PDHonline Course E306 (4 PDH)

Profiles of Energy Efficient Technology

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2020

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Profiles of Energy Efficient Technologies

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Introduction

This course profiles several technologies that are likely to play prominent roles in reducing greenhouse gases in the future. This material provides a brief overview of each technology and the status of the research and commercialization efforts for the technology. Most of the technologies are related to the generation of electric power, but a few of the technologies concern the energy efficiency of buildings and building systems.
The technologies profiled in the course include biopower, geothermal, concentrating solar power, photovoltaics, wind energy, hydrogen, advanced hydropower, building technologies, reciprocating engines, microturbines, fuel cells, batteries, advanced energy storage, superconducting power technology, and thermally activated technologies.

The first chapter covers biopower, which is the generation of electric power from biomass resources.

Chapter 1
Biopower Technology

Biopower, or biomass power, is the generation of electric power from biomass resources such as waste wood, crop, and forest residues. In the future, crops may be grown specifically for energy production. Biopower reduces most emissions (including emissions of greenhouse gases-GHGs) compared with fossil fuel-based electricity. Because biomass absorbs CO_2 as it grows the entire biopower cycle of growing, converting to electricity, and re-growing biomass can result in very low CO_2 emissions compared to fossil energy without carbon sequestration, such as coal, oil or natural gas.
Biomass products must be processed into a suitable form to be used as a fuel for electric power generation. Three of the most common feedstock conversion technologies include homogenization, gasification, and anaerobic digestion. *Homogenization* is a process by which feedstock is made physically uniform for further processing or for combustion and includes chopping, grinding, baling, cubing, and pelletizing. *Gasification*, from pyrolysis, partial oxidation, or steam reforming, converts biomass to a fuel gas that can be substituted for natural gas in combustion turbines or reformed into H_2 for fuel cell applications. *Anaerobic digestion* produces biogas that can be used in standard or combined heat and power (CHP) applications. Agricultural digester systems use animal or agricultural waste. Landfill gas also is produced anaerobically. Biofuels production for power and heat provides liquid-based fuels such as methanol, ethanol, hydrogen, or biodiesel.

Once the feedstock is converted into a suitable fuel, the fuel can be converted to power and heat by either direct combustion or as a chemical fuel in a fuel cell. Direct combustion systems burn biomass fuel in a boiler to produce steam that is expanded in a Rankine Cycle prime mover to produce power. *Co-firing* substitutes biomass for coal and allows either or both fuels to be used in existing coal-fired boilers. Biomass or biomass-derived fuels, such as ethanol or biodiesel, can also be burned in combustion turbines or engines to produce power. When further processed, biomass-derived fuels can be used by fuels cells to produce electricity.

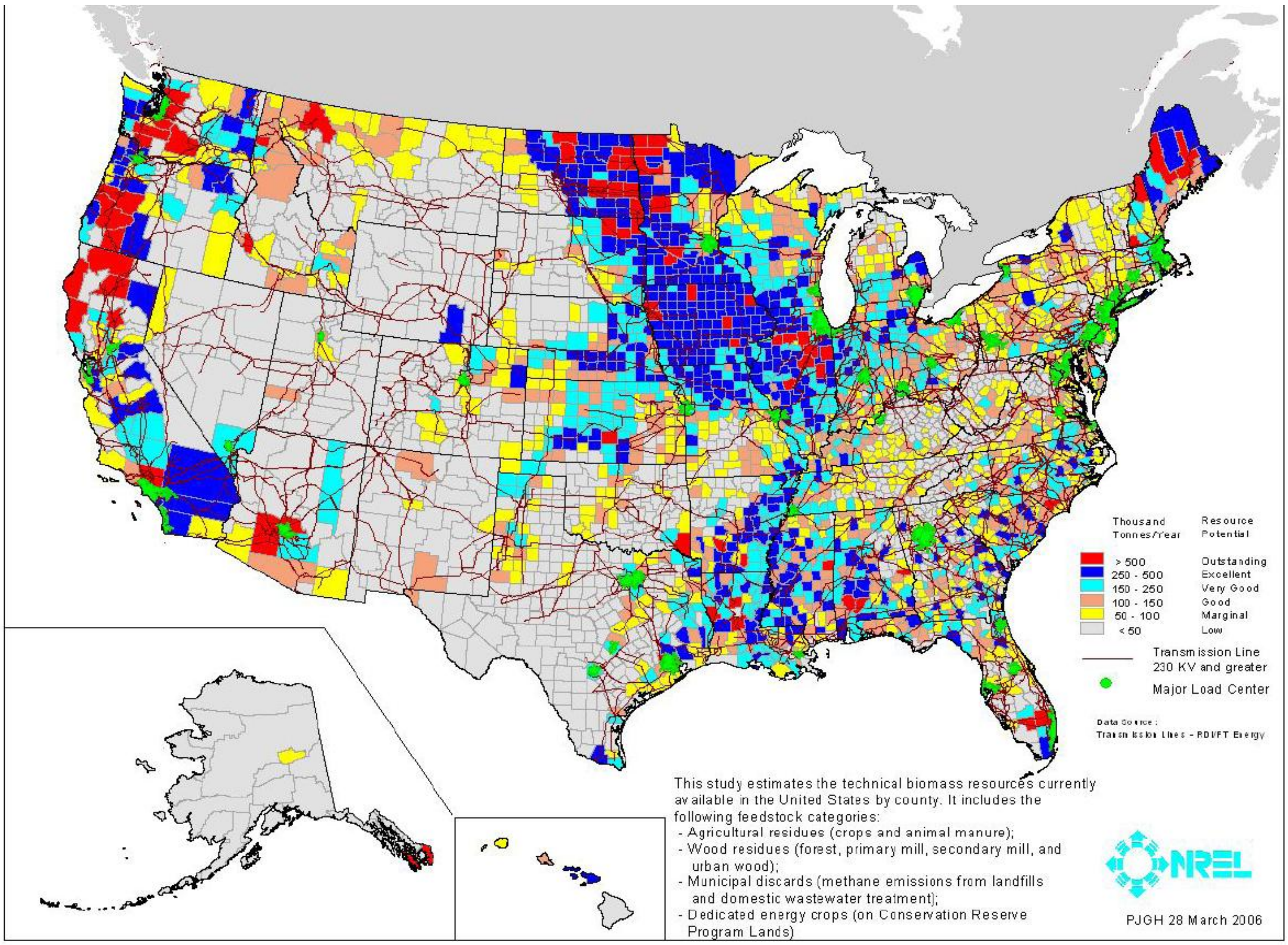
Biopower is generally used in combined heat and power (CHP) systems where the system not only generates electricity, but also recovers heat for steam and/or hot water.

Nearly all current biopower generation is based on direct combustion in small, biomass-only plants with relatively low electric efficiency (20%), although total system efficiencies for CHP can approach 90%. Most biomass direct-combustion generation facilities utilize the basic Rankine cycle for electric-power generation, which is made up of the steam boiler, turbine, condenser, and pump.

For the near term, co-firing is the most cost-effective of the power-only technologies. Large coal steam plants have electric efficiencies near 33%. The highest levels of coal co-firing, 15% on a heat-input basis, require separate feed preparation and injection systems.

Biomass gasification combined-cycle plants promise comparable or higher electric efficiencies - greater than 40% - using only biomass, because they involve gas turbines, which are more efficient than Rankine cycles. Other technologies being developed include integrated gasification/fuel cell and bio-refinery concepts.

The following map shows the biomass resources in United States.



The existing biopower sector – nearly 1,000 plants – is mainly comprised of direct-combustion plants, with an additional small amount of co-firing. Plant size averages 20 MW, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity has increased from less than 200 MW in 1978 to more than 15,000 MW in 2014. More than

70% of this power is generated in the forest products industry's CHP applications for process heat. Wood-fired systems account for close to 95% of this capacity. Municipal solid waste and landfill gas generating capacity is slightly less than 30% of the total biomass power.

CHP applications using a waste fuel are generally the most cost-effective biopower option. Growth is limited by availability of waste fuel and heat demand. Biomass co-firing with coal is the most near-term option for large-scale use of biomass for power-only electricity generation. Co-firing also reduces sulfur dioxide and nitrogen oxide emissions. When co-firing with crop and forest-product residues, greenhouse gas (GHG) emissions are reduced by a greater percentage. For example, a 15% co-firing can reduce GHG emissions by 23%.

Biomass gasification for large-scale (20-100MW) power production is being commercialized and it will be an important technology for cogeneration in the forest-products industries, as well as for new baseload capacity. Gasification also is important as a potential platform for a bio-refinery.

Approximately 20 million gallons of biodiesel are produced annually in the United States. Utility and industrial biopower generation is more than 90 billion kWh, representing about 75% of non-hydroelectric renewable generation. About two-thirds of this energy is derived from wood and wood wastes, while one-third of the biopower is from municipal solid waste and landfill gas.

The levelized cost of electricity (in constant 2000 $/kWh) for biomass direct-fired and gasification configurations are projected to be:

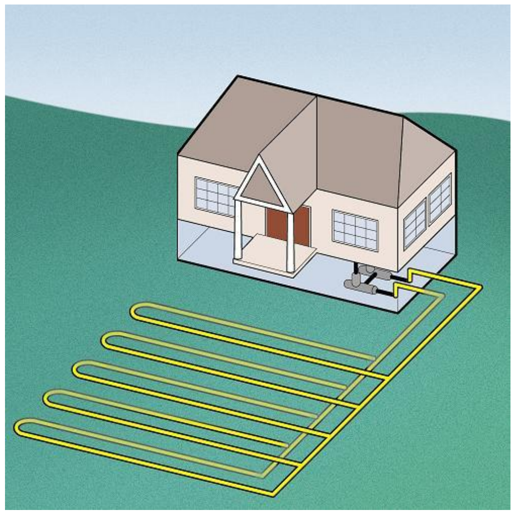
Biopower electricity cost (cents/kwh)		
Type	**2000**	**2020**
Direct fired	8.1	6.2
Gasification	7.2	5.8

Future biopower technology improvements include the development of better ways to prepare, inject, and control biomass combustion in a coal-fired boiler. Improved methods for combining coal and biomass fuels will maximize efficiency and minimize emissions. Systems are expected to include biomass co-firing up to 5% of natural gas combined-cycle capacity.

Chapter2
Geothermal Energy

Geothermal energy is heat from within the Earth. Hot water or steam are used to produce electricity or applied directly for space heating and industrial processes. This energy can offset the emission of carbon dioxide from conventional fossil-powered electricity generation, industrial processes, building thermal systems, and other applications.

Geophysical, geochemical, and geological exploration is used to identify geothermal reservoirs and their fracture systems. Once identified, the sites are drilled, reservoirs are tested, and modeling is done to optimize production and predict useful lifetime. These sites include highly permeable hot reservoirs, shallow warm groundwater, hot impermeable rock masses, and highly pressured hot fluids. Well fields and distribution systems are designed to allow the hot fluids to move to the point of use, and afterward, back to the earth. The geothermal energy can either be used to drive steam turbines by using natural steam or hot water flashed to steam to produce electricity or binary conversion systems can produce electricity from water not hot enough to flash. Direct applications use the heat from geothermal fluids without conversion to electricity. Another form of geothermal energy is the use of geothermal heat pumps, which use the shallow earth as a heat source and heat sink for heating and cooling applications. The drawing on right shows a typical geothermal heat pump loop system.



With improved technology, the United States has a resource base capable of producing up to 100 GW of electricity. Hydrothermal reservoirs are being used to produce electricity with an online availability of up to 97% and advanced energy-conversion technologies are being implemented to improve plant thermal efficiency. Direct-use applications are successful throughout the western United States and provide heat for space heating, aquaculture, greenhouses, spas, and other applications. Geothermal heat pumps continue to penetrate both residential and commercial markets for heating/cooling (HVAC) services.

The levelized cost of electricity (in constant 2000 $/kWh) for the two major future geothermal energy configurations are projected to be:

Geothermal electricity cost (cents/kwh)		
Type	**2000**	**2020**
Flash	3.0	2.1
Binary	3.6	2.7

According to the DOE, costs at the best sites are competitive at today's energy prices, but investment is limited by uncertainty in prices; lack of new, confirmed resources; high front-end costs; and lag time between investment and return. Improvements in cost and accuracy of resource exploration and characterization can lower the electricity cost; demonstration of new resource concepts, such as enhanced geothermal systems, would allow a large expansion of the U.S. use of hydrothermal when economics become favorable.

Hydrothermal reservoirs have an installed electrical capacity of about 3,800 MW in the United States and about 8,000 MW worldwide. Direct-use applications have an installed thermal capacity of about 600 MW in the United States.

Geothermal will continue production at existing plants with future construction potential of 100 GW by 2040. By 2020, an installed electricity capacity of 20 GW from hydrothermal plants and 20 GW from enhanced geothermal systems is projected.

Chapter 3
Concentrating Solar Power

Concentrating Solar Power (CSP) systems concentrate solar energy 50 to 10,000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed or bulk generation process applications.

In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400°C to 800°C in the working fluid of a receiver. This heat is used in conventional heat engines, such as steam, gas turbines or Sterling engines, to produce electricity at solar-to-electric efficiencies for the system of up to 30% and when coupled with a storage system, CSP technologies can provide firm, non-intermittent electricity generation for peaking or intermediate loads. Because solar-thermal technologies can yield extremely high temperatures they may some day be used for direct conversion of natural gas or water into hydrogen for future hydrogen-based economies.

A *parabolic trough* system focuses solar energy on a linear oil-filled receiver to collect heat to generate steam to power a steam turbine. Some of the new trough plants include thermal storage. Plant sizes can range from 1.0 to 100 MW. Parabolic trough collectors capable of generating temperatures greater than 500ºC were initially developed for industrial process heat (IPH) applications. Parabolic trough development taking place in Europe has culminated with the construction of a distributed collector system in Spain. This facility consisted of two parabolic trough solar fields – one using a single-axis tracking collector and a double-axis tracking parabolic trough collector. In 1982, Luz International Limited (Luz) developed a parabolic trough collector for IPH applications. Southern California Edison (SCE) signed a power purchase agreement with Luz for the Solar Electric Generating System (SEGS) I and II plants, which came online in 1985. The 354 MW of SEGS trough systems are still being operated today. Experience gained through their operation will allow the next generation of trough technology to be installed and operated much more cost-effectively.

A *power tower* system uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored extremely efficiently to allow power production to match utility demand, even when the sun is not shining. Plant size can range from 30 to 200 MW. A number of experimental power tower systems and components have been field-tested around the world in the past 15 years, demonstrating the engineering feasibility and economic potential of the technology. In early power towers, the thermal energy collected at the receiver was used to generate steam directly to drive a turbine generator. A project known as Solar Two was designed to demonstrate the dispatchability provided by molten-salt storage and to provide the experience necessary to lessen the perception of risk from these large systems.

A *dish/engine* system uses a dish-shaped reflector to power a small Sterling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2-25 kW in size and can be used individually or in small groups for distributed, remote, or village power; or in clusters (1-10 MW) for utility-scale applications, including end-of-line support. These systems can be used in dual fuel applications with a fossil fuel fired system. Dish/engine technology is the oldest of the solar technologies, dating back to the 1800's when a number of companies demonstrated solar-powered steam Rankine and Sterling-based systems.

In addition to the 354 MW parabolic trough plants operating in California a number of prototype dish/Sterling systems are currently operating in Nevada, Arizona, and Colorado. High levels of performance have been established, but durability remains to be proven, although some systems have operated for more than 10,000 hours.

New commercial plants are being considered for California, Nevada, New Mexico, Colorado, and Arizona. A 1-MW power plant began operation in Arizona in 2005. Operations and maintenance costs have been reduced through technology improvements at the commercial parabolic trough plants in California by 40%.

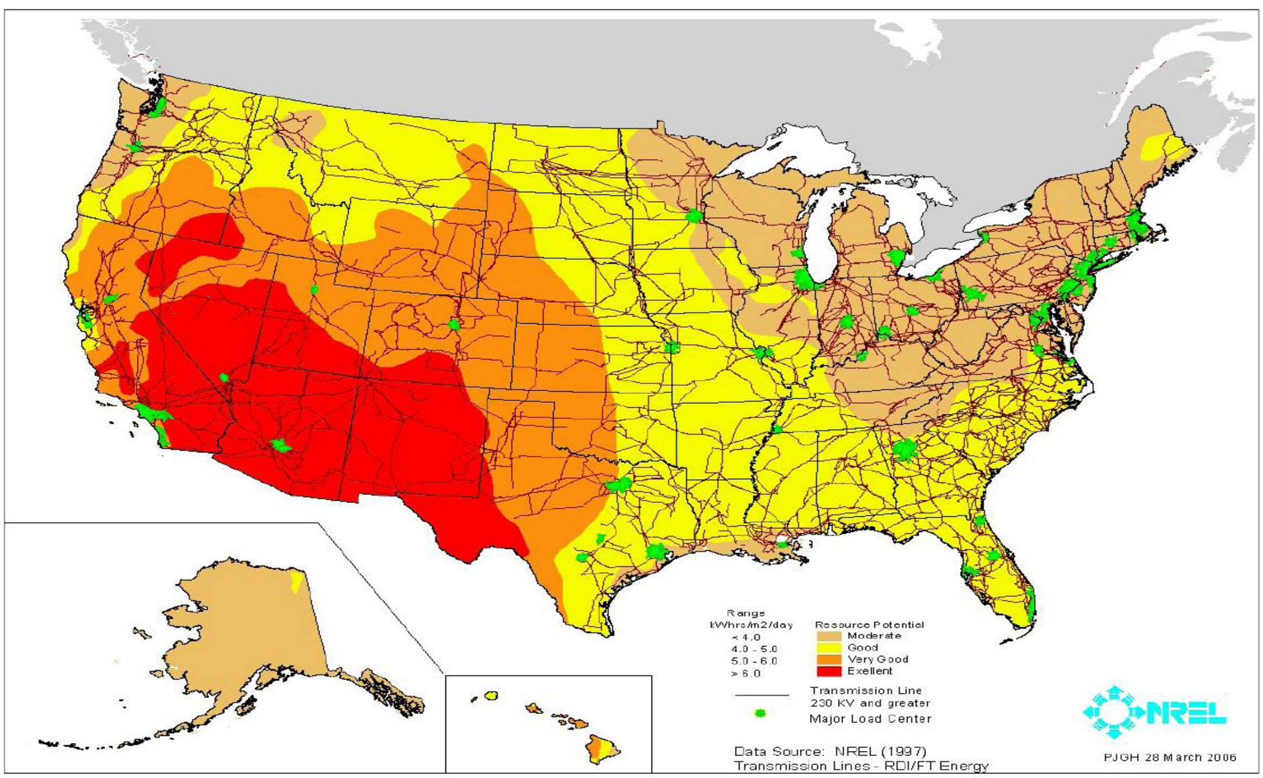
Overall there is slightly more than 1,700 MW of CSP in the United States.

Chapter 4
Photovoltaics

Solar-
Photovoltaics

Solar photovoltaic (PV) arrays use semiconductor devices called solar cells to convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases. Using solar PV for electricity – and eventually using solar PV to produce hydrogen for fuel cells for electric vehicles, by producing hydrogen from water – will help reduce carbon dioxide emissions worldwide.

PV modules are mounted on a either a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures. The DC output from PV can be conditioned into grid-quality AC electricity, or DC can be used to charge batteries or to split water to produce hydrogen. PV systems are expected to be used in the United States for residential and commercial buildings, peak-power shaving, and intermediate daytime load. With energy storage, PV can provide dispatchable electricity. Almost all locations in the United States have enough sunlight for cost-effective PV. For example, sunlight in the contiguous states varies by only about 25% from an average in Kansas. PV can be more easily sited in a distributed fashion than almost all other renewable technologies. The following map shows the solar insolation for the continental United States.



Wafers of single-crystal or polycrystalline silicon can achieve 25% efficiency and in commercial modules the efficiency can approach 12%. Silicon modules dominate the PV market and currently cost about $1/Wp to manufacture. Thin-film semiconductors, such as amorphous silicon, copper indium diselenide, cadmium telluride, and dye-sensitized cells have efficiencies of 12%, but in commercial modules the efficiency is only 6%. A new generation of thin-film PV modules is going through the high-risk transition to first-time and large-scale manufacturing. If successful, market share could increase rapidly. High-efficiency, single-crystal silicon and multi-junction gallium-arsenide-alloy cells for concentrators have efficiencies of 27% and commercial modules may reach 15%. Prototype systems are being tested in high solar areas in the southwest United States. Grid-connected PV systems currently sell for about $4/Watt, including support structures, power conditioning, and land.

PV systems can be installed as either grid-supply technologies or as customer-sited alternatives to retail electricity. As suppliers of bulk grid power, PV modules would typically be installed in large array fields ranging in total peak output from a few megawatts on up. Very few of these systems have been installed to-date. A greater focus of the recent marketplace is on customer-sited systems, which may be installed to meet a variety of customer needs. These installations may be residential-size systems of just 1-kilowatt, or commercial-size systems of several hundred kilowatts. In either case, PV systems meet customer needs for alternatives to purchased power, reliable power, and protection from price escalation, desire for green power, etc. Interest is growing in the use of PV systems as part of the building structure or façade. Such systems use PV modules designed to look like shingles, windows, or other common building elements. PV systems are expected to be used in the United States for residential and commercial buildings; distributed utility systems for grid support, peak power shaving, and intermediate daytime load following; with electric storage and improved transmission for dispatchable electricity; and H_2 production for portable fuel.

Other applications for PV systems include electricity for remote locations, especially for billions of people worldwide who do not have electricity. Typically, these applications will be in hybrid mini-grid or battery-charging configurations.

Industry cost reductions of more than 60% and a sixteen-fold increase of manufacturing capacity has occurred in recent years. A new generation of potentially lower-cost technologies is entering the marketplace. Two plants using even newer thin films (cadmium telluride and copper indium diselenide alloys) are in first-time manufacturing at the megawatt-scale. Thin-film PV has been a focus of efforts of the past decade, because it holds promise for module cost reductions. During the past two years, record sunlight-to-electricity conversion efficiencies for solar cells were set in copper indium gallium diselenide (19%-efficient cells and 13%-efficient modules) and cadmium telluride (16%-efficient cells and 11%efficient modules). Cell and module efficiencies for these technologies have increased more than 50% in the past decade. A unique multi-junction cell was spun off to the space power industry, leading to record cell efficiency of 35%. This device configuration is expected to dominate future space power for commercial and military satellites.

The levelized cost of electricity (in constant 2000 $/kWh) for PV are projected to be:

Photovoltaic Power (cents/kwh)		
Type	2020	2025
Utility owned - Residential	9.4	n/a
Concentrator	n/a	5.6

There is over 18,000 MW of conventional solar power generation in the United States. Hundreds of applications are cost-effective for off-grid needs. However, the fastest-growing segment of the market is battery-free, grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California is subsidizing PV systems to reduce their dependence on natural gas, especially for peak daytime loads that match PV output, such as air-conditioning. U.S. markets include retail electricity for residential and commercial buildings; distributed utility systems for grid support, peak-shaving, and other daytime uses such as remote water pumping.

Chapter 5
Wind Energy

Wind turbine technology converts the kinetic energy in wind into electricity. Grid-connected wind power reduces greenhouse gas emissions by displacing the need for natural gas and coal-fired generation.

Most modern wind turbines operate using aerodynamic lift generated by airfoil-type blades, yielding much higher efficiency than traditional windmills that relied on wind "pushing" the blades. Lifting forces spin the blades, driving a generator that produces electric power in proportion to wind speed. Turbines either rotate at constant speed directly linked to the grid, or at variable speed for better performance and use power electronics for grid connection. Utility-scale turbines for wind plants range in size up to several megawatts, and smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and standalone power applications.

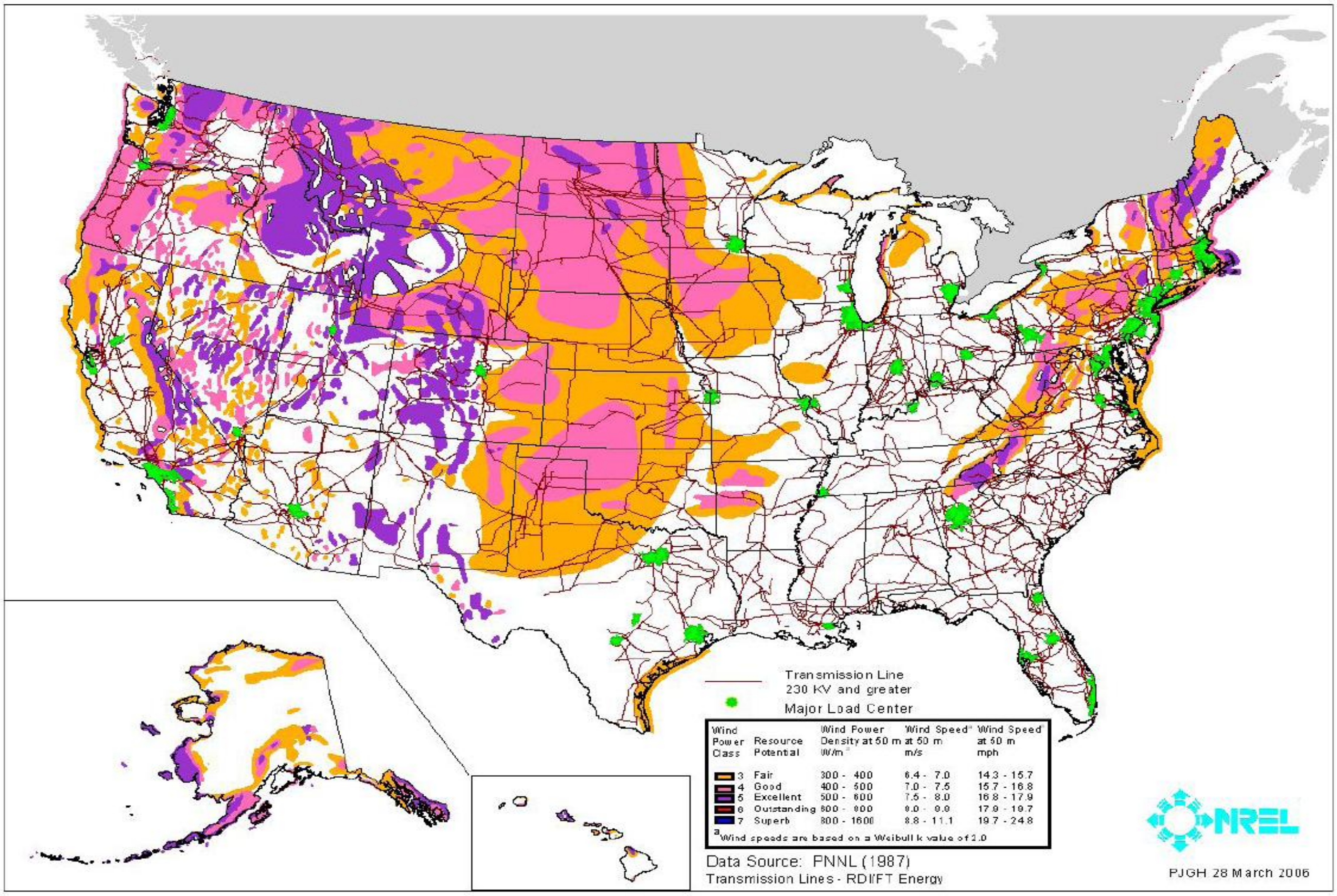
The most common machine configuration is a three-bladed wind turbine, which operates "upwind" of the tower, with the blades facing into the wind. To improve the cost-effectiveness of wind turbines, technology advances are being made for rotors and controls, drive trains, towers, manufacturing methods, site-tailored designs, and offshore and onshore foundations.

In the United States, the wind energy capacity increased from 1,600 MW in 1994 to more than 66,000 MW by the end of 2013. Current performance is characterized by capacity factors of 30%, total installed costs of approximately $1,300/kW, and efficiencies of 65% of theoretical (Betz limit) maximum.

> The ***Betz Limit*** says that no wind turbine can convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor.

Wind power is the world's fastest-growing energy source. In the past decade, the global wind energy capacity has increased tenfold. In 2014 alone over 4,800MW's of new capacity was added worldwide.

Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power throughout the country.



The levelized cost of electricity (2000 $/MWh) for wind energy technology is projected to be:

Wind Power Electricity Costs Cents/kWh		
Class	**2005**	**2020**
Class 4	5.3	3.0
Class 6	3.9	2.5

Installed wind capacity in the United States is about one-third of renewable generation.

California has the greatest installed wind capacity, followed by Texas, Iowa, Minnesota, Oregon, Washington, Wyoming, New Mexico, Colorado, and Oklahoma. Wind technology is competitive today in bulk power markets at Class 5 and 6 wind sites, with support from the production tax credit. Continued cost reductions from low wind-speed technologies will increase the resource areas available for wind development and may move wind generation closer to major load centers. Emerging markets for wind energy include providing energy for water purification, irrigation, and hydrogen production.

Wind deployments of up to 15%-20% of the total U.S. electric system capacity are not expected to introduce significant grid reliability issues. However, because the wind resource is variable, intensive use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of wind turbines. Due to its variability, wind is not dispatchable without energy storage.

Small wind turbines, 100 kW and smaller, for distributed and residential grid-connected applications, are being used to harness the nation's abundant wind resources and defer impacts to the long-distance transmission market. Key market drivers for continued deployment of wind technology include state renewable portfolio standards, incentive programs, and demand for community-owned wind applications.

Chapter 6
Hydrogen Technology

Similar to electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Hydrogen and electricity can be converted from one to the other using *electrolyzers* (electricity to hydrogen) and *fuel cells* (hydrogen to electricity). Hydrogen is a clean energy storage medium, particularly for distributed generation. When hydrogen produced from renewable resources is used in fuel cell vehicles or power devices, there are very few emissions – the major byproduct is water. With improved conventional energy conversion and carbon-capture technologies, hydrogen from fossil resources can be used efficiently with few emissions.

The Hydrogen Economy vision is based on this cycle: separate water into hydrogen and oxygen using renewable or nuclear energy, or fossil resources with carbon sequestration. Use the hydrogen to power a fuel cell, internal combustion engine, or turbine, where hydrogen and oxygen (from air) recombine to produce electrical energy, heat, and water to complete the cycle. This process produces no particulate matter, no carbon dioxide, and no pollution.

Hydrogen can be used as a sustainable transportation fuel or stored to meet peak-power demand. It also can be used as a feedstock in chemical processes. Hydrogen produced by decarbonization of fossil fuels followed by sequestration of the carbon can enable the continued, clean use of fossil fuels during the transition to a carbon-free Hydrogen Economy. A hydrogen system is comprised of the production, storage, distribution, and use of the hydrogen.

Production

Hydrogen production can take the form of,

1. Thermochemical conversion of fossil fuels, biomass, and wastes to produce hydrogen and CO_2 with the CO_2 available for sequestration (large-scale steam methane reforming is widely commercialized).
2. Renewable (wind, solar, geothermal, hydro) and nuclear electricity converted to hydrogen by electrolysis of water (commercially available electrolyzers supply a small but important part of the super-high-purity hydrogen market).
3. Photoelectrochemical and photobiological processes for direct production of hydrogen from sunlight and water.

Hydrogen production from conventional fossil-fuel feedstocks is commercial, and results in significant CO_2 emissions. Large-scale CO_2 sequestration options have not been proved. Current commercial electrolyzer systems are 55-75% efficient, but the cost of hydrogen is strongly dependent on the cost of electricity. Production processes using wastes and biomass are under development, with a number of engineering scale-up projects underway. Direct conversion of sunlight to hydrogen using a semiconductor-based photoelectrochemical cell was recently demonstrated at 12.4% efficiency.

Hydrogen storage

Storage methods include,

1. Pressurized gas and cryogenic liquid.
2. Higher pressure (10,000 psi), carbon-wrapped conformable gas cylinders.
3. Cryogenic gas.
4. Chemically bound as metal or chemical hydrides or physically adsorbed on carbon nanostructures.

Liquid and compressed gas tanks are available and have been demonstrated in a small number of bus and automobile demonstration projects. Lightweight, fiber-wrapped tanks have been developed and tested for higher-pressure hydrogen storage. Experimental metal hydride tanks have been used in automobile demonstrations. Alternative solid-state storage systems using alanates and carbon nanotubes are under development.

Hydrogen distribution

Hydrogen can be distributed using conventional methods such as,

1. By pipeline.
2. By decentralized or point-of-use production using natural gas or electricity.
3. By truck.

Hydrogen use

Hydrogen will find uses in transportation, manufacturing, commercial buildings, and power generation,

1. Transportation sector: internal combustion engines or fuel cells to power vehicles with electric power trains. Potential long-term use as an aviation fuel and in marine applications
2. Industrial sector: ammonia production, reductant in metal production, hydrotreating of crude oils, hydrogenation of oils in the food industry, reducing agent in electronics industry.
3. Buildings sector: combined heat, power, and fuel applications using fuel cells.
4. Power sector: fuel cells, gas turbines, generators for distributed power generation.

Small demonstrations by domestic and foreign bus and energy companies have been undertaken. Small-scale power systems using fuel cells fuel cells have been introduced to the power generation market, but subsidies are required to be economically competitive. Small fuel cells for battery replacement applications have been developed. Major industrial companies are pursuing R&D in fuel cells and hydrogen production technologies with a five-year time frame for deployment for both stationary and vehicular applications.

Fuel cells are a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric vehicles. Although these applications would ideally run off pure hydrogen, in the near-term they are likely to be fueled with natural gas, methanol, or even gasoline. Reforming these fuels to create hydrogen will allow the use of much of our current energy infrastructure—gas stations, natural gas pipelines—while fuel cells are phased in.

In the United States, nearly all of the hydrogen used as a chemical is produced from natural gas. The main use of hydrogen as a fuel today is by NASA to propel rockets. Hydrogen's potential use in fuel and energy applications includes powering vehicles, running turbines or fuel cells to produce electricity, and generating heat and electricity for buildings. The current focus is on hydrogen's use in fuel cells.

Currently, 48% of the worldwide production of hydrogen is via large-scale steam reforming of natural gas. About 90 billion cubic meters of hydrogen is used yearly. Hydrogen technologies are in various stages of development and this includes production, storage, as well as use of the hydrogen.

The electricity grid and the natural gas pipeline system will serve to supply primary energy to hydrogen producers. By 2010, advances will be made in photobiological and photoelectrochemical processes for hydrogen production, efficiencies of fuel cells for electric power generation will increase, and advances will be made in fuel cell systems based on carbon structures, alanates, and metal hydrides.

Although comparatively little hydrogen is currently used as fuel or as an energy carrier, the long-term potential is for us to make a transition to a hydrogen-based economy in which hydrogen will join electricity as a major energy carrier. Furthermore, much of the hydrogen will be derived from domestically plentiful renewable energy or fossil resources, making the Hydrogen Economy synonymous with sustainable development and energy security.

For a fully developed hydrogen energy system, a new hydrogen infrastructure/delivery system will be required. In the future, hydrogen also could join electricity as an important *energy* *carrier*. An energy carrier stores, moves, and delivers energy in a usable form to consumers. Renewable energy sources, such as the sun or wind, can't produce energy all the time. The sun doesn't always shine nor the wind blow. But hydrogen can store this energy until it is needed and it can be transported to where it is needed. Some experts think that hydrogen will form the basic energy infrastructure that will power future societies, replacing today's natural gas, oil, coal, and electricity infrastructures. They see a new *hydrogen economy* to replace our current energy economies, although that vision probably won't happen until far in the future.

Chapter 7
Advanced Hydropower

Hydroelectric power does not generate greenhouse gas. With due consideration to water use policies in much of the United States, hydropower will continue to be an important part of a greenhouse gas emissions-free energy portfolio. Advanced hydropower is technology that produces hydroelectricity both efficiently and with improved environmental performance. Some in the environmental community complain that traditional hydropower may have environmental effects, such as fish mortality and changes to downstream water quality and quantity. The goal of advanced hydropower is to maximize the use of water for generation while improving environmental performance.


Photo courtesy: DOE

Conventional hydropower projects use either impulse or reaction turbines to convert kinetic energy in flowing or falling water into turbine torque and power. Source water may be from free-flowing rivers, streams, or canals, or water released from upstream storage reservoirs. New environmental and biological criteria for turbine design and operation are being developed to help sustain hydropower's role as a clean, renewable energy source – and to enable upgrades of existing facilities and retrofits at existing dams.

Some of the features of the advanced hydropower plant equipment are,

- New turbine designs to improve survivability of fish that pass through the power plant.
- Auto-venting turbines to increase dissolved oxygen in discharges downstream of dams.
- Re-regulating and aerating weirs used to stabilize tailwater discharges and improve water quality.
- Adjustable-speed generators producing hydroelectricity over a wider range of heads and providing more uniform instream-flow releases without sacrificing generation opportunities.
- New assessment methods to balance instream-flow needs of fish with water for energy production and to optimize operation of reservoir systems.
- Advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

Hydropower provides about 79,000 MW of the nation's electrical-generating capability. This is about 50 percent of the electricity generated from renewable energy sources. Existing hydropower generation faces a combination of real and perceived environmental effects, competing uses of water, regulatory pressures, and changes in energy economics and potential hydropower resources are not being developed for similar reasons. Some new environmentally friendly technologies such as low head and low impact hydroelectric are being implemented in part stimulated by green power programs.

TVA has demonstrated that improved turbine designs, equipment upgrades, and systems optimization can lead to significant economic and environmental benefits – energy production was increased approximately 12% while downstream fish resources were significantly improved. Field-testing indicates that fish survival can be significantly increased, if conventional turbines are modified.

New strobe lighting systems have been developed to force fish away from hydropower intakes and to avoid entrainment mortality in turbines. Implementation at more sites may allow improved environmental performance with reduced spillage.

Advanced hydropower products can be applied at more than 80% of existing hydropower projects and the potential market also includes 15-20 GW at existing dams as well as more than 30 GW of undeveloped hydropower. Retrofitting advanced technology and optimizing system operations at existing facilities would lead to at least a 6% increase in energy output and if fully implemented, this would equate to 5 GW and 18,600 GWh of new, clean energy production.

Chapter 8
Building Technologies

This section includes information about various technologies that can improve the energy efficiency of buildings. Building technology improvements have the potential to reduce power consumption by increasing the efficiency of building equipment, the building envelope, and integration of equipment, thereby helping to reduce greenhouse gases.

Building equipment

Energy use in buildings depends on equipment to transform fuel or electricity into end-use services such as delivered heat or cooling, light, fresh air, vertical transport, cleaning of clothes or dishes, and information processing. There are energy-saving opportunities within individual pieces of equipment – as well as at the system level – through proper sizing, reduced distribution and standby losses, heat recovery and storage, and optimal control.

Major categories of end-use equipment include heating, cooling, and hot water; ventilation and thermal distribution; lighting; home appliances; miscellaneous (process equipment and consumer products); and on-site energy and power. Key components vary by type of equipment, but some generic opportunities for efficiency include improved materials, efficient low-emissions combustion and heat transfer, advanced refrigerants and cycles, electrode-less and solid-state lighting, smart sensors and controls, improved small-power supplies, variable-capacity systems, reduction of thermal and electrical standby losses, cogeneration based on modular fuel cells and microturbines, and utilization of waste heat from fuel cells and microturbines.

Potential building equipment includes,

- Residential gas-fired absorption heat pumps
- Centrifugal chillers
- Desiccant pre-conditioners for treating ventilation air
- Heat-pump water heaters
- Proton exchange membrane fuel cells
- Heat pump water heaters
- Solid-state lighting
- Lighting controls

Technology improvements during the past 20 years have improved efficiencies in lighting and equipment by 15% to 75%, depending on the type of equipment. Efficiencies of compact fluorescent lamps are 70% better than incandescent lamps; refrigerator energy use has been reduced by more than three-quarters during the past 20 years; and H-axis clothes washers are

50% more efficient than current minimum standards. In addition, electronic equipment has achieved order-of-magnitude efficiency gains, at the microchip level, every two to three years.

Recent research includes an improved air-conditioning cycle to reduce over sizing and improve efficiency and a replacement for inefficient, high-temperature halogen up-lights, which use only 25% of the power, last longer, and eliminate potential fire hazards and ozone-safe refrigerants.

Building equipment, appliances, and lighting systems currently on the market vary from 20% to 100% efficient (heat pumps can exceed this level by using "free" energy drawn from the environment). This efficiency range is narrower where cost-effective appliance standards have previously eliminated the least-efficient models. The energy consumption and energy intensity of homes are growing faster than in the past as manufacturers introduce new types of equipment, more sophisticated and automated technologies, and increased levels of end-use services.

The rapid turnover and growth of many types of building equipment – especially electronics for computing, control, communications, and entertainment – represent important opportunities to rapidly introduce new, efficient technologies and quickly propagate them throughout the stock. The market success of most new equipment and appliance technologies is virtually ensured if the efficiency improvement has a 3-year payback or better and amenities are maintained; technologies with payback of 4 to 8-plus years also can succeed in the market, provided that they offer other customer-valued features (e.g., reliability, longer life, improved comfort or convenience, quiet operation, smaller size, lower pollution levels).

Applications extend to every segment of the residential and non-residential sectors. Major government, institutional, and corporate buyers represent a special target group for voluntary early deployment of the best new technologies. Building equipment and appliances represent an annual market in the United States, alone, of more than $200B, involving thousands of large and small companies.

Building envelope

The building envelope is the interface between the interior of a building and the outdoor environment. In most buildings, the envelope is the primary determinant of the amount of energy used to heat, cool, and ventilate. A more energy-efficient envelope means lower energy use in a building and lower greenhouse gas emissions. The envelope concept can be extended to that of the "building fabric," which includes the interior partitions, ceilings, and floors. Interior elements and surfaces can be used to store, release, control, and distribute energy, thereby further increasing the overall efficiency of the buildings.

Control of envelope characteristics provides control of the flow of heat, air, moisture, and light into the building. These flows and the interior energy and environmental loads determine the size and energy use of HVAC and distribution systems.
Materials for exterior walls, roofs, foundations, windows, doors, interior partition walls, ceilings, and floors that can impact future energy use include insulation with innovative formula foams and vacuum panels; optical control coatings for windows and roofs; and thermal storage materials, including lightweight heat-storage systems.

The following three concepts have the ability to revolutionize building envelope design.

1. Super-insulation: Vacuum powder-filled, gas-filled, and vacuum fiber-filled panels; structurally reinforced beaded vacuum panels; and switchable evacuated panels with insulating values more than four times those of the best currently available materials should soon be available for niche markets. High-thermal-resistant foam insulations with acceptable ozone depletion and global warming characteristics should allow for continued use of this highly desirable thermal insulation.

2. Advanced window systems: Krypton-filled, triple-glazed, low-E windows; electro-chromic glazing; and hybrid electro-chromic/photovoltaic films and coatings should provide improved lighting and thermal control of fenestration systems. Advanced techniques for integration, control, and distribution of daylight should significantly reduce the need for electric lighting in buildings. Self-drying wall and roof designs should allow for improved insulation levels and increase the lifetimes for these components. More durable high-reflectance coatings should allow better control of solar heat on building surfaces.

Fenestration is any opening in a building's envelope such as windows, doors, and skylights

3. Advanced thermal storage materials: Dry phase-change materials and encapsulated materials should allow significant load distribution over the full diurnal cycle and significant load reduction when used with passive solar systems.

Building insulations have improved from the 2-4 hr-ºF-ft^2/Btu/in fibrous materials available before 1970 to foams reaching 7 hr-ºF-ft^2/Btu/in. Super-insulations of more than 25 hr-ºF-ft^2/Btu/in will be available for niche markets soon. Improvements in window performance have been even more spectacular. In the 1970's, window thermal resistance was 1 to 2 hr-ºF-ft^2/Btu. Now, new windows have thermal resistance of up to 6 hr-ºF-ft^2/Btu. Windows are now widely available with selective coatings that reduce infrared transmittance without reducing visible transmittance. In addition, variable-transmittance windows under development will allow optimal control to minimize heating, cooling, and lighting loads.

Recent research has helped the industry find a replacement for chlorofluorocarbons (CFCs) in polyisocyanurate foam insulation. This effort enabled the buildings industry to transition from CFC-11 to HCFC-141b. Spectrally selective window glazing – which reduce solar heat gain and lower cooling loads – and high-performance insulating materials for demanding thermal applications are available.

A critical challenge is to ensure that new homes and buildings are constructed with good thermal envelopes and windows when the technologies are most cost-effective to implement. The market potential is significant for building owners taking some actions to improve building envelopes. Currently, 40% of residences are well insulated, 40% are adequately insulated, and 20% are poorly insulated. More than 40% of new window sales are of advanced types (low-E and gas-filled). In commercial buildings, more than 17% of all windows are advanced types. More than 70% of commercial buildings have roof insulation; somewhat fewer have insulated walls. Building products are mostly commodity products. A number of companies produce them; and each has a diverse distribution system, including direct sales, contractors, retailers, and discount stores. Another critical challenge is improving the efficiency of retrofits of existing buildings. Retrofitting is seldom cost-effective on a stand-alone basis. New materials and techniques are required. Many advanced envelope products are cost-competitive now, and new technologies will become so on an ongoing basis. There will be modest cost reductions over time as manufacturers compete. Building structures represent an annual market in the United States of more than $70B/year and involve thousands of large and small product manufacturers and a large, diverse distribution system that plays a crucial role in product marketing.

Whole building integration

Whole building integration uses data from design (together with sensed data) to automatically configure controls and operate buildings. Control systems use advanced, techniques and are based on smaller, less expensive, and much more abundant sensors. These data ensure optimal building performance by enabling control of building systems in an integrated manner and continuously re-commissioning them using automated tools that detect and diagnose performance anomalies and degradation. Whole building integration systems optimize operation across building systems, inform and implement energy purchasing, guide maintenance activities, document and report building performance, and optimally coordinate on-site energy generation with building energy demand and the electric power grid, while ensuring that occupant needs for comfort, health, and safety are met at the lowest possible cost.

The system consists of design tools, automated diagnostics, interoperable control-system components, wireless sensors and controls, and highly integrated operation of energy-using and producing systems. These components will work together to collect data, configure controls, monitor operations, optimize control, and correct out-of-range conditions that contribute to poor building performance. Whole building integration ensures that essential information – especially the design intent and construction implementation data – is preserved and shared across many applications throughout the lifetime of the building.

Equipment and system performance records are stored as part of a networked building performance knowledge base, which can grow over time and provide feedback to designers, equipment manufacturers, and building operators and owners. Optimally, the system will integrate on-site power production with building energy needs and the electric-power grid by applying intelligent control to building cooling, heating, and power.

Savings from improved operation and maintenance procedures can save more than 30% of the annual energy costs of existing commercial buildings. These technologies will have very short paybacks, because they will ensure that technologies are performing as promised, for a fraction of the cost of the installed technology. Savings for new buildings can exceed 70%, using integration of building systems; and, with combined cooling, heating and power, buildings may become net electricity producers and distributed suppliers to the electric power grid.

One future vision of building technologies is one of “net zero energy” buildings which use a combination of integrated electricity generation--such as photovoltaics--paired with energy efficiency and power controls, to create a building that on average during a year produces enough energy for all the energy demands within the building. However, design tools for energy efficiency are used by fewer than 2% of the professionals involved in the design, construction, and operation of commercial buildings in the United States. A larger fraction of commercial buildings have central building-control systems. Few diagnostic tools are available commercially beyond those used for air-balancing or integrated into equipment.

Deployment involves four major aspects: seamless integration into existing building design and operation practices and platforms, lowering the cost of intelligent-building and enabling technologies, transforming markets to rapidly introduce new energy-efficient technologies, and a focus on conveying benefits that are desired in the marketplace.

These technologies would apply to all buildings, but especially to existing commercial buildings and all new buildings. In addition, new technologies would be integrated into the building design and operation processes.

Chapter 9
Reciprocating Engines

Reciprocating engines, also known as internal combustion engines, require fuel, air, compression, and a combustion source to function. They make up the largest share of the small power generation market and can be used in a variety of applications due to their small size, low unit costs, and useful thermal output.

Reciprocating engines fall into one of two categories depending on the ignition source: spark ignition (SI), typically fueled by gasoline or natural gas; or compression ignition (CI), which are typically fueled by diesel oil. Reciprocating engines also are categorized by the number of revolutions it takes to complete a combustion cycle. A two-stroke engine completes its combustion cycle in one revolution, and a four-stroke engine completes the combustion process in two revolutions.

The four-stroke SI engine has an intake, compression, power, and exhaust cycle. In the intake stroke, as the piston moves downward in its cylinder, the intake valve opens and the upper portion of the cylinder fills with fuel and air. When the piston returns upward in the compression cycle, the spark plug fires and ignites the fuel/air mixture. This controlled combustion forces the piston down in the power stroke, turning the crankshaft and producing useful shaft power. Finally, the piston moves up again, exhausting the burnt fuel and air in the exhaust stroke. The four-stroke CI engine operates in a similar manner, except diesel fuel and air ignite when the piston compresses the mixture to a critical pressure. At this pressure, no spark or ignition system is needed because the mixture ignites spontaneously, providing the energy to push the piston down in the power stroke. The two-stroke engine, whether SI or CI, has a higher power density, because it requires half as many crankshaft revolutions to produce power. However, two-stroke engines are prone to let more fuel pass through, resulting in higher hydrocarbon emissions in the form of unburned fuel.

Reciprocating engines can be installed to accommodate baseload, peaking, emergency or standby power applications. Commercially available engines range in size from 10 kW to more than 7 MW, making them suitable for many distributed-power applications.

Utilities can install engines to provide baseload or peak shaving power. However, the most promising markets for reciprocating engines are on-site at commercial, industrial, and institutional facilities. With fast start-up time, reciprocating engines can play integral backup roles in many building energy systems. On-site reciprocating engines become even more attractive in regions with high electric rates. When properly treated, the engines can run on fuel generated by waste treatment (methane) and other biofuels. By using the recuperators that capture and return waste exhaust heat, reciprocating engines can be used in combined heat and power (CHP) systems to achieve energy efficiency levels approaching 80%. In fact, reciprocating engines make up a large portion of the CHP or cogeneration market.

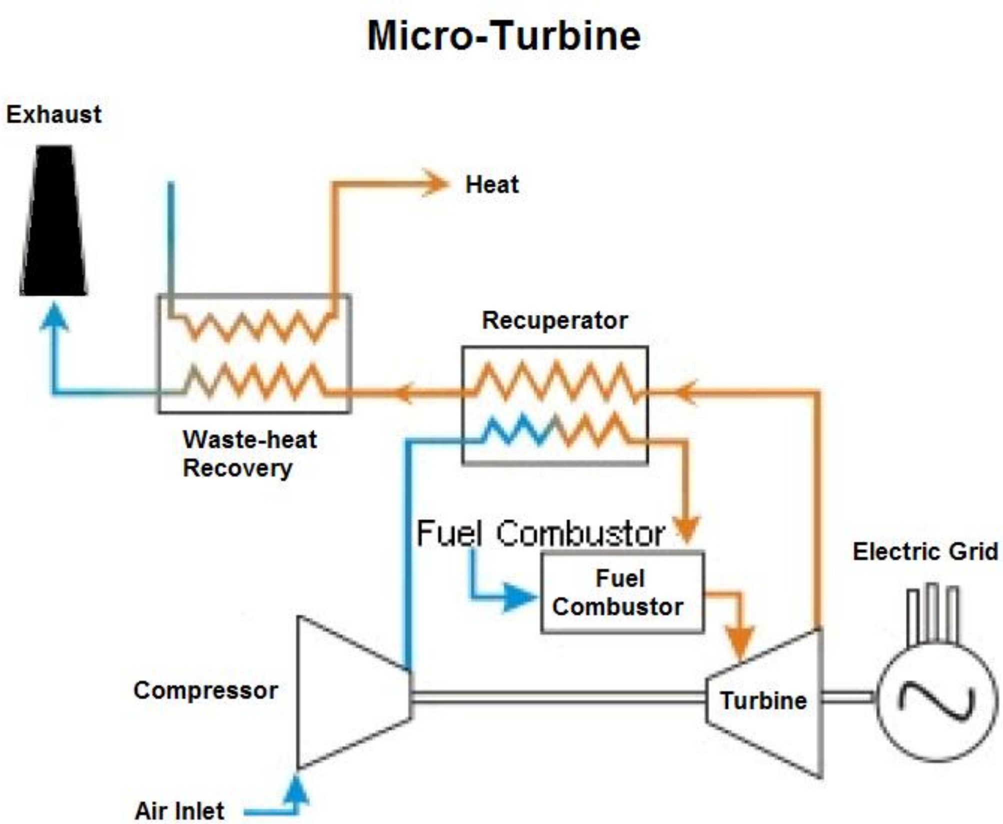
Commercially available engines have efficiencies between 28% and 50% and yield NOx emissions of 0.5-2.0 grams per horsepower hour (hp-hr) for lean-burn natural gas engines and 3.5-6.0 g/bhp-hr for conventional dual-fuel engines.
Installed cost for reciprocating engines range between $700 and $1,400/ kW depending on size and whether the unit is for a straight generation or cogeneration application. Operating and maintenance costs range from $0.008 to $0.018/kWh. Exhaust temperature for most reciprocating engines is 375-650 °C in non-CHP mode and 175-250 °C in a CHP system after heat recovery. Noise levels with sound enclosures are typically between 70-80 dB. The reciprocating-engine systems typically include several major parts: fuel storage, handling, and conditioning, prime mover, emission controls, waste recovery and radiators, and electrical switchgear.

The DOE has developed the following performance targets for reciprocating engines,

- *High Efficiency*. Fuel-to-electricity conversion efficiency is 50% by 2010.
- *Environment.* Engine improvements in efficiency, combustion strategy, and emissions reductions will substantially reduce overall emissions to the environments. The NOx target is 0.1 g/hp-hr.
- *Fuel Flexibility*. Natural gas-fired engines are to be adapted to handle biogas, renewables, propane and hydrogen, as well as dual fuel capabilities.
- *Cost of Power*. The target for energy costs, including operating and maintenance costs, is 10% less than current state-of-the-art engine systems.
- *Availability, Reliability, and Maintainability*. The goal is to maintain levels equivalent to current state-of-the-art systems. This may include: new turbocharger methods, heat recovery equipment specific to the reciprocating engine, alternate ignition system, emission-control technologies, improved generator technology, frequency inverters, controls/sensors, higher compression ratio, and dedicated natural-gas cylinder heads.

Chapter 10
Microturbines

Microturbines are small combustion turbines of a size comparable to a refrigerator and with outputs of 30 kW to 400 kW. They are used for stationary energy generation applications at sites with space limitations for power production. They are fuel-flexible machines that can run on natural gas, biogas, propane, butane, diesel, and kerosene. Microturbines have few moving parts, high efficiency, low emissions, low electricity costs, and waste heat utilization opportunities; and are lightweight and compact in size. Waste heat recovery can be used in combined heat and power (CHP) systems to achieve energy efficiency levels greater than 80%.



Microturbines consist of a compressor, combustor, turbine, alternator, recuperator, and generator. Microturbines are classified by the physical arrangement of the component parts: single shaft or two-shaft, simple cycle or recuperated, inter-cooled, and reheat. The machines generally operate at more than 40,000 rpm, while some machines operate at more than 100,000 rpm. A single shaft is the more common design, because it is simpler and less expensive to build. Conversely, the split shaft is necessary for machine-drive applications, which do not require an inverter to change the frequency of the AC power. Efficiency gains can be achieved with greater use of materials like ceramics, which perform well at higher engine-operating temperatures.

Microturbines in a simple-cycle, or un-recuperated, turbine; heated, compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is allowed to expand through a turbine to perform work. Simple-cycle microturbines have a lower cost, higher reliability, and more heat available for CHP applications than recuperated units. Recuperated units use a sheet-metal heat exchanger that recovers some of the heat from an exhaust stream and transfers it to the incoming air stream. The preheated air is then used in the combustion process. If the air is preheated, less fuel is necessary to raise its temperature to the required level at the turbine inlet. Recuperated units have a higher efficiency and thermal-to-electric ratio than un-recuperated units, and yield 30%-40% fuel savings from preheating.

Microturbines can be used in a wide range of applications in the commercial, industrial, and institutional sectors. Microturbines can be used for backup power, baseload power, premium power, remote power, grid support, peak shaving, cooling and heating power, mechanical drive, and use of wastes and biofuels. Microturbines can be paired with other distributed energy resources such as energy-storage devices and thermally activated technologies.

Microturbine systems have recently entered the market, and the manufacturers are targeting both traditional and nontraditional applications in the industrial and buildings sectors, including CHP, backup power, continuous power generation, and peak shaving. The most popular microturbine installed is a 30-kW system manufactured by Capstone. These units have efficiencies of 25-29%.

The typical 30 kW unit package cost averages $1,100/kW and for gas-fired microturbines, the present installation cost averages $2,200/kW for power only systems and $2,600 for CHP systems.

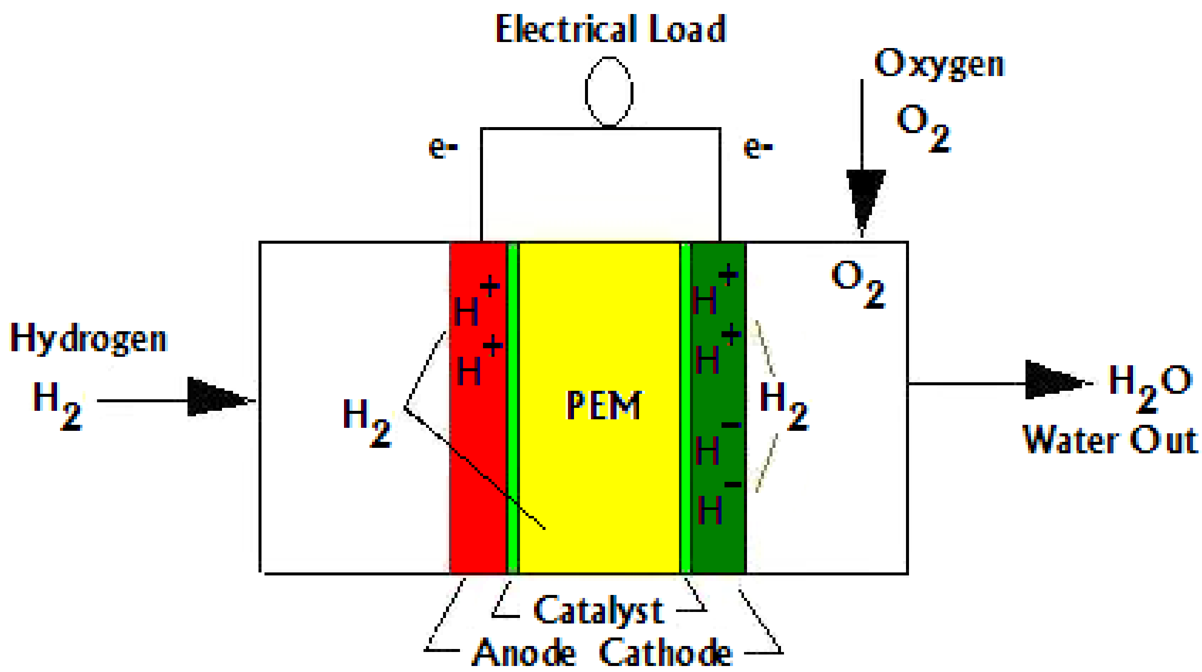
The acceptable cost target for microturbine energy is $0.05/kWh. The current research is focusing on Ultra-clean, high-efficiency microturbine product designs with the following performance targets,

- High Efficiency - Fuel-to-electricity conversion efficiency of at least 40%.
- Environment - NOx < 7 ppm (natural gas).
- Durability - 1,000 hours of reliable operations between major overhauls and a service life of at least 45,000 hours.
- Cost of Power - System costs < $500/kW, costs of electricity that are competitive with grid power for market applications in the 30-60 kW range.
- Fuel Flexibility - Options for using multiple fuels including diesel, ethanol, landfill gas, and biofuels.

Chapter 11
Fuel Cells Technology

A fuel cell is an electrochemical energy conversion device that converts hydrogen and oxygen into electricity and water. This unique process is practically silent, nearly eliminates emissions, and has no moving parts.

Similar to a battery, fuel cells have an anode and a cathode separated by an electrolyte. Hydrogen enters the anode and air (oxygen) enters the cathode. The hydrogen and oxygen are separated into ions and electrons, in the presence of a catalyst. Ions are conducted through the electrolyte while the electrons flow through the anode and the cathode via an external circuit. The current produced can be utilized for electricity.



Fuel Cell

The ions and electrons then recombine, with water and heat as the only byproducts.

Fuel cell systems typically consist of a fuel processor, fuel cell stack, and power conditioner. The fuel processor, or reformer, converts hydrocarbon fuels to a mixture of hydrogen-rich gases and, depending on the type of fuel cell, can remove contaminants to provide pure hydrogen. The fuel cell stack is where the hydrogen and oxygen electrochemically combine to produce electricity. The electricity produced is direct current (DC) and the power conditioner converts the

DC electricity to alternating current (AC) electricity, for which most of the end-use technologies are designed. As a hydrogen infrastructure emerges, the need for the reformer will disappear as pure hydrogen will be available near point of use.

The primary fuel cell technologies under development are Phosphoric acid fuel cells, Polymer electrolyte membrane, solid oxide fuel cells, Direct-methanol fuel cell, molten carbonate fuel cell, alkaline fuel cell, and regenerative fuel cells. Each is briefly explained below.

Phosphoric acid fuel cell (PAFC) -A phosphoric acid fuel cell (PAFC) consists of an anode and a cathode made of a finely dispersed platinum catalyst on carbon paper, and a silicon carbide matrix that holds the phosphoric acid electrolyte. These fuel cells operate at 190-210°C and achieve 35 to 45% fuel-to-electricity efficiencies and have commercially-validated reliabilities of 90-95%. This is the most commercially developed type of fuel cell and is being used in hotels, hospitals, and office buildings. More than 250 commercial units exist in 19 countries on five continents. This fuel cell also can be used in large vehicles, such as buses.

Polymer electrolyte membrane (PEM) fuel cell - The polymer electrolyte membrane (PEM) fuel cell uses a thin fluorinated plastic sheet that allows hydrogen ions (protons) to pass through it. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts. Proton Exchange Membrane Fuel Cells (PEMFCs) operate at relatively low temperatures of 70-100°C have high-power density, can vary their output quickly to meet shifts in power demand, and are suited for applications where quick start-up is required (e.g., transportation and power generation).

Solid oxide fuel cells (SOFC) – These units operate at temperatures up to 1,000°C. A solid oxide system usually uses a hard ceramic material such as a thin layer of zirconium oxide instead of a liquid electrolyte. The cathode is lanthanum manganate and the anode is nickel-zirconia. The solid-state ceramic construction of SOFC's enables high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability. SOFCs are capable of fuel-to-electricity efficiencies of 45% to 55% and total system thermal efficiencies up to 85% in combined-cycle applications. This is a promising option for high-powered applications, such as industrial uses or central electricity generating stations.

Direct-methanol fuel cell (DMFC) - A relatively new member of the fuel cell family, the direct-methanol fuel cell (DMFC) is similar to the PEM cell in that it uses a polymer membrane as an electrolyte. However, a catalyst on the DMFC anode draws hydrogen from liquid methanol, eliminating the need for a fuel reformer.

Molten carbonate fuel cell (MCFC) - The molten carbonate fuel cell uses a molten carbonate salt as the electrolyte. MCFC technology has the potential to reach fuel-to-electricity efficiencies of

45% to 60%. Operating temperatures for MCFCs are around 650° C, which allows total system thermal efficiencies up to 50% in combined-cycle applications. MCFCs have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products.

Alkaline fuel cell (AFC) -The alkaline fuel cell uses an alkaline electrolyte such as potassium hydroxide. Originally used by NASA on missions, it is now finding applications in hydrogen-powered vehicles. AFCs contain a potassium hydroxide (KOH) solution as the electrolyte and operate at temperatures between 60 and 260°C. The fuel supplied to an AFC must be pure hydrogen. Carbon monoxide poisons an AFC, and carbon dioxide (even the small amount in the air) reacts with the electrolyte to form potassium carbonate.

Regenerative Fuel Cells - This special class of fuel cells produces electricity from hydrogen and oxygen, but can be reversed and powered with electricity to produce hydrogen and oxygen.

Fuel cell systems can be sized for grid-connected applications or customer-sited applications in residential, commercial, and industrial facilities. Depending on the type of fuel cell, useful heat can be captured and used in combined heat and power systems (CHP). Premium power applications are an important niche market for fuel cells. Multiple fuel cells can be used to provide extremely high reliability and high-quality power for critical loads. Data centers and sensitive manufacturing processes are ideal settings for fuel cells. Fuel cells also can provide power for vehicles and portable power. PEMFCs are a leading candidate for powering the next generation of vehicles. The military is interested in the high-efficiency, low-noise, and small-footprint portable power.

More than 250 PAFC systems are in service worldwide and have surpassed 2 million total operating hours with excellent operational characteristics and high availability. The chart below shows the characteristics of a commercially available PAFC.

Specifications of a 200 kW PAFC		
Expense	**Description**	**Cost**
Capital Cost	PAFC power plant	$850,000
Installation	Electrical, plumbing, and foundation	$ 40,000
Operation	Natural gas costs	$ 5.35/MMcf
Maintenance	Routine maintenance	$ 20,000/yr
Major Overhaul	Replacement of the cell stack (every 5 yrs)	$320,000

PEM systems up to 200 kW are operating in several hydrogen-powered buses. Most units are less than 10 kW. PEMFCs currently cost several thousand dollars per kW.

A small, 25 kW natural gas tubular SOFC systems has accumulated more than 70,000 hours of operations, displaying all the essential systems parameters needed to proceed to commercial configurations. Both 5 kW and 250 kW models are in demonstration.

50 kW and 2 MW systems have been field-tested. Commercial offerings are in the 250-2,000 kW range.

The following table shows the status of the various types of fuel cell designs.

Status of Fuel Cells by type

Type	Electrolyte	Operating Temp (°C)	Electrical Efficiency (%)	Commercial Availability	Size Range (kW)	Startup time (hours)
AFC	KOH	260	32-40	1960's	5-250	< 0.1
PEMFC	Nafion	65-85	30-40	2000	200	1-4
PAFC	Phosphoric Acid	190-210	35-45	1992		
MCFC	Lithium, potassium, carbonate salt	650-700	40-50	Future	250-2,000	5-10
SOFC	Yttrium & zirconium	750-1000	45-55	Future	5-250	5-10

Fuel cells are currently being developed for stationary power generation. Industry will introduce high-temperature natural gas-fueled MCFC and SOFC at $1,000 - $1,500 per kW that are capable of 60% efficiency, ultra-low emissions, and 40,000 hour stack life. DOE is working with industry to test and validate the PEM technology at the 1–kW level. Other efforts include raising the operating temperature of the PEM fuel cell for building, cooling, heating, and power applications and improve reformer technologies to extract hydrogen from a variety of fuels, including natural gas, propane, and methanol.

Chapter 12
Batteries

Batteries are the most widely known type of energy storage. They store and release electricity through electrochemical processes and come in a variety of shapes and sizes. Some are small enough to fit on a computer circuit board, while others are large enough to power a submarine. Some batteries are used several times a day while others may sit idle for 10 or 20 years before they are ever used. Obviously, for such a diversity of uses, a variety of battery types are necessary. But all of them work from the same basic principles.

Battery electrode plates, typically consisting of chemically reactive materials, are placed in an electrolyte, which facilitates the transfer of ions in the battery. The negative electrode gives up electrons during the discharge cycle. This flow of electrons creates electricity that is supplied to any load connected to the battery. The electrons are then transported to the positive electrode. This process is reversed during charging. Batteries store and deliver direct current (DC) electricity. Thus, power-conversion equipment is required to connect a battery to the alternating current (AC) electric grid.

Lead Acid Battery
(SLI Type for Special Applications)

The most mature battery systems are based on lead-acid technology. There are two major kinds of lead acid batteries: flooded lead acid batteries and valve-regulated-lead-acid (VRLA) batteries. There are several rechargeable, advanced batteries under development for stationary and mobile applications, including lithium-ion, lithium polymer, nickel metal hydride, zinc-air, zinc-bromine, sodium sulfur, and sodium bromide. These advanced batteries offer potential advantages over lead acid batteries in terms of cost, energy density, footprint, lifetime, operating characteristics, reduced maintenance, and improved performance.

Lead-acid batteries are the most common energy storage technology for stationary and mobile applications. They offer maximum efficiency and reliability for the widest variety of stationary applications: telecommunications, utility switchgear and control, uninterruptible power supplies (UPS), photovoltaic, and nuclear power plants. They provide instantaneous discharge for a few seconds or a few hours. Installations can be any size. Lead-acid batteries provide power quality, reliability, peak shaving, spinning reserve, and other ancillary services. The disadvantages of the flooded lead-acid battery include the need for periodic addition of water, and the need for adequate ventilation because the batteries can give off hydrogen gas when charging.

VRLA batteries are sealed batteries fitted with pressure-release valves. They have been called low-maintenance batteries, because they do not require periodic adding of water. They can be stacked horizontally as well as vertically, resulting in a smaller footprint than flooded lead-acid batteries. Disadvantages include higher cost and increased sensitivity to the charging cycle used. High temperature results in reduced battery life and performance. Several advanced "flow batteries" are being developed. The zinc-bromine battery consists of a zinc positive electrode and a bromine negative electrode separated by a micro-porous separator. An aqueous solution of zinc/bromide is circulated through the two compartments of the cell from two separate reservoirs. Zinc-bromine batteries are currently being demonstrated in a number of hybrid installations, with microturbines and diesel generators. Sodium bromide/sodium bromine batteries are similar to zinc bromine batteries in function and are under development for large-scale, utility applications. The advantages of flow-battery technologies are low cost, modularity, scalability, transportability, low weight, flexible operation – and all components are easily recyclable. The major disadvantage is relatively low cycle efficiency.

Other advanced batteries include the lithium-ion, lithium-polymer, and sodium-sulfur batteries. The advantages of lithium batteries include their high specific energy (four times that of lead-acid batteries) and charge retention. Sodium sulfur batteries operate at high temperature and are being tested for utility load-leveling applications.

Energy storage systems for large-scale power quality applications (~10 MW) are economically viable. Utility-grade batteries are sized 17-40 MWh and range in efficiency from 70% to 80%. Such batteries have power densities ranging from 0.2 to 0.4 kW/kg and 30-50 Wh/kg in energy density.

Two utility grade applications include a 10 MW-120 MWh sodium bromide system under construction by the Tennessee Valley Authority and a 40 MW nickel cadmium system being built for transmission-line support and stabilization in Alaska.

Lead-acid batteries provide the best long-term power in terms of cycles and float life; and, as a result, will likely remain a strong technology in the future.

Battery manufacturers are working on incremental improvements in energy and power density. The battery industry is trying to improve manufacturing practices and build more batteries at lower costs to stay competitive. Gains in development of batteries for mobile applications will likely crossover to the stationary market.

Chapter 13
Advanced Energy Storage

Advanced storage technologies include flywheels, pneumatics, advanced batteries, reversible fuel cells, hydrogen, ultra-capacitors, and superconducting magnetic storage processes. 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. However, the use of advanced energy storage in conjunction with intermittent renewable energy sources (such as photovoltaics and wind) does have a positive impact on 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.

Stationary applications

Electric demand falls at night, providing an opportunity for the most cost effective electric generators, such as nuclear units, to produce low cost power at night for storage. The stored energy could displace high cost, less efficient power normally produced at the peak during the day. Energy storage also can be used to alleviate the pressure on highly loaded components in the grid such as transmission lines and transformers, which 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, advanced energy storage technology would improve their applicability.

Power quality and reliability

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. 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.

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. Ultra-capacitors 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.

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 control 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.

The following chart shows the status of various advanced energy storage systems for utility applications.

Advanced Energy Storage Technologies				
Technology	Efficiency (%)	Energy Density (W-h/kg)	Power Density (kW/kg)	Sizes (MW-h)
Pumped Hydro	75	0.27 per 100m	Low	5,000 – 20,000
Compressed Gas	70	n/a	Low	250-2,200
SMES	90	n/a	High	20 MW
Batteries	75	30-50	0.2-0.4	17-40
Flywheels	90	15-30	1-3	0.1-20 kWh
Ultra-Capacitors	90	2-10	High	0.1-0.5

Only pumped storage hydro (PSH) has made a significant penetration into the advanced energy storage utility market. There is presently about 21 GW of installed PSH and 150 MW of utility peak-shaving batteries are in service in Japan. Megawatt-scale power quality systems can be cost effective for some technologies and are now entering the marketplace.

Chapter 14
Superconducting Power Technology

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. 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-1980's and are brittle oxide, or ceramic-like materials, that can carry electricity with virtually no resistance losses. 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, etc.

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.

HTS wires and cables

HTS cables have almost no resistance losses and can transport three-to-five times as much power as a conventional cable in the same size conduit. 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.

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 100 m lengths by industry and are to be scaled up in 2008 to 1,000-m lengths. The 100-m tapes carry approximately 100 amperes of current in nitrogen.

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 underway. A 600-m cable to be operated at 138-kV will be installed on Long Island, New York; a 350-m distribution cable is installed in downtown Albany, New York; and a 200-m HTS distribution cable carrying 3,000 amperes is installed at a suburban substation in Columbus, Ohio.

HTS transformers

Compared to conventional transformers, HTS power transformers have about 30% less losses, can be 50% smaller and lighter, may have a total ownership cost that is about 20% lower, are nonflammable, and do not contain oil or any other potential pollutant. 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. Waukesha Electric Systems demonstrated a 1-MVA single-phase prototype transformer in 1999 and is leading a team to develop technology for electrical insulations for three-phase power transformers.

HTS motors

HTS motors are 50% smaller and lighter than conventional motors. 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. Rockwell Automation successfully demonstrated a prototype 750-kW motor in 2000 and is researching motor components with improved performance characteristics.

The development of ion-beam assisted deposition and rolling-assisted, bi-axially textured substrate (RABiTSTM) technologies for producing high-performance HTS film conductors suitable for cables and transformers has led to a potentially commercially viable HTS product. 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 2001. Short lengths of coated conductors made under stringent laboratory conditions have exceeded 1,000 A/cm in width.

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 at this time.

Chapter 15
Thermally Activated Technologies

This technology enables highly efficient heat pump cycles to replace the best natural gas furnaces, reducing energy use as much as 50%. Thermally Activated Technologies (TAT's), such as heat pumps, absorption chillers, and desiccant units, provide on-site space conditioning and water heating, which greatly reduce the electric load of a residential or commercial facility. These technologies can greatly contribute to system reliability.

Heat pumps take in heat at a lower temperature and release it a higher one, with a reversing valve that allows the heat pump to provide space heating or cooling as necessary. In the heating mode, heat is taken from outside air when the refrigerant evaporates and is delivered to the building interior when it condenses. In the cooling mode, the function of the two heat-exchanger coils is reversed, so heat moves inside to outside. *Thermally activated heat pumps* are a new generation of advanced absorption cycle heat pumps that can efficiently condition residential and commercial space.

Absorption chillers provide cooling to buildings by using heat. Unlike conventional electric chillers, which use mechanical energy in a vapor-compression process to provide refrigeration, absorption chillers primarily use heat energy with limited mechanical energy for pumping. The chiller transfers thermal energy from the heat source to the heat sink through an absorbent fluid and a refrigerant. The chiller achieves its refrigeration effect by absorbing and then releasing water vapor into and out of a lithium bromide solution. In the process, heat is applied at the generator and water vapor is driven off to a condenser. The cooled water vapor then passes through an expansion valve, reducing the pressure. The low-pressure water vapor then enters an evaporator, where ambient heat is added from a load and the actual cooling takes place. The heated, low-pressure vapor returns to the absorber, where it recombines with lithium bromide and becomes a low-pressure liquid. This low-pressure solution is pumped to a higher pressure and into the generator to repeat the process.

Desiccant equipment is useful for mitigation of indoor air-quality problems and for improved humidity control in buildings. Commercially available desiccants include silica gel, activated alumina, natural and synthetic zealots, lithium chloride, and synthetic polymers. The wheel is rotated through supply air, usually from the outside, and the material naturally attracts the moisture from the air before it is routed to the building. The desiccant is then regenerated using thermal energy from natural gas, the sun, or waste heat.

Thermally activated heat pumps can revolutionize the way residential and commercial buildings are heated and cooled. Different heat pumps will be best suited for different applications. For example, the GAX heat pump is targeted for northern states because of its superior heating performance; and the Hi-Cool heat pump targets the South, where cooling is a priority. Absorption chillers can change a building's thermal and electric profile by shifting the cooling from an electric load to a thermal load. This shift can be very important for facilities with time-of-day electrical rates, high cooling-season rates, and high demand charges. Facilities with high thermal loads, such as data centers, grocery stores, and casinos, are promising markets for absorption chillers. Desiccant technology can either supplement a conventional air-conditioning system or act as a standalone operation. A desiccant can remove moisture, odors, and pollutants for a healthier and more comfortable indoor environment.

TAT's may be powered by natural gas, fuel oil, propane, or biogas, avoiding substantial energy conversion losses associated with electric power transmission, distribution, and generation. These technologies may use the waste heat from on-site power generation and provide total energy solutions for onsite cooling, heating, and power.

Facilities with stringent indoor air-quality needs (schools, hospitals, grocery stores, hotels) have adapted desiccant technology. Combined heat and power applications are well suited for TAT's. They offer a source of "free" fuel in the form of waste heat that can power heat pumps and absorption chillers, and regenerate desiccant units.

This technology will expand the residential market with the second-generation Hi-Cool residential absorption heat pump technology. However, to reach a targeted 30% improvement in cooling performance there must be major new advancements in absorption technology or engine-driven systems.

Summary

This course is a brief overview of several technologies that many consider will be key to reducing greenhouse gases.

The DOE is assisting industry with R&D efforts to bring new energy efficiency technologies to market. These technologies include biopower, geothermal, concentrating solar power, photovoltaics, wind energy, hydrogen, advanced hydropower, building technologies, reciprocating engines, microturbines, fuel cells, batteries, advanced energy storage, superconducting power technology, and thermally activated technologies. All of these technologies hold promise in helping the United States reduce greenhouse gases and to develop a more energy efficiency economy.