, microturbines, energy-storage devices, wind turbines, and concentrating solar power collectors. These technologies can meet a variety of consumer energy needs including continuous power, backup power, remote power, and peak shaving. They can be installed directly on the consumer's premise or located nearby in district energy systems, power parks, and mini-grids.
- CHP technologies have the potential to take all of the distributed generation technologies one step further in pollution prevention by utilizing the waste heat from the generation of electricity for the making of steam, heating of water, or for the production of cooling energy. The average power plant in the United States converts approximately one-third of the input energy into output electricity and then discards the remaining two-thirds of the energy as waste heat. Integrated DG systems with CHP similarly produce electricity at 30% to 45% efficiency, but then capture much of the waste heat to make steam, heat, or cool water – or meet other thermal needs and increase the overall efficiency of the system to greater than 70%.

System Components

- Advanced industrial turbines and microturbines – combustion turbines are a class of electric-generation devices that produce high temperature, high-pressure gas to induce shaft rotation by impingement of the gas on a series of specially designed blades. Simple cycle efficiencies range from 21% to 40%. Turbines produce high-quality heat and can be used for CHP production. Microturbines are small combustion turbines with outputs of 25-1,000 kW. Microturbines evolved from automotive and truck turbochargers.
- Energy-storage systems – the combination of an energy-storage device (e.g., a battery or a flywheel) and a power-conversion system to connect the storage device with the local grid.
- Concentrating solar power – concentrating solar power systems use suntracking mirrors to reflect and concentrate sunlight into receivers where it is converted to high-temperature thermal energy, which can then be used to drive turbines to generate electricity.
- Fuel cells – power is produced in fuel cells electrochemically by passing a hydrogen-rich fuel over an anode and air over a cathode and separating the two by an electrolyte in producing electricity. The only byproducts are heat, water, and carbon dioxide.
- Natural Gas Engines – the reciprocating engine is widespread and well-known technology. Spark ignition gas-fired units (the focus here) typically use natural gas or propane. Capacities are typically in the 0.5- to 5-megawatt range.
- Photovoltaic Systems – photovoltaic systems use semiconductor-based cells to convert sunlight directly to electricity.
- Hybrid Systems – hybrid systems consist of two or more types of distributed energy technologies.
- Wind Energy Systems – wind turbines convert the kinetic energy of wind into electricity.

Technology Status/Applications

- Industrial gas turbines and natural gas reciprocating engines are existing technologies that are being utilized and have a great deal of potential.
- Microturbines, concentrating solar power, fuel cells, wind energy, photovoltaic systems, and hybrid systems are currently under development.
- CHP is a proven technology, responsible for 8% of U.S. electricity generation. The potential for expanding the use of CHP in the United States is enormous – the Department of Energy and the Environmental Protection Agency have a goal of doubling CHP capacity to 92 GW by 2010.

Current Research, Development, and Demonstration

RD&D Goals

- Research is needed to increase the efficiency and reduce the emissions from microturbines, reciprocating engines, and industrial gas turbines to allow them to be sited anywhere, even in nonattainment areas.
- Research is needed to increase the efficiency of waste-heat-driven absorption chillers and desiccant systems to overall efficiencies well above 80%
- The overall research goal of the Distributed Energy Program is to develop and make available, by 2015, a diverse array of high-efficiency, integrated distributed generation and thermal energy technologies, at market-competitive prices, enabling and facilitating widespread adoption and use by homes, businesses, industry, communities, and electricity companies that may elect to use them.
- If successful, these technologies will enable the achievement of a 20% increase in a building's energy utilization (when compared to a building built to ASHRAE 90.1 standards), using load management, CHP, and energy-storage technologies that are replicable to other localities.

RD&D Challenges

- Provide lower cost and more efficient systems.
- Improve the reliability.
- Solve the institutional and regulatory barriers such as a lack of widely used technical interconnection standards.
- Enhance the implementation of CHP with technologies such as microturbines, fuel cells, gas turbines and reciprocating engines.

RD&D Activities
RD&D Activities • Direct and coordinate a diverse portfolio of research development and demonstration investments in distributed natural gas technologies. • Conduct supporting RD&D and enabling technologies. • Direct and coordinate a diverse portfolio of RD&D energy generation and delivery systems architecture for distributed energy. • Coordinate activities with RD&D and renewable energy technologies. • Conduct system integration, implementation, and outreach activities aimed at addressing infrastructure, institutional, and regulatory needs.
Recent Progress
• DOE's advanced turbine system program has developed an industrial gas turbine with Solar Turbines, Inc., for a 48%-efficient simple-cycle machine. CHP is currently at 50 GW of installed capacity. • Wind energy generation is experiencing rapid growth in various western and eastern United States locations. • Microturbines have achieved more than 10,000 hours of operations and preliminary tests. • The Southern Company accepted a SAFT/SatCon LiIon System developed by the DOE ESS program that provided three times the 100kW/1 minute rated performance. Southern agreed to test the battery system at no cost, because it can supplement a distributed energy resource (in this case a microturbine) and provide load-following capability.
Commercialization and Deployment Activities
• Advanced industrial gas turbines in the range of 1 to 50 MW are starting to be deployed. • Natural gas reciprocating engines of 0.5-5 MW with efficiencies of 30%-40% are now being deployed. • The DOE and EPA CHP programs are cooperating to actively promote the use of CHP to add about 46 GW of new CHP capacity by 2010. **Markets** • Distributed generation, including CHP, is currently helping the U.S. economy and has the potential to enhance the electric infrastructure. These technologies could produce more than 100 GW of generated capacity for the U.S. electric system.

1.3.4 ENERGY STORAGE

Technology Description

A 5-MVA battery energy-storage system for power quality and peak shaving.

Advanced storage technologies under active development include processes that are mechanical (flywheels, pneumatic), electrochemical (advanced batteries, reversible fuel cells, hydrogen, ultracapacitors), and purely electrical (superconducting magnetic storage). Energy storage devices are added to the utility grid to improve productivity, increase reliability or defer equipment upgrades. Energy storage devices must be charged and recharged with electricity generated elsewhere. Because the storage efficiency (output compared to input energy) is less than 100%, on a kilowatt-per-kilowatt basis, energy storage does not directly decrease CO_2 production. The exception to this rule is the use of advanced energy storage in conjunction with intermittent renewable energy sources, such as photovoltaics and wind, that produce no direct CO_2. Energy storage allows these intermittent resources to be dispatchable.

Energy-storage devices do positively affect CO_2 production on an industrial output basis by providing high-quality power, maximizing industrial productivity. New battery technologies, including sodium sulfur and flow batteries, significantly improve the energy and power densities for stationary battery storage as compared to traditional flooded lead-acid batteries.

System Concepts

- *Stationary applications:* The efficiency of a typical steam-power plant falls from about 38% at peak load to 28%-31% at night. Utilities and customers could store electrical energy at off-peak times, allowing power plants to operate near peak efficiency. The stored energy could be used during high-demand periods displacing low-efficiency peaking generators. CO_2 emissions would be reduced if the efficiency of the energy storage were greater than 85%. Energy storage also can be used to alleviate the pressure on highly loaded components in the grid (transmission lines, transformers, etc.) These components are typically only loaded heavily for a small portion of the day. The storage system would be placed downstream from the heavily loaded component. This would reduce electrical losses of overloaded systems. Equipment upgrades also would be postponed, allowing the most efficient use of capital by utility companies. For intermittent renewables, advnaced energy storage technology would improve their applicability.
- *Power quality:* The operation of modern, computerized manufacturing depends directly on the quality of power the plant receives. Any voltage sag or momentary interruption can trip off a manufacturing line and electronic equipment. Industries that are particularly sensitive are semiconductor manufacturing, plastics and paper manufacturing, electronic retailers, and financial services such as banking, stock brokerages, and credit card-processing centers. If an interruption occurs that disrupts these processes, product is often lost, plant cleanup can be required, equipment can be damaged, and transactions can be lost. Any loss must be made up decreasing the overall efficiency of the operation, thereby increasing the amount of CO_2 production required for each unit of output. Energy-storage value is usually measured economically with

the cost of power-quality losses, which is estimated in excess of $1.5 B/year in the United States alone. Industry is also installing energy-storage systems to purchase relatively cheap off-peak power for use during on-peak times. This use dovetails very nicely with the utilities' interest in minimizing the load on highly loaded sections of the electric grid. Many energy-storage systems offer multiple benefits. (An example is shown in the photo.) This 5-MVA, 3.5-MWh valve-regulated lead-acid battery system is installed at a lead recycling plant in the Los Angeles, California, area. The system provides power-quality protection for the plant's pollution-control equipment, preventing an environmental release in the event of a loss of power. The system carries the critical plant loads while an orderly shutdown occurs. The battery system also in discharged daily during the afternoon peak (and recharged nightly), reducing the plant's energy costs.

Representative Technologies

For utilities, the most mature storage technology is pumped hydro; however, it requires topography with significant differences in elevation, so it's only practical in certain locations. Compressed-air energy storage uses off-peak electricity to force air into underground caverns or dedicated tanks, and releases the air to drive turbines to generate on-peak electricity; this, too, is location specific. Batteries, both conventional and advanced, are commonly used for energy-storage systems. Advanced flowing electrolyte batteries offer the promise of longer lifetimes and easier scalability to large, multi-MW systems. Superconducting magnetic energy storage (SMES) is largely focused on high-power, short-duration applications such as power quality and transmission system stability. Ultracapacitors have very high power density but currently have relatively low total energy capacity and are also applicable for high-power, short-duration applications. Flywheels are now commercially viable in power quality and UPS applications, and emerging for high power, high-energy applications.

Technology Status - Utilities

Technology	Efficiency [%]	Energy density [W-h/kg]	Power density [kW/kg]	Sizes [MW-h]	Comments
Pumped hydro	75	0.27/100 m	low	5,000-20,000	37 existing in U.S.
Compressed gas	70	0	low	250-2,200	1 U.S., 1 German
SMES	90+	0	high	20 MW	high-power applications
Batteries	70–84	30-50	0.2-0.4	17-40	Most common device
Flywheels	90+	15-30	1-3	0.1-20 kWh	US & foreign development
Ultracapacitors	90+	2-10	high	0.1-0.5 kWh	High-power density

System Components

Each energy-storage system consists of four major components: the storage device (battery, flywheel, etc.); a power-conversion system; a control system for the storage system, possibly tied in with a utility SCADA (Supervisory Control And Data Acquisition) system or industrial facility control system; and interconnection hardware connecting the storage system to the grid. All common energy-storage devices are DC devices (battery) or produce a varying output (flywheels) requiring a power conversion system to connect it to the AC grid. The control system must manage the charging and discharging of the system, monitor the state of health of the various components and interface with the local environment at a minimum to receive on/off signals. Interconnection hardware allows for the safe connection between the storage system and the local grid.

Current Research, Development, and Demonstration

RD&D Goals

- Research program goals in this area focus on energy-storage technologies with high reliability and affordable costs. For capital cost this is interpreted to mean less than or equal to those of some of lower cost new power generation options ($400–$600/kW). Battery storage systems range from $300-$2000/kW. For operating cost, this figure would range from compressed gas energy storage, which can cost as little as $1 to $5/kWh, to pumped hydro storage, which can range between $10 and $45/kWh.

RD&D Challenges

- The major hurdles for all storage technologies are cost reduction and developing methods of accurately identifying all the potential value streams from a given installation. Advanced batteries need field experience and manufacturing increases to bring down costs. Flywheels need further development of failsafe designs and/or lightweight containment. Magnetic bearings could reduce parasitic loads and make flywheels attractive for small uninterruptible power supplies and possibly larger systems using multiple individual units. Ultracapacitor development requires improved large modules to deliver the required larger energies. Advanced higher-power batteries with greater energy storage and longer cycle life are necessary for economic large-scale utility and industrial applications.

RD&D Activities

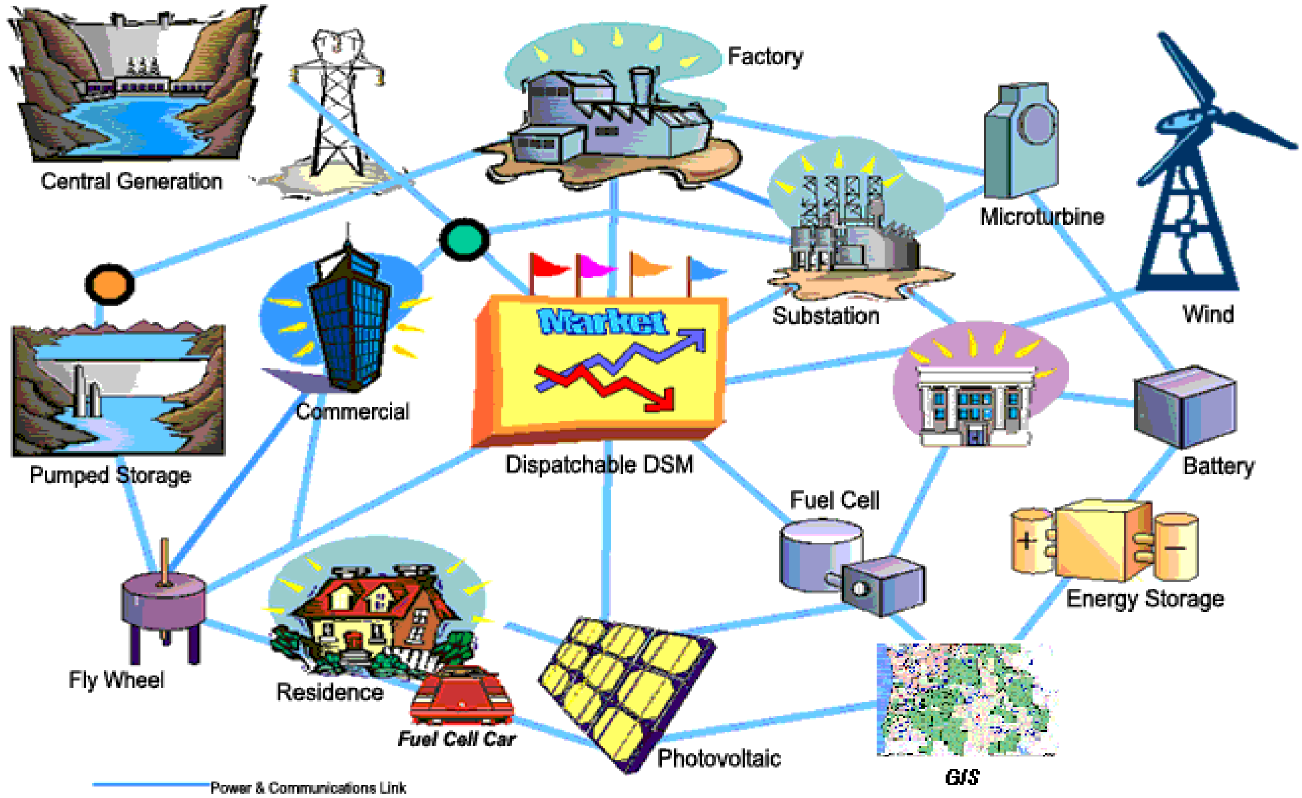
- The Japanese are investing heavily in high-temperature, sodium-sulfur batteries for utility load-leveling applications. They also are pursuing large-scale vanadium reduction-oxidation battery chemistries. The British are developing a utility-scale flow battery system based on sodium bromine/sodium bromide chemistry. DOE's Energy Storage Systems Program works on improved and advanced electrical energy storage for stationary (utility, customer-side, and renewables) applications. It focuses on three areas: system integration using near-term components including field evaluations, advanced component development, and systems analysis. This work is being done in collaboration with a number of universities and industrial partners.

Commercialization and Deployment Activities

- For utilities, only pumped hydro has made a significant penetration with approximately 37 GW.
- Approximately 150 MW of utility peak-shaving batteries are in service in Japan.
- Two 10-MW flow battery systems are under construction – one in the United Kingdom and the other in the United States.
- Megawatt-scale power quality systems are cost effective and entering the marketplace today.

1.3.5 SENSORS, CONTROLS, AND COMMUNICATIONS

Technology Description



Improved sensors and controls, as part of the next-generation electricity transmission and distribution system, could significantly increase the efficiency of electricity generation and delivery, thereby reducing the greenhouse gas emissions intensity associated with the electric grid. Sensors and controls can play a key role in the development of the nation's next-generation electric T&D system. In the grid of the future, distributed energy resources can be fully integrated into grid operations, providing a robust energy infrastructure enhanced by local protection and control measures. The communication and control challenges associated with this evolution are significant. Local system conditions can be sensed, and local intelligent agents can process the data and communicate decision commands to local controllers for problem rectification and performance optimization. These local sensors and distributed software agents can assess adequacy and security with only high-level oversight from the central control authority. Distribution system and transmission grid reliability can be significantly improved by higher levels of local distributed energy generation using power electronics to control and manage two-way power flow as directed by local sensors and intelligent agents. Research on sensors, controls, and communications focuses on developing distributed intelligent systems to diagnose local faults and coordinate with power electronics and other existing, conventional protection schemes that will provide autonomous control and protection at the local level. This hierarchy will enable isolation and mitigation of faults before they cascade through the system. The work will also help users and electric power-system operators achieve optimized control of a large, complex network of systems; and will provide remote detection, protection, control, and contingency measures for the electric system.

System Concepts

- In the future, there must be a rapid, widespread measurement and control system that enables distributed energy generation to provide highly reliable services under all disturbance scenarios. Local control of such highly reliable services will improve local power quality and improve the efficiency of the distribution

system. This will be done with local sensors and "intelligent agents" that monitor local conditions and provide local responses.
- Conventional utility sensors, while robust and reliable, are quite expensive. Low-cost, reliable and robust sensors must be developed that can monitor current flow, voltage, and phase angle throughout the distribution system. These sensors would provide the intelligent agents with the information they need to make rapid, correct decisions.

Representative Technologies
- Low-cost physical sensors will be used to measure voltage, current, temperature, phase angle, and for other electric distribution and grid system characterization applications.
- The system architecture will be dependent on the ability of intelligent agents to diagnose and forecast local faults. This will involve placing a number of sensors, intelligent agents, and controllers at strategic locations.
- The sensing, communication, and information analysis required for intelligent decision making must happen in real time or near real time (in seconds), sufficiently faster than the time required to affect coordination, control, and protection schemes.
- Communications must take place to advise the central controller of the local system status, perform critical nonrepudiating functions to manage the electricity commerce, and enable real-time markets for energy and ancillary services.

Technology Status/Applications
- The variety of transduction methods and the capability to fabricate small, rugged sensor devices has advanced tremendously during the past five years. Modern techniques for fabricating electronic devices allow unprecedented miniaturization of sensors and electronic controls.
- Rapid analysis of sensor data and feedback control is also advancing, often enabled by microprocessor technology.
- Rapid, low-cost communications methods are also undergoing fast-paced advancement in wireless and fiber-optic technologies.

Current Research, Development, and Demonstration

RD&D Goals
- The initial research program goals for sensors, controls, and communications will be to develop, validate, and test computer-simulation models of the distribution system to assess the alternative situations. Once the models have been validated on a sufficiently large scale, the functional requirements and architecture specifications can be completed. Then, more specific technology solutions can be explored that would conform to the established architecture.

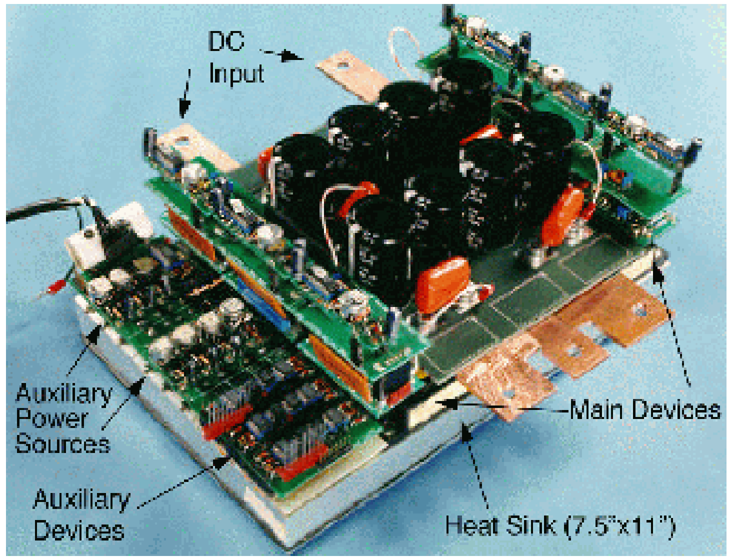
RD&D Challenges
- A challenge will be the development of cost-effective fault detection and control systems that can be readily implemented in the nation's power grid. The electricity market with an ever-increasing demand for highly reliable services is a key factor in the development of the new control system.
- In response to market communications, distributed energy generation must be capable of supplying the highly reliable services presently provided by large turbine generators, such as spinning reserves, reactive power supply, and voltage and frequency regulation. The entire control scheme is now based on the response of the large generation stations to supply these services. Traditionally, it has been considered to be too difficult to use distributed energy generation to supply these services because there are simply too many units to control reliably and quickly.

RD&D Activities
- Within DOE, sensor and control programs are being developed to focus on issues related to system architecture, distributed intelligence, interconnection technologies and standards, simulation and modeling of the distribution system, load/demand management, and aggregation testing and control of a suite of distributed energy resources.
- Workshops have been held with utilities; energy service companies; and providers of communications, sensor, control, and information technologies to plan strategies and develop roadmaps.

Recent Progress
• A Grid-Friendly™ appliance controller, based on the gate array chip, is being developed to monitor the power grid while controlling on-off operations of household appliances (refrigerators, air conditioners, water heaters, etc.) in response to power grid overload. This device has been tested in a laboratory environment and will be tested in a demonstration in the Pacific Northwest, using 200 grid-connected household clothes washer/dryer pairs. • A wireless end-device controller is installed at more than 200 facilities in southwest Connecticut, with the goal of controlling 2-3 megawatts of electricity on a real-time dispatchable basis. The controller collects real-time energy-use information and controls end-use loads (lighting, vending machines, etc.) to manage system peak demand.
Commercialization and Deployment Activities
• There are more than 4,200 sensor and control companies in the United States. Commercialization of sensor technology depends on demonstrating economic viability at a level commensurate with the risks small businesses can assume. **Market Context** • The market for improved sensors and controls cuts across all industrial and transportation sectors. Nuclear, fossil, and end-use efficiency technologies would all benefit.

1.3.6 POWER ELECTRONICS

Technology Description



Improved power electronics, as part of the next-generation electricity T&D system, could significantly increase the efficiency of electricity generation and delivery, thereby reducing the greenhouse gas emissions intensity associated with the electric grid. Power electronics is the technology that is used to provide the interface between different types of electrical power, such as DC and 60-Hz AC. Power electronics equipment transforms frequency, voltage, and power factor. Power levels and voltages from a few kilowatts and 120 volts – all the way up to transmission-level powers and voltages – are now possible with today's technology. Power electronics can enable the simple connection of various types of electrical infrastructure links like distributed energy resources. It can help to regulate voltage in the distribution system and transmission grid, and can solve power-quality and voltage-dip problems. Most important, power electronics can provide for an integrated approach to reliability, where all the components – energy conversion, energy storage, control, and power electronics – work together.

About 60%-70% of the nation's electrical power is used to drive motors and motors are reasonably efficient at their designed or rated speed and load. However, efficiencies can be tremendously improved by operating motors at variable speeds that match the system requirements. Motors driven by power electronics to achieve variable speed capability are increasing dramatically in numbers as the technologies become available. Continued development of power electronic devices with higher power-handling capability and reliability will offer an unprecedented opportunity for U.S. industry and utilities to reduce energy consumption and improve competitiveness.

Power electronic structures have been developed to overcome shortcomings in solid-state switching device ratings so that they can be applied to high-voltage electrical systems. The unique structure of multilevel voltage source power electronics allows them to reach high voltages with low harmonics without the use of transformers. This makes these power electronics suitable for flexible AC transmission systems (FACTS) and custom power applications. The use of power electronics to control the frequency, voltage output (including phase angle), and real and reactive power flow at a DC/AC interface provides significant opportunities in the control of distributed power systems.

As distributed power sources become increasingly prevalent in the near future, power electronics will be able to provide significant advantages in processing power from renewable energy sources using fast response and autonomous control. Additionally, power electronics can control real and reactive power flow from a utility-connected renewable energy source. These power electronic topologies are attractive for continuous control of system dynamic behavior and to reduce problems such as voltage harmonics, voltage imbalance, or sags.

System Concepts

- Advanced inverter topologies: Inverter circuitry that accommodates and takes advantage of advanced solid-state devices while further improving the overall efficiency, packaging, and performance of the inverter.

Representative Technologies

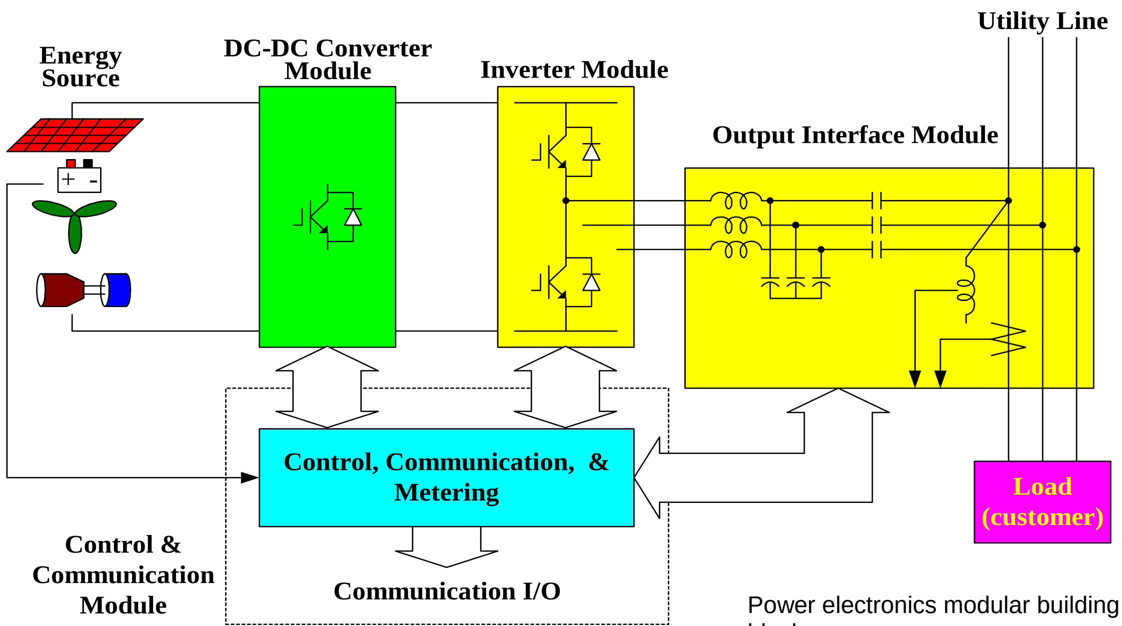
- Megawatt-level inverters, fast semiconductor switches, sensors, and devices for Flexible AC Transmission Systems (FACTS).

Technology Status/Applications

- Transportation: Displacement of internal combustion engines and enabling power electronic components for alternate approaches to standard systems (traction drives, flywheels, auxiliary drives, alternators).

- Industrial: Enabling components for more efficient motors and introduction of adjustable speed drives to match drives to loads for fans, pumps, and compressors.
- Utilities: Power-quality systems, high-voltage DC power transmission systems.
- Renewable energy: Inverters to convert DC power from photovoltaics and wind turbines to AC power.
- Power supplies: Converters embedded in systems to alter the electrical power from one type to another.
- Defense: Grid and equipment interfaces to allow for mobile and emergency backup of transmission and distribution infras.

Current Research, Development, and Demonstration



Power electronics modular building blocks.

RD&D Goals

- The research program goal in this area is to build a power electronic system on a base of modules. Each module or block would be a subsystem containing several components, and each one has common power terminals and communication connections.
- The figure represents a strategy in which the interface is partitioned into four basic blocks with each one performing a different system function: (1) DC-DC converter; (2) power electronics, (3) output interface and filtering; and (4) control, communication, and metering. Each of the power blocks will have their own control and communication interface such that a group of modules can coordinate their actions to act as an ideal interface to interconnect distributed energy resources to the utility system. Also, with each block having its own control and communication interface, these modules can be combined to form a multilevel configuration as well as other series/parallel connections as necessary to meet the voltage and current requirements for the particular installation. In addition, this approach will allow for future capacity increases, enhancement to functionality, redundancy, and reconfiguration.

RD&D Challenges

- Smaller, lighter, more efficient, and lower-cost inverters.
- Increase reliability and lower cost.
- Improved materials and devices: Solders, capacitors, ferrite semiconductors, low-loss drivers, thermal management, passive devices, DC disconnects, connectors, and new semiconductor materials such as silicon carbide.
- Increase modularity of power electronic components.
- Present-day power electronics exhibit a number of serious problems and limitations. Some of the most

significant of these are (1) the need for difficult-to-meet switching device ratings (and associated reliability issues), (2) the need for transformers (and associated design limitations), (3) high cost, (4) control limitations, (5) limitations on voltages that can be attained, (6) creation of high levels of harmonic distortion.

- USCAR is pursuing the development of electric devices as an enabling technology.
- Developing power electronic building blocks.
- The Federal initiatives in transmission and distribution system long-range R&D were canceled.

RD&D Activities

- The DOE Energy Storage Program supports research in power electronics for megawatt-level inverters, fast semiconductor switches, sensors, and devices for Flexible AC Transmission Systems (FACTS). Projects in these areas recently won two R&D 100 awards.
- Office of Naval Research and DOE have a joint program to develop power electronic building blocks.
- The military is developing more electricity-intensive aircraft, ships, and land vehicles, providing power electronic spin-offs for infrastructure applications.
- The Superconductivity Technology Program funds R&D of more efficient motor technology under the Superconductivity Partnership Initiative.

Recent Progress

- Soft-switching inverter topologies have been recently developed for improved inverter efficiency, reliability, and performance.
- High-power solid-state inverters with improved efficiency and reduced cost and size have been developed.
- A multilevel inverter has been developed, which when deployed will allow 26% more energy to be extracted from photovoltaic or other renewable energy sources.

Commercialization and Deployment Activities

- Major U.S. motor and drive manufacturers are beginning to expand their product lines to include improved power electronics.
- U.S. power semiconductor manufacturers are expanding product lines and facilities to regain market position from foreign competitors.