Biopower

Technology Description

Biopower, also called biomass power, is the generation of electric power from biomass resources – now usually urban waste wood, crop, and forest residues; and, in the future, crops 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 regrowing biomass can result in very low CO_2 emissions compared to fossil energy without carbon sequestration, such as coal, oil or natural gas. Through the use of residues, biopower systems can even represent a net sink for GHG emissions by avoiding methane emissions that would result from landfilling of the unused biomass.

Representative Technologies for Conversion of Feedstock to Fuel for Power and Heat

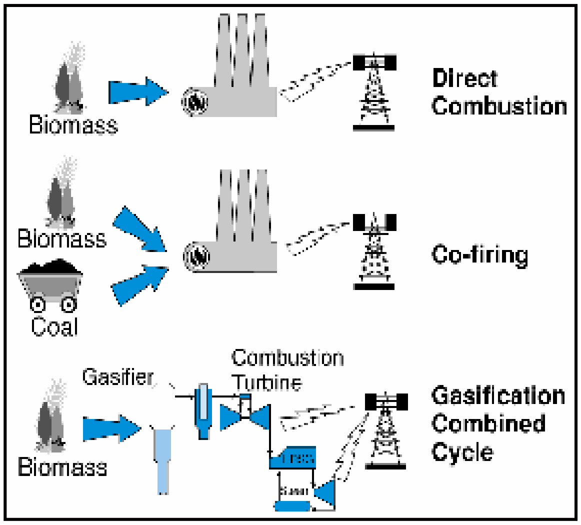
- *Homogenization* is a process by which feedstock is made physically uniform for further processing or for combustion (includes chopping, grinding, baling, cubing, and pelletizing).
- *Gasification* (via pyrolysis, partial oxidation, or steam reforming) converts biomass to a fuel gas that can be substituted 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.

Representative Technologies for Conversion of Fuel to Power and Heat

- Direct combustion systems burn biomass fuel in a boiler to produce steam that is expanded in a Rankine Cycle prime mover to produce power.
- Cofiring substitutes biomass for coal or other fossil fuels in existing coal-fired boilers.
- Biomass or biomass-derived fuels (e.g. syngas, ethanol, biodiesel) also can be burned in combustion turbines (Brayton cycle) or engines (Otto or Diesel cycle) to produce power.
- When further processed, biomass-derived fuels can be used by fuels cells to produce electricity

System Concepts

- CHP applications involve recovery of heat for steam and/or hot water for district energy, industrial processes, and other applications.



- 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 generator (boiler), turbine, condenser, and pump.
- For the near term, cofiring is the most cost-effective of the power-only technologies. Large coal steam plants have electric efficiencies near 33%. The highest levels of coal cofiring (15% on a heat-input basis) require separate feed preparation and injection systems.
- Biomass gasification combined-cycle plants promise comparable or higher electric efficiencies (> 40%) using only biomass, because they involve gas turbines (Brayton cycle), which are more efficient than Rankine cycles, as is true for coal. Other technologies being developed include integrated gasification/fuel cell and biorefinery concepts.

Technology Applications

- The existing biopower sector – nearly 1,000 plants – is mainly comprised of direct-combustion plants, with an additional small amount of cofiring (six operating plants). Plant size averages 20 MW_e, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity has increased from less than 200 MW_e in 1978 to more than 9,700 MW_e in 2001. More than 75% 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. In addition, about 3,300 MW_e of municipal solid waste and landfill gas generating capacity exists. Recent studies estimate that on a life-cycle basis, existing biopower plants represent an annual net carbon sink of 4 MMTCe. Prices generally range from 8¢/kWh to 12¢/kWh.

Current Status

- 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 cofiring with coal ($50 - 250/kW of biomass capacity) is the most near-term option for large-scale use of biomass for power-only electricity generation. Cofiring also reduces sulfur dioxide and nitrogen oxide emissions. In addition, when cofiring crop and forest-product residues, GHG emissions are reduced by a greater percentage (e.g. 23% GHG emissions reduction with 15% cofiring).
- Biomass gasification for large-scale (20-100MW_e) power production is being commercialized. It will be an important technology for cogeneration in the forest-products industries (which project a need for biomass and black liquor CHP technologies with a higher electric-thermal ratio), as well as for new baseload capacity. Gasification also is important as a potential platform for a biorefinery.
- Small biopower and biodiesel systems have been used for many years in the developing world for electricity generation. However, these systems have not always been reliable and clean. DOE is developing systems for village-power applications and for developed-world distributed generation that are efficient, reliable, and clean. These systems range in size from 3kW to 5MW and completed field verification by 2003.
- Approximately 15 million to 21 million gallons of biodiesel are produced annually in the United States.
- Utility and industrial biopower generation totaled more than 60 billion kWh in 2001, representing about 75% of nonhydroelectric 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. Industry consumes more than 2.1 quadrillion Btu of primary biomass energy.

Technology History

- In the latter part of the 19th century, wood was the primary fuel for residential, commercial, and transportation uses. By the 1950s, other fuels had supplanted wood. In 1973, wood use had dropped to 50 million tons per year.
- At that point, the forest products and pulp-and-paper industries began to use wood with coal in new plants and switched to wood-fired steam power generation.
- The Public Utility Regulatory Policies Act (PURPA) of 1978 stimulated the development of nonutility cogeneration and small-scale plants to in the wood-processing and pulp-and-paper sectors and increased supply of power to the grid.
- The combination of low natural gas prices, improved economies of scale in combined cycle palns, and withdrawal of incentives in the late 1980s, led to annual installations declining from about 600 MW in 1989, to 300-350MW in 1990.
- There are now nearly 1,000 wood-fired plants in the United States, with about two-thirds of those providing power (and heat) for on-site uses only.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for biomass direct-fired and gasification configurations are projected to be:

	2000	2010	2020
Direct-fired	7.5	7.0	5.8
Gasification	6.7	6.1	5.4

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.

- R&D directions include:

Gasification – This technology requires extensive field verification in order to be adopted by the relatively conservative utility and forest-products industries, especially to demonstrate integrated operation of biomass gasifier with advanced-power generation (turbines and/or fuel cells). Integration of gasification into a biorefinery platform is a key new research area.

Small Modular Systems – Small-scale systems for distributed or minigrid (for premium or village power) applications will be increasingly in demand.

Cofiring – The DOE biopower program is moving away from research on cofiring, as this technology has reached a mature status. However, continued industry research and field verifications are needed to address specific technical and nontechnical barriers to cofiring. Future technology development will benefit from finding ways to better 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 cofiring up to 5% of natural gas combined-cycle capacity.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Biomass

Market Data

Cumulative Generating Capability, by Type (MW)

Source: Energy Information Administration (EIA), EIA, *Annual Energy Review 2004*, DOE/EIA-0384(2004) (Washington, D.C., August 2005), Tables 8.11a and 8.11c, and world data from United Nations Development Program, World Energy Assessment, 2000, Table 7.25.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
U.S. Electric Power Sector													
Municipal Solid Waste[1]	N/A	151	1,852	2,733	2,600	2,528	2,636	2,614	2,789	2,993	2,949	2,842	2,856
Wood and Other Biomass[2]	78	200	964	1,451	1,425	1,452	1,438	1,484	1,486	1,487	1,410	1,389	1,389
U.S. Cogenerators[3]													
Municipal Solid Waste[1]			659	786	998	1,062	1,058	1,046	1,094	834	842	961	961
Wood and Other Biomass[2]			4,585	5,298	5,382	5,472	5,364	5,311	4,655	4,394	4,399	4,482	4,502
U.S. Total													
Municipal Solid Waste[1]	NA	151	2,511	3,519	3,598	3,590	3,694	3,660	3,883	3,827	3,845	3,803	3,817
Wood and Other Biomass[2]	78	200	5,549	6,750	6,808	6,924	6,802	6,795	6,141	5,882	5,844	5,871	5,891
Biomass Total	78	351	8,061	10,269	10,405	10,515	10,495	10,454	10,024	9,709	9,689	9,674	9,708
Rest of World Total[4]							29,505						
World Total							40,000						

[1] Municipal solid waste, landfill gas, sludge waste, tires, agricultural byproducts, and other biomass.

[2] Wood, black liquor, and other wood waste.

[3] Data include electric power sector and end-use sector (industrial and commercial) generators.

[4] Number derived from subtracting U.S. total from the world total. Figures may not add due to rounding.

U.S. Annual Installed Generating Capability, by Type (MW)

Source: *Renewable Electric Plant Information System (REPiS)*, Version 7, NREL, 2003.

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003[1]
Agricultural Waste[2]	22.6	20.1	0	4.0	0	21.6	0	0	0	0	0	0
Biogas[3]	0.1	58.6	51.3	17.5	74.8	92.7	87.3	107.6	43.8	66.8	30.2	23.1
Municipal Solid Waste[4]	50.0	117.2	260.3	94.5	0	0	0	22.0	0	0	0	30.0
Wood Residues[5]	260.4	254.8	299.4	66.5	91.6	40.0	90.3	13.0	0	11.3	38.8	0
Total	333.0	450.7	611.0	182.5	166.4	154.3	177.6	142.6	43.8	78.1	69.0	53.1

U.S. Cumulative Generating Capability, by Type[6] (MW)

Source: *Renewable Electric Plant Information System (REPiS)*, Version 7, NREL, 2003.

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003[1]
Agricultural Waste[2]	40	92	165	351	351	373	373	373	373	373	373	373
Biogas[3]	18	117	361	526	601	694	781	889	933	999	1,030	1,053
Municipal Solid Waste[4]	263	697	2,172	2,948	2,948	2,948	2,948	2,970	2,970	2,970	2,970	3,000
Wood Residues[5]	3,576	4,935	6,305	7,212	7,303	7,343	7,434	7,447	7,447	7,458	7,497	7,497
Total	3,897	5,840	9,003	11,037	11,203	11,358	11,535	11,678	11,722	11,800	11,869	11,922

Note: The data in this table does not match data in the previous table, due to different coverage ratios in EIA and REPIS databases.

[1] 2003 data not complete as REPiS database is updated through 2002.

[2] Agricultural residues, cannery wastes, nut hulls, fruit pits, nut shells

[3] Biogas, alcohol (includes butahol, ethanol, and methanol), bagasse, hydrogen, landfill gas, livestock manure, wood gas (from wood gasifier)

[4] Municipal solid waste (includes industrial and medical), hazardous waste, scrap tires, wastewater sludge, refused-derived fuel

[5] Timber and logging residues (includes tree bark, wood chips, saw dust, pulping liquor, peat, tree pitch, wood or wood waste)

[6] There are an additional 65.45 MW of Ag Waste, 5.445 MW of Bio Gas, and 483.31 MW of Wood Residues that are not accounted for here because they have no specific online date.

Generation from Cumulative Capacity, by Type (Million kWh)

Source: EIA, *Annual Energy Review 2003*, Tables 8.2a and 8.2c, and world data from United Nations Development Program, World Energy Assessment, 2000, Table 7.25.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
U.S. Electric Power Sector													
Municipal Solid Waste[1]	158	640	10,245	16,326	16,078	16,397	16,963	17,112	17,592	17,221	17,359	18,141	17,809
Wood and Other Biomass[2]	275	743	5,327	5,885	6,493	6,468	6,644	7,254	7,301	6,571	7,265	7,402	7,475
U.S. Cogenerators[3]													
Municipal Solid Waste[1]			2,904	4,079	4,834	5,312	5,485	5,460	5,540	4,543	5,498	5,889	4,938
Wood and Other Biomass[2]			26,939	30,636	30,307	30,480	29,694	29,787	30,294	28,629	31,400	29,735	29,820
U.S. Total													
Municipal Solid Waste[1]	158	640	13,149	20,405	20,911	21,709	22,448	22,572	23,131	21,765	22,857	23,736	22,747
Wood and Other Biomass[2]	275	743	32,266	36,521	36,800	36,948	36,338	37,041	37,595	35,200	38,665	37,529	37,295
Biomass Total	433	1,383	45,415	56,926	57,712	58,658	58,786	59,613	60,726	56,964	61,522	61,265	60,042
Rest of World Total[4]							101,214						
World Total							160,000						

[1] Municipal solid waste, landfill gas, sludge waste, tires, agricultural byproducts, and other biomass.

[2] Wood, black liquor, and other wood waste.

[3] Data include electric power sector and end-use sector (industrial and commercial) generators.

[4] Number derived from subtracting U.S. total from the world total. Figures may not add due to rounding.

U.S. Annual Energy Consumption for Electricity Generation (Trillion Btu)

Source: EIA, *Annual Energy Review 2004*, Tables 8.4b and 8.4c

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Electric-Power Sector	4.5	14.4	285.9	388.0	397.3	408.3	412.0	415.5	420.7	430.4	494.1	493.1	492.4
Commercial Sector[1]			16.7	22.3	32.1	34.3	32.7	33.5	26.5	22.6	28.5	30.6	32.2
Industrial Sector[1]			351.0	385.3	407.1	380.7	362.0	373.0	378.8	379.6	481.5	378.7	567.8
Total Biomass	4.5	14.4	653.5	795.6	836.5	823.3	806.8	822.0	825.9	832.6	1,004.1	902.4	1,092.4

Data include wood (wood, black liquor, and other wood waste) and waste (municipal solid waste, landfill gas, sludge waste, tires, agricultural byproducts, and other biomass).

[1] Data includes combined-heat-and-power (CHP) and electricity-only plants.

Technology Performance

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.

Efficiency		1980	1990	1995[1]	2000	2005	2010	2015[2]	2020
Capacity Factor (%)	Direct-fired			80.0	80.0	80.0	80.0	80.0	80.0
	Cofired			85.0	85.0	85.0	85.0	85.0	85.0
	Gasification			80.0	80.0	80.0	80.0	80.0	80.0
Efficiency (%)	Direct-fired			23.0	27.7	27.7	27.7	30.8	33.9
	Cofired			32.7	32.5	32.5	32.5	32.5	32.5
	Gasification			36.0	36.0	37.0	37.0	39.3	41.5
Net Heat Rate (kJ/kWh)	Direct-fired			15,280	13,000	13,000	13,000	11,810	10,620
	Cofired			11,015	11,066	11,066	11,066	11,066	11,066
	Gasification			10,000	10,000	9,730	9,730	9,200	8,670

Cost		1980	1990	1995[1]	2000	2005	2010	2015	2020
Total Capital Cost ($/kW)	Direct-fired			1,965	1,745	1,510	1,346	1,231	1,115
	Cofired[3]			272	256	241	230	224	217
	Gasification			2,102	1,892	1,650	1,464	1,361	1,258
Feed Cost ($/GJ)	Direct-fired			2.50	2.50	2.50	2.50	2.50	2.50
	Cofired[3]			-0.73	-0.73	-0.73	-0.73	-0.73	-0.73
	Gasification			2.50	2.50	2.50	2.50	2.50	2.50
Fixed Operating Cost ($/kW-yr)	Direct-fired			73.0	60.0	60.0	60.0	54.5	49.0
	Cofired[3]			10.4	10.1	9.8	9.6	9.5	9.3
	Gasification			68.7	43.4	43.4	43.4	43.4	43.4
		1980	1990	1995[1]	2000	2005	2010	2015	2020
Variable Operating Costs ($/kWh)	Direct-fired			0.009	0.007	0.007	0.007	0.006	0.006
	Cofired[3]			-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
	Gasification			0.004	0.004	0.004	0.004	0.004	0.004
Total Operating Costs ($/kWh)	Direct-fired			0.055	0.047	0.047	0.047	0.043	0.039
	Cofired[3]			-0.008	-0.008	-0.008	-0.009	-0.009	-0.009
	Gasification			0.040	0.036	0.036	0.036	0.034	0.033
Levelized Cost of Energy ($/kWh)	Direct-fired			0.087	0.075		0.070		0.058
	Cofired[3]			N/A	N/A	N/A	N/A	N/A	N/A
	Gasification			0.073	0.067		0.061		0.054

[1] Data is for 1997, the base year of the Renewable Energy Technology Characterizations analysis.

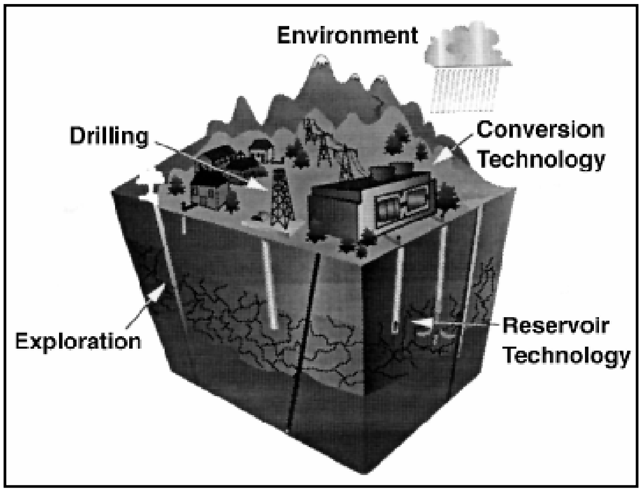
[2] Number derived by interpolation.

[3] Note that cofired cost characteristics represent only the biomass portion of costs for capital and incremental costs above conventional costs for Operations & Maintenance (O&M), and assume $9.14/dry tonne biomass and $39.09/tonne coal, a heat input from biomass at 19,104 kJ/kg, and that variable O&M includes an SO2 credit valued at $110/tonne SO2. No cofiring COE is reported in the *RETC*.

Geothermal Energy

Technology Description

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.



System Concepts

- Geophysical, geochemical, and geological exploration locates resources to drill, including highly permeable hot reservoirs, shallow warm groundwater, hot impermeable rock masses, and highly pressured hot fluids.
- Well fields and distribution systems allow the hot fluids to move to the point of use, and afterward, back to the earth.
- Utilization systems may apply the heat directly or convert it to another form of energy such as electricity.

Representative Technologies

- Exploration technologies identify geothermal reservoirs and their fracture systems; drilling, reservoir testing, and modeling optimize production and predict useful lifetime; steam turbines use natural steam or hot water flashed to steam to produce electricity; binary conversion systems produce electricity from water not hot enough to flash.
- Direct applications use the heat from geothermal fluids without conversion to electricity. Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications.
- Coproduction, the recovery of minerals and metals from geothermal brine, is being pursued. Zinc is recovered at the Salton Sea geothermal field in California.

Technology Applications

- With improved technology, the United States has a resource base capable of producing up to 100 GW of electricity at less than 5¢/kWh.
- Hydrothermal reservoirs are being used to produce electricity with an online availability of up to 97%; 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 markets for heating/cooling (HVAC) services.

Current Status

- The DOE Geothermal Program sponsored research that won two R&D 100 Awards in 2003: Acoustic Telemetry Technology, which provides a high speed data link between the surface and the drill bit; and Low Emission Atmospheric Monitoring Separator, which safely contains and cleans vented steam during drilling, well testing, and plant start-up.
- A second pipeline to carry replacement water has been completed through the joint efforts of industry and federal, state, and local agencies. This will increase production and extend the lifetime of The Geysers Geothermal Field in California. The second pipeline adds 85 MW of capacity.

Technology History

- The use of geothermal energy as a source of hot water for spas dates back thousands of years.
- In 1892, the world's first district heating system was built in Boise, Idaho, as water was piped from hot springs to town buildings. Within a few years, the system was serving 200 homes and 40 downtown businesses. Today, the Boise district heating system continues to flourish. Although no one imitated this system for nearly 70 years, there are now 17 district heating systems in the United States and dozens more around the world.
- The United States' first geothermal power plant went into operation in 1922 at The Geysers in California. The plant was 250 kW, but fell into disuse.
- In 1960, the country's first large-scale geothermal electricity-generating plant began operation. Pacific Gas and Electric operated the plant, located at The Geysers. The resource at The Geysers is dry steam. The first turbine produces 11 megawatts (MW) of net power and operated successfully for more than 30 years.
- In 1979, the first electrical development of a water-dominated geothermal resource occurred at the East Mesa field in the Imperial Valley in California.
- In 1980, UNOCAL built the country's first flash plant, generating 10 MW at Brawley, California.
- In 1981, with a supporting loan from DOE, Ormat International Inc. successfully demonstrated binary technology in the Imperial Valley of California. This project established the technical feasibility of larger-scale commercial binary power plants. The project was so successful that Ormat repaid the loan within a year.
- By the mid-1980s, electricity was being generated by geothermal power in four western states: California, Hawaii, Utah, and Nevada.
- In the 1990s, the U.S. geothermal industry focused its attention on building power plants overseas, with major projects in Indonesia and the Philippines.
- In 1997, a pipeline began delivering treated municipal wastewater and lake water to The Geysers steamfield in California, increasing the operating capacity by 70 MW.
- In 2000, DOE initiated its GeoPowering the West program to encourage development of geothermal resources in the western United States by reducing nontechnical barriers.
- The DOE Geothermal Program sponsored research that won two R&D awards in 2003, advancing this renewable energy.
- With approval of the federal production tax credit and with support from state-level renewable portfolio standards, U.S. geothermal power is poised to double in capacity within the next couple of years.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for the two major future geothermal energy configurations are projected to be:

	2000	2010	2020
Hydrothermal Flash	3.0	2.4	2.1
Hydrothermal Binary	3.6	2.9	2.7

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.

- Costs at the best sites are competitive at today's energy prices – and 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.

Market Context

- Hydrothermal reservoirs have an installed capacity of about 2,133 MW electric in the United States and about 8,000 MW worldwide. Direct-use applications have an installed capacity of about 600 MW thermal in the United States. About 300 MW electric are being developed in California, Nevada, and Idaho.
- Geothermal will continue production at existing plants (2.1 GW) with future construction potential (100 GW by 2040). Direct heat will replace existing systems in markets in 19 western states.
- By 2015, geothermal could provide about 10 GW, enough heat and electricity for 7 million homes; by 2020, an installed electricity capacity of 20,000 MW from hydrothermal plants and 20,000 MW from enhanced geothermal systems is projected.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term*. DOE/PI-0002. November 2003 (draft update, September 2005).

Geothermal

Market Data

Cumulative Installed Capacity

Source: U.S. electricity data from EIA, *Annual Energy Review 2004*, DOE/EIA-0384(2004) (Washington, D.C., August 2005), Table 8.11a; world totals from *Renewable Energy World*/July-August 2000, page 123, Table 1; 1998 world totals from *UNDP World Energy Assessment 2000*, Tables 7.20 and 7.25; 1997 world electricity and U.S. and world direct-use heat data from Stefansson and Fridleifsson 1998, “Geothermal Energy: European and World-wide Perspective.”

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Electricity (MW$_e$)													
U.S.	909	1,580	2,666	2,968	2,893	2,893	2,893	2,846	2,793	2,216	2,252	2,133	2,133
Rest of World	1,191	3,184	3,166	3,829		5,128	5,346		5,181				
World Total	2,100	4,764	5,832	6,797		8,021	8,239		7,974				
Direct-Use Heat (MW$_{th}$)													
U.S.						1,905							
Rest of World						7,799							
World Total	1,950	7,072	8,064	8,664		9,704	11,000		17,175				

Cumulative Installed Capacity

Source: International Geothermal Association, http://iga.igg.cnr.it/index.php

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Electricity (MW$_e$)												
U.S.			2,775	2,817					2,228			2,020
Rest of World			3,057	4,016					5,746			6,382
World Total			5,832	6,833					7,974			8,402
Direct-Use Heat (MW$_{th}$)												
U.S.				1,874					3,766			4,350
Rest of World				6,730					11,379			
World Total				8,604					15,145			

Annual Installed Electric Capacity (MW_e)

Source: *Renewable Electric Plant Information System (REPiS)*, Version 7, NREL, 2003.

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003*
U.S.	251.0	352.9	48.6		36.0				59.9			

Cumulative Installed Electric Capacity (MW_e)

Source: Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003*
U.S.	802	1,698	2,540	2,684	2,720	2,720	2,720	2,720	2,779	2,779	2,779	2,779

* 2003 data not complete as REPiS database is updated through 2002.

Installed Capacity and Power Generation/Energy Production from Installed Capacity

Source: Lund and Freeston, *World-Wide Direct Uses of Geothermal Energy 2000*, Lund and Boyd, Geothermal Direct-Use in the United States Update: 1995-1999, J. Lund, *World Status of Geothermal Energy Use Overview 1995-1999* http://www.geothermie.de/europaundweltweit/Lund/wsoge_index.htm, Sifford and Blommquist, *Geothermal Electric Power Production in the United States: A Survey and Update for 1995-1999*, and G. Huttrer, *The Status of World Geothermal Power Generation 1995-2000.* Proceedings of the World Geothermal Congress 2000 http://geothermal.stanford.edu/wgc2000/SessionList.htm, Kyushu-Tohoku, Japan, May 28-June10, 2000.

Cumulative Installed Capacity

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Electricity (MW_e)									
U.S.				2,369	2,343	2,314	2,284	2,293	2,228
Rest of World				4,464					5,746
World Total	3,887	4,764	5,832	6,833					7,974
Direct-Use Heat* (MW_{th})									
U.S.									4,200
Rest of World									12,975
World Total	1,950	7,072	8,064	8,664				16,209	17,175

Annual Generation/Energy Production from Cumulative Installed Capacity

	1980	1985	1990	1995	1996	1997	1998	1999	2000
Electricity (Billion kWh$_e$)									
U.S.				14.4	15.1	14.6	14.7	15.0	15.5
Rest of World									33.8
World Total									49.3
Direct-Use Heat* (TJ)									
U.S.				13,890				20,302	21,700
Rest of World				98,551				141,707	163,439
World Total		86,249		112,441				162,009	185,139

* Direct-use heat includes geothermal heat pumps as well as traditional uses. Geothermal heat pumps account for 1854 MW$_{th}$ (14,617 TJ) in 1995 and 6849 MW$_{th}$ (23,214 TJ) in 1999 of the world totals and 3600 MW$_{th}$ (8,800 TJ) in 2000 of the U.S. total. Conversion of GWh to TJ is done at 1TJ = 0.2778 GWh.

Annual Generation from Cumulative Installed Capacity

Source: U.S. electricity data from EIA, *Annual Energy Review 2004*, DOE/EIA-0384(2004) (Washington, D.C., August 2005), Table 8.2a; world electricity totals from *Renewable Energy World*/July-August 2000, page 126, Table 2; 1997 world electricity and U.S. and world direct-use heat data from Stefansson and Fridleifsson 1998, “Geothermal Energy: European and World-wide Perspective.” 1998 world totals from UNDP World Energy Assessment 2000, Table 7.25; 1995, 2000, and 2003 direct-use heat and 1999 electricity world total from International Geothermal Association, http://iga.igg.cnr.it/index.php.

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Electricity (Billion kWh$_e$)													
U.S.	5.1	9.3	15.4	13.4	14.3	14.7	14.8	14.8	14.1	13.7	14.5	14.4	14.4
Rest of World	8.9	7.7	3.6	6.6		29.0	31.2		35.2				
World Total	14	17	19	20		43.8	46	49	49.3				
Direct-Use Heat (billion kWhth)													
U.S.				3.9		4.0			5.6			6.2	
Rest of World						31.1							
World Total				31.2			40		53.0				
			27.4					47.3					
					35.1								

Annual Geothermal Energy Consumption for Electric Generation (Trillion Btu)

Source: EIA, *Annual Energy Review 2004*, DOE/EIA-0384(2004) (Washington, D.C., August 2005), Table 8.4a.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
U.S.	110	198	326	280	300	309	311	312	296	289	305	303	302
Rest of World													
World Total													

Annual U.S. Geothermal Heat Pump Shipments, by type (units)

Source: EIA, *Renewable Energy Annual 2004*, DOE/EIA-0603(2004) (Washington, D.C., June 2006), Table 58.

			1996	**1997**	**1998**	**1999**	**2000**	**2001***	**2002**	**2003**	**2004**
ARI-320		4,696	4,697	7,772	10,510	7,910	7,808	N/A	6,445	10,306	9,130
ARI-325/330		26,800	25,697	28,335	26,042	31,631	26,219	N/A	26,802	25,211	31,855
Other non-ARI Rated	**1995**	838	991	1,327	1,714	2,138	1,554	N/A	3,892	922	2,821
Totals		32,334	31,385	37,434	38,266	41,679	35,581	N/A	37,139	36,439	43,806

* No survey was conducted for 2001.

Capacity of U.S. Heat Pump Shipments (Rated Tons)

Source: EIA, *Renewable Energy Annual 2004*, DOE/EIA-0603(2004) (Washington, D.C., June 2006), Table 59.

			1996	**1997**	**1998**	**1999**	**2000**	**2001***	**2002**	**2003**	**2004**
ARI-320		13,120	15,060	24,708	35,776	27,970	26,469	N/A	16,756	29,238	23,764
ARI-325/330		113,925	92,819	110,186	98,912	153,947	130,132	N/A	96,541	89,731	100,317
Other non-ARI Rated	**1995**	3,935	5,091	6,662	6,758	9,735	7,590	N/A	12,000	5,469	20,220
Totals		130,980	112,970	141,556	141,446	191,652	164,191	N/A	125,297	124,438	144,301

1 One Rated Ton of Capacity equals 12,000 Btu's.

2 No survey was conducted for 2001.

Annual U.S. Geothermal Heat Pump Shipments by Customer Type and Model Type (units)

Source: EIA, *Renewable Energy Annual 2004*, DOE/EIA-0603(2003) (Washington, D.C., June 2006), Table 61, REA 2003 Table 40, REA 2002 Table 40, REA 2001 Table 40, REA 2000 Table 38, REA 1999 Table 38, and REA 1998 Table 40.

	1996	**1997**	**1998**	**1999**	**2000**	**2001***	**2002**	**2003**	**2004**
Exporter	2,276	226	109	6,172	784	N/A	1,165	945	1,092
Wholesale Distributor	21,444	29,181	14,377	9,193	9,804	N/A	20,888	16,167	23,647
Retail Distributor	8,336	829	3,222	2,555	2,272	N/A	552	1,145	355
Installer	18,762	25,302	18,429	24,917	20,491	N/A	10,999	10,784	13,562

End User	689	657	994	66	63	N/A	207	1,103	397
Others	13	1,727	1,135	6,259	2,167	N/A	3,328	6,295	4,753
Total	51,520	57,922	38,266	49,162	35,581	N/A	37,139	36,439	43,806

Annual U.S. Geothermal Heat Pump Shipments by Export & Census Region (units)

Source: EIA, *Renewable Energy Annual 2004*, DOE/EIA-0603(2003) (Washington, D.C., June 2006), Table 60, REA 2003 Table 39, REA 2002 Table 39, REA 2001 Table 39, REA 2000 Table 37, REA 1999 Table 37, and REA 1998 Table 39.

	1996	**1997**	**1998**	**1999**	**2000**	**2001***	**2002**	**2003**	**2004**
Export	4,090	2,427	481	6,303	1,220	N/A	3,271	2,764	2,984
Midwest	11,874	13,402	12,240	13,112	10,749	N/A	12,982	12,042	14,650
Northeast	6,417	9,280	5,403	6,044	4,138	N/A	3,903	5,924	8,060
South	25,302	26,788	16,195	20,935	17,403	N/A	13,660	12,543	14,674
West	3,837	6,025	3,947	2,768	2,071	N/A	3,323	3,166	3,438
Total	51,520	57,922	38,266	49,162	35,581	N/A	37,139	36,439	43,806

Technology Performance

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.

Efficiency		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capacity Factor (%)	Flashed Steam			89	92	93	95	96	96
	Binary			89	92	93	95	96	96
	Hot Dry Rock			80	81	82	83	84	85

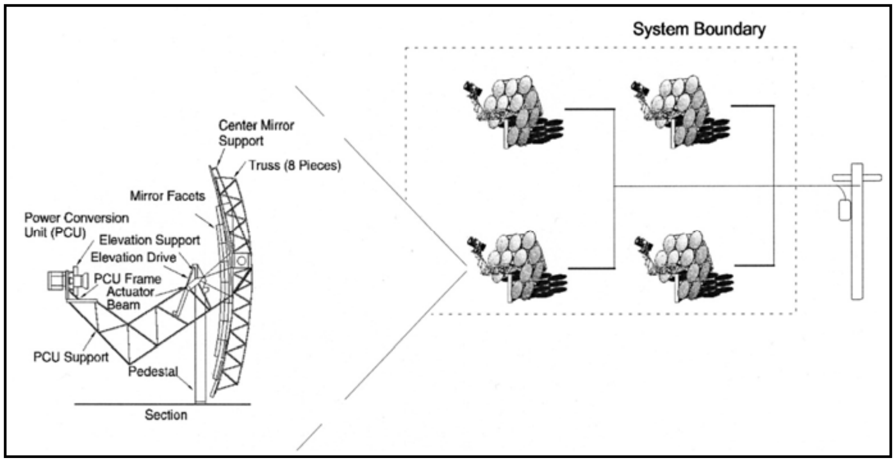
Cost		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capital Cost ($/kW)	Flashed Steam			1,444	1,372	1,250	1,194	1,147	1,100
	Binary			2,112	1,994	1,875	1,754	1,696	1,637
	Hot Dry Rock			5,519	5,176	4,756	4,312	3,794	3,276
Fixed O&M ($/kW-yr)	Flashed Steam			96.4	87.1	74.8	66.3	62.25	58.2
	Binary			87.4	78.5	66.8	59.5	55.95	52.4
	Hot Dry Rock			219	207	191	179	171	163

Concentrating Solar Power

Technology Description

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.

System Concepts



- 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 (steam or gas turbines or Stirling engines) to produce electricity at solar-to-electric efficiencies for the system of up to 30%.
- CSP technologies provide firm, nonintermittent electricity generation (peaking or intermediate load capacity) when coupled with storage.
- Because solar-thermal technologies can yield extremely high temperatures, the technologies could some day be used for direct conversion (rather than indirect conversion through electrochemical reactions) of natural gas or water into hydrogen for future hydrogen-based economies.

Representative Technologies

- A parabolic trough system focuses solar energy on a linear oil-filled receiver to collect heat to generate steam to power a steam turbine. When the sun is not shining, steam can be generated with a fossil fuel to meet utility needs. Some of the new trough plants include thermal storage. Plant sizes can range from 1.0 to 100 MW$_e$.
- 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$_e$.
- A dish/engine system uses a dish-shaped reflector to power a small Stirling 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$_e$) for utility-scale applications, including end-of-line support. They are easily hybridized with fossil fuel.

Technology Applications

- Nine parabolic trough plants, with a rated capacity of 354 MW$_e$, have been operating in California since the 1980s. Trough system electricity costs of about 12¢-14¢/kWh have been demonstrated commercially.
- Solar Two, a 10-MW$_e$ pilot power tower with three hours of storage, provided all the information needed to scale up to a 30-100 MW commercial plant, the first of which is now being planned in Spain.
- A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for more than 10,000 hours.

Current Status

- New commercial plants are being considered for California, Nevada, New Mexico, Colorado, and Arizona. A 1MW power plant began operation in Arizona in 2005.
- The 10-MW Solar Two pilot power tower plant operated successfully near Barstow, California, leading to the first commercial plant being planned in Spain.
- Operations and maintenance costs have been reduced through technology improvements at the commercial parabolic trough plants in California by 40%, saving plant operators $50 million.

Technology History

Organized, large-scale development of solar collectors began in the United States in the mid-1970s under the Energy Research and Development Administration (ERDA) and continued with the establishment of the U.S. Department of Energy (DOE) in 1978.

Troughs:

- Parabolic trough collectors capable of generating temperatures greater than 500ºC (932 F) were initially developed for industrial process heat (IPH) applications. Acurex, SunTec, and Solar Kinetics were the key parabolic trough manufacturers in the United States during this period.
- Parabolic trough development also was taking place in Europe and culminated with the construction of the IEA Small Solar Power Systems (SSPS) Project/Distributed Collector System in Tabernas, Spain, in 1981. This facility consisted of two parabolic trough solar fields – one using a single-axis tracking Acurex collector and one the double-axis tracking parabolic trough collectors developed by M.A.N. of Munich, Germany.
- In 1982, Luz International Limited (Luz) developed a parabolic trough collector for IPH applications that was based largely on the experience that had been gained by DOE/Sandia and the SSPS projects.
- 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. Luz later signed a number of Standard Offer (SO) power purchase contracts under the Public Utility Regulatory Policies Act (PURPA), leading to the development of the SEGS III through SEGS IX projects. Initially, the plants were limited by PURPA to 30 MW in size; later this limit was raised to 80 MW. In 1991, Luz filed for bankruptcy when it was unable to secure construction financing for its 10th plant (SEGS X).
- The 354 MWe 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.

Power Towers:

- 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.
- Since the early 1980s, power towers have been fielded in Russia, Italy, Spain, Japan, and the United States.
- In early power towers, the thermal energy collected at the receiver was used to generate steam directly to drive a turbine generator.
- The U.S.-sponsored 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.
- U.S. industry is currently pursuing a subsidized power tower project opportunity in Spain. This project, dubbed “Solar Tres,” represents a 4x scale-up of the Solar 2 design.

Dish/Engine Systems:

- Dish/engine technology is the oldest of the solar technologies, dating back to the 1800s when a number of companies demonstrated solar-powered steam Rankine and Stirling-based systems.

- Development of modern technology began in the late 1970s and early 1980s. This technology used directly illuminated, tubular solar receivers, a kinematic Stirling engine developed for automotive applications, and silver/glass mirror dishes. Systems, nominally rated at 25 kWe, achieved solar-to-electric conversion efficiencies of around 30%. Eight prototype systems were deployed and operated on a daily basis from 1986 through 1988.
- In the early 1990s, Cummins Engine Company attempted to commercialize dish/Stirling systems based on free-piston Stirling engine technology. Efforts included a 5 to 10 kWe dish/Stirling system for remote power applications, and a 25 kWe dish/engine system for utility applications. However, largely because of a corporate decision to focus on its core diesel-engine business, Cummins canceled their solar development in 1996. Technical difficulties with Cummins' free-piston Stirling engines were never resolved.
- Current dish/engine efforts are being continued by three U.S. industry teams – Science Applications International Corp. (SAIC) teamed with STM Corp., Boeing with Stirling Energy Systems, and WG Associates with Sunfire Corporation. SAIC and Boeing together have five 25kW systems under test and evaluation at utility, industry, and university sites in Arizona, California, and Nevada. WGA has two 10kW systems under test in New Mexico, with a third off-grid system being developed in 2002 on an Indian reservation for water-pumping applications.

Technology Future

The levelized cost of electricity (in constant 2003$/kWh) for three CSP configurations are projected at:

	2003	2007	2012	2025
Trough	11.3	6.4	5.4	N/A
Power Tower	12.0	5.7	4.0	N/A
Dish/Engine	40.0	20.0	N/A	6

Source: *Solar Energy Technologies Program Multiyear Technical Plan*, NREL Report No. MP-520-33875; DOE/GO-102004-1775.

- Parabolic troughs have been commercialized and nine plants (354 MW total) have operated in California since the 1980s.
- A 64-MW parabolic trough plant is under construction near Boulder City, Nevada. Nevada Power and Sierra Pacific Power will purchase the power to comply with the solar portion of Nevada’s renewable portfolio standard.
- The World Bank’s Solar Initiative is pursuing CSP technologies for less-developed countries. The World Bank considers CSP to be a primary candidate for Global Environment Facility funding.

Market Context

- There is currently 350 MW of CSP generation in the United States, all of it in Southern California's Mojave Desert.
- Power purchase agreements have been signed for 800 MW of new dish/engine capacity in California. The plants are anticipated to come on-line within the next several years. Significant domestic and international interest will likely result in additional projects.
- According to a recent study commissioned by the Department of Energy, CSP technologies can achieve significantly lower costs (below 6¢/kWh) at modest production volumes.
- At Congress’ request, DOE scoped out what would be required to deploy 1,000MW of CSP in the Southwest United States. DOE is actively engaged with the Western Governors’ Association to map a strategy to deploy 1-4 GW of CSP in the Southwest by 2015.
- A near-term to midterm opportunity exists to build production capacity in the United States for both domestic use and international exports.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Concentrating Solar Power

Market Data

U.S. Installations (electric only)

Source: *Renewable Electric Plant Information System (REPiS)*, Version 7, NREL, 2003, and *Renewable Energy Technology Characterizations,* EPRI TR-109496.

Cumulative (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
U.S.	0	24	274	354	364	364	364	364	354	354	354
Power Tower	0	10	0	0	10	10	10	10	0	0	0
Trough	0	14	274	354	354	354	354	354	354	354	354
Dish/Engine	0	0	0	0	0	0	0.125	0.125	0.125	0.125	0.125

Annual Generation from Cumulative Installed Capacity (Billion kWh)

Source: EIA, *Annual Energy Outlook* 1998-2006, Table A16, Renewable Resources in the Electric Supply, 1993, Table 4.

	1990	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
U.S.	1*	0.82	0.90	0.89	0.89	0.87	0.49	0.54	0.54	0.57	0.58

* Includes both solar thermal and less than 0.02 billion kilowatthours grid-connected photovoltaic generation.

Annual U.S. Solar Thermal Shipments (Thousand Square Feet)

Source: EIA - *Annual Energy Review 2004,* Table 10.3 and *Renewable Energy Annual 2004* Table 30.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004^P**
Total[1]	19,398	NA	11,409	7,666	7,616	8,138	7,756	8,583	8,354	11,189	11,663	11,444	14,114
Imports	235	NA	1,562	2,037	1,930	2,102	2,206	2,352	2,201	3,502	3,068	2,986	3,723
Exports	1,115	NA	245	530	454	379	360	537	496	840	659	518	813

[1] Total shipments as reported by respondents include all domestic and export shipments and may include imports that subsequently were shipped to domestic or to foreign customers.

No data are available for 1985. ^{P} = Preliminary

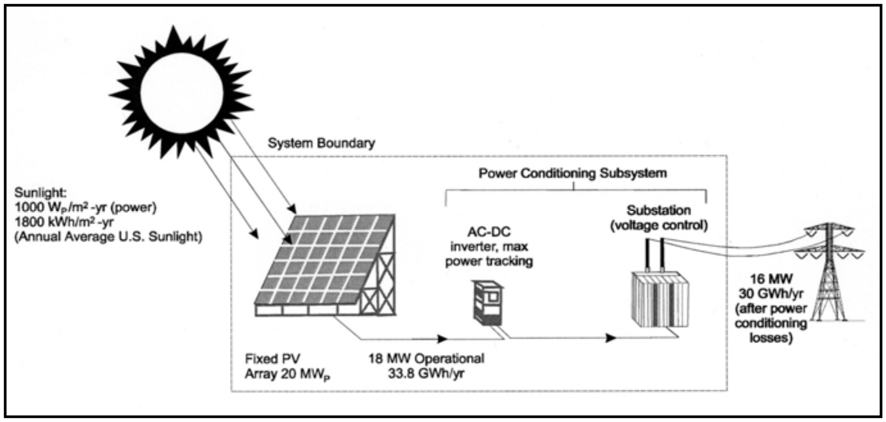
Technology Performance

Efficiency	Source: *Solar Energy Technologies Program Multiyear Technical Plan,* NREL Report No. MP-520-33875; DOE/GO-102004-1775.						
		2003	**2005**	**2007**	**2012**	**2018**	**2025**
Capacity Factor (%)	Power Tower	78	75	73	NA	72	NA
	Trough	28	39	56	56	NA	NA
	Dish	24	NA	24	NA	NA	50
Solar to Electric Eff. (%)	Power Tower	14	16	17	NA	18	NA
	Trough	13	13	16	17	NA	NA
	Dish	20	NA	23	NA	NA	26

Cost*		**2003**	**2005**	**2007**	**2012**	**2018**	**2025**
Total ($/kWe)	Power Tower	6800	4100	3500	NA	2500	NA
	Trough	2805	3556	3422	2920	NA	NA
	Dish	NA	NA	NA	NA	NA	NA
O&M ($/kWh)	Power Tower	.04	.01	.01	NA	.01	NA
	Trough	.02	.01	.01	.007	NA	NA
	Dish	NA	NA	NA	NA	NA	NA
Levelized Cost of Energy ($/kWh)	Power Tower	.12	.06	.06	NA	.04	NA
	Trough	.11	.10	.06	.05	NA	NA
	Dish	.40	NA	.20	NA	NA	.06

Photovoltaics

Technology Description



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.

System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures (e.g., semitransparent solar canopy). 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 (electrolysis of water).
- 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 and/or produce hydrogen.
- Almost all locations in the United States and worldwide have enough sunlight for cost-effective PV. For example, U.S. sunlight in the contiguous states varies by only about 25% from an average in Kansas. Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (for example, on roofs or above parking lots), a PV-generating station 140 km by 140 km sited at a high solar insolation location in the United States (such as the desert Southwest) could generate all of the electricity needed in the country (2.5×10^6 GWh/year, assuming a system efficiency of 10% and an area packing factor of 50% to avoid self-shading).

Representative Technologies

- Wafers of single-crystal or polycrystalline silicon – best cells: 25% efficiency; commercial modules: 12%-17%. Silicon modules dominate the PV market and currently cost about $\$2/W_p$ to manufacture.
- Thin-film semiconductors (e.g., amorphous silicon, copper indium diselenide, cadmium telluride, and dye-sensitized cells) – best cells: 12%-19%; commercial modules: 6%-11%. 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 multijunction gallium-arsenide-alloy cells for concentrators – best cells: 27%-39% efficient; precommercial modules: 15%-24%; prototype systems are being tested in high solar areas in the southwest United States.
- Grid-connected PV systems currently sell for about $\$6\text{-}\$7/W_p$ (17¢-22¢/kWh), including support structures, power conditioning, and land.

Technology Applications

- 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, 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 ("building integrated"). 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 minigrid or battery-charging configurations.
- Almost all locations in the United States and worldwide have enough sunlight for PV (e.g., U.S. sunlight varies by only about 25% from an average in Kansas).
- Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (e.g., on roofs or above parking lots), a PV-generating station 140 km-by-140 km sited at an average solar location in the United States could generate all of the electricity needed in the country (2.5×10^6 GWh/year), assuming a system efficiency of 10% and an area packing factor of 50% (to avoid self-shading). This area (0.3% of U.S.) is less than one-third of the area used for military purposes in the United States.

Current Status

- Because of public/private partnerships, such as the Thin-Film Partnership with its national research teams, U.S. PV technology leads the world in measurable results such as record efficiencies for cells and modules. Another partnership, the PV Advanced Manufacturing R&D program, has resulted in industry cost reductions of more than 60% and facilitated a sixteen-fold increase of manufacturing capacity during the past 12 years.
- A new generation of potentially lower-cost technologies (thin films) is entering the marketplace. A 30-megawatt amorphous silicon thin-film plant by United Solar reached full production in 2005. Two plants (First Solar and Shell Solar) using even newer thin films (cadmium telluride and copper indium diselenide alloys) are in first-time manufacturing at the MW-scale. Thin-film PV has been a focus of the federal R&D 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 by federally funded universities, national labs, or industry 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 multijunction (III-V materials alloy) cell was spun off to the space power industry, leading to a record cell efficiency (35%) and an R&D 100 Award in 2001. This device configuration is expected to dominate future space power for commercial and military satellites. Recent champion cell efficiency has reached 39% under concentrated sunlight. DOE is interested in this technology (III-V multijunctions), as an insertion candidate for high efficiency terrestrial PV concentrator systems.

Technology History

- French physicist Edmond Becquerel first described the photovoltaic (PV) effect in 1839, but it remained a curiosity of science for the next three quarters of a century. At only 19, Becquerel found that certain materials would produce small amounts of electric current when exposed to light. The effect was first studied in solids, such as selenium, by Heinrich Hertz in the 1870s. Soon afterward, selenium PV cells were converting light to electricity at more than 1% efficiency. As a result, selenium was quickly adopted in the emerging field of photography for use in light-measuring devices.

- Major steps toward commercializing PV were taken in the 1940s and early 1950s, when the Czochralski process was developed for producing highly pure crystalline silicon. In 1954, scientists at Bell Laboratories depended on the Czochralski process to develop the first crystalline silicon photovoltaic cell, which had an efficiency of 4%. Although a few attempts were made in the 1950s to use silicon cells in commercial products, it was the new space program that gave the technology its first major application. In 1958, the U.S. Vanguard space satellite carried a small array of PV cells to power its radio. The cells worked so well that PV technology has been part of the space program ever since.
- Even today, PV plays an important role in space, supplying nearly all power for satellites. The commercial integrated circuit technology also contributed to the development of PV cells. Transistors and PV cells are made from similar materials and operate on similar physical mechanisms. As a result, advances in transistor research provided a steady flow of new information about PV cell technology. (Today, however, this technology transfer process often works in reverse, as advances in PV research and development are sometimes adopted by the integrated circuit industry.)
- Despite these advances, PV devices in 1970 were still too expensive for most “down-to-Earth” uses. But, in the mid-1970s, increasing energy costs, sparked by a world oil crisis, renewed interest in making PV technology more affordable. Since then, the federal government, industry, and research organizations have invested billions of dollars in research, development, and production. A thriving industry now exists to meet the rapidly growing demand for photovoltaic products.

Technology Future

The levelized cost of electricity (in constant 2003$/kWh) for PV are projected to be:

	2003	2007	2020	2025
Utility-owned Residential (crystalline Si)	0.25-0.40	0.22	0.8-0.10	NA
Concentrator	0.40	0.20	NA	0.04-0.06

Source: *Solar Energy Technologies Program Multiyear Technical Plan,* NREL Report No. MP-520-33875; DOE/GO-102004-1775.

- Worldwide, approximately 1,200 MW of PV were sold in 2004, with systems valued at more than $7 billion; total installed PV is more than 2 GW. The U.S. world market share fell to about 12% in 2004.
- Worldwide, market growth for PV has averaged more than 20%/year for the past decade as a result of reduced prices and successful global marketing. Worldwide sales grew 36% in 2001, 44% in 2002, 33% in 2003, and 60% in 2004.
- 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.

Market Context

- Electricity for remote locations, especially for billions of people worldwide who do not have electricity.
- U.S. markets include retail electricity for residential and commercial buildings; distributed utility systems for grid support, peak-shaving, and other daytime uses (e.g., remote water pumping).
- Future electricity and hydrogen storage for dispatchable electricity, electric car-charging stations, and hydrogen production for portable fuel.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Photovoltaics

Market Data

PV Cell/Module Production (Shipments)

Source: *PV News,* Vol. 15, No. 2, Feb. 1996; Vol. 16, No. 2, Feb. 1997; Vol. 20, No. 2, Feb. 2001; Vol. 22, No. 5, May 2003; and Volume 23, No. 4, April 2004. Paul Maycock, www.pvenergy.com

Annual (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
U.S.	3	8	15	35	39	51	54	61	75	100	121	103
Japan	1	10	17	16	21	35	49	80	129	171	251	364
Europe	0	3	10	20	19	30	34	40	61	87	135	193
Rest of World	0	1	5	6	10	9	19	21	23	33	54	84
World Total	4	23	47	78	89	126	155	201	288	391	560	744

Cumulative (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
U.S.	5	45	101	219	258	309	363	424	499	599	720	823
Japan	1	26	95	185	206	241	290	370	499	670	921	1,285
Europe	1	13	47	136	155	185	219	259	320	407	542	735
Rest of World	0	3	20	45	55	65	83	104	127	160	214	298
World Total	7	87	263	585	674	800	954	1,156	1,444	1,835	2,395	3,139

U.S. % of World Sales	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Annual	71%	34%	32%	44%	44%	41%	35%	30%	26%	26%	22%	14%
Cumulative	75%	52%	39%	37%	38%	39%	38%	37%	35%	33%	30%	26%

Annual Capacity (Shipments retained, MW)*

Source: *Strategies Unlimited*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	1.4	4.2	5.1	8.4	9.2	10.5	13.6	18.4	21.3
Total World	3	15	39	68	79	110	131	170	246

*Excludes indoor consumer (watches/calculators).

Cumulative Capacity (Shipments retained, MW)*	1980	1985	1990	1995	1996	1997	1998	1999	2000
U.S.	3	23	43	76	85	96	109	128	149
Total World	6	61	199	474	552	663	794	964	1,210

Source: *Strategies Unlimited*

*Excludes indoor consumer (watches/calculators).

U.S. Shipments (MW)

Source: *EIA, Annual Energy Review 2004,* DOE/EIA-0384(2004) (Washington, D.C., September 2004), Tables 10.5 and 10.6; and EIA, *Renewable Energy Annual 2003*, DOE/EIA-0603(2003) (Washington, D.C., December 2004) Table 26.

Annual Shipments	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Total	5.8	13.8	31.1	35.5	46.4	50.6	76.8	88.2	97.7	112.1	109.4	181.1
Imports	0.3	1.4	1.3	1.9	1.9	1.9	4.8	8.8	10.2	7.3	9.7	47.7
Exports	1.7	7.5	19.9	22.4	33.8	35.5	55.6	68.4	61.4	66.8	60.7	102.8
Domestic Total On-Grid*	0.4	0.2	1.7	1.8	2.2	4.2	6.9	4.9	10.1	13.7	18.9	55.9
Domestic Total Off-Grid*	3.7	6.1	9.5	11.2	10.3	10.8	14.4	15.0	26.2	31.6	29.8	22.4

Cumulative Shipments (since 1982)	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Total	35.2	84.7	193.3	228.8	275.2	325.7	402.5	490.7	588.4	700.5	809.8	991.0
Imports	1.0	5.6	14.3	16.2	18	19.9	24.7	33.5	43.7	51.0	60.8	108.5
Exports	5.7	32.9	104	126.5	160.3	195.8	251.3	319.7	381.0	447.8	508.5	611.3
Domestic Total On-Grid*	2.9	4.7	8.2	10.0	12.2	16.5	23.3	28.2	38.3	52.0	70.9	126.9
Domestic Total Off-Grid*	26.6	47.2	81.1	92.3	102.7	113.5	127.9	142.8	169.0	200.6	230.4	252.8

* Domestic Totals include imports and exclude exports. Electricity generation only, excludes water pumping, communications, transportation, consumer goods, health, and original equipment manufacturers.

U.S. Shipments (MW)

Source: *Renewable Energy World*, July-August 2003, Volume 6, Number 4; and *PV News*, Vol. 23, No. 5, May 2004

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003
Total				34.8	38.9	51.0	53.7	60.8	75.0	100.3	120.6	103.0
Imports								2.0	4.0	5.0	9.0	18.0
Exports				24.0	25.1	36.3	37.9	39.8	55.0	73.3	81.2	54.0

Annual U.S. Installations (MW)	Source: *The 2002 National Survey Report of Photovoltaic Power Applications in the United States*, prepared by Paul D. Maycock and Ward Bower, May 31, 2003, prepared for the IEA, Table 1. http://www.oja-services.nl/iea-pvps/nsr02/download/usa.pdf; and PV News, Vol. 23 No. 5.										
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Grid-Connected Distributed				1.5	2.0	2.0	2.2	3.7	5.5	12.0	22.0	32.0
Off-Grid Consumer				3.5	4.0	4.2	4.5	5.5	6.0	7.0	8.4	9.0
Government				0.8	1.2	1.5	1.5	2.5	2.5	1.0	1.0	1.0
Off-Grid Industrial/Commercial				4.0	4.4	4.8	5.2	6.5	7.5	9.0	13.0	16.0
Consumer (<40 w)				2.0	2.2	2.2	2.4	2.5	2.5	3.0	4.0	4.0
Central Station				0	0	0	0	0	0	0	0	5.0
Total				11.8	13.8	14.7	15.8	20.7	24.0	32.0	48.4	67.0

Cumulative U.S. Installations* (MW)	Source: *The 2002 National Survey Report of Photovoltaic Power Applications in the United States,* prepared by Paul D. Maycock and Ward Bower, May 31, 2003, prepared for the IEA, Table 1 http://www.oja-services.nl/iea-pvps/nsr02/usa2.htm.											
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Off-grid Residential				19.3	23.3	27.5	32.0	37.5	43.5	50.5		
Off-grid Nonresidential				25.8	30.2	35.0	40.2	46.7	55.2	64.7		
On-grid Distributed				9.7	11.0	13.7	15.9	21.1	28.1	40.6		
On-grid Centralized				12.0	12.0	12.0	12.0	12.0	12.0	12.0		
Total				66.8	76.5	88.2	100.1	117.3	138.8	167.8		

* Excludes installations less than 40kW.

Annual World Installations (MW)	Source: *Renewable Energy World,* July-August 2003, Volume 6, Number 4.										
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Consumer Products			16		22	26	30	35	40	45	60
U.S. Off-Grid Residential			3		8	9	10	13	15	19	25
World Off-Grid Rural			6		15	19	24	31	38	45	60
Communications/ Signal	N/A	N/A	14	N/A	23	28	31	35	40	46	60
PV/Diesel, Commercial			7		12	16	20	25	30	36	45
Grid-Conn. Res., Comm.			1		7	27	36	60	120	199	270
Central Station (>100kW)			1		2	2	2		5	5	5
Total			48		89	127	153	201	288	395	525

Annual U.S. Shipments by Cell Type (MW)

Source: *PV News,* Vol. 15, No. 2, Feb. 1996; Vol. 16, No. 2, Feb. 1997; Vol. 17, No. 2, Feb. 1998; Vol. 18, No. 2, Feb. 1999; Vol. 19, No. 3, March 2000; Vol. 20, No. 3, March 2001; Vol. 21, No. 3, March 2002; Vol. 22, No. 5, May 2003; and *Renewable Energy World*, July-August 2003, Volume 6, Number 4.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Single Crystal				22.0	24.1	31.8	30.0	36.6	44.0	63.0	71.9
Flat-Plate Polycrystal (other than ribbon)				9.0	10.3	14.0	14.7	16.0	17.0	20.6	24
Amorphous Silicon				1.3	1.1	2.5	3.8	5.3	6.5	7.3	11
Crystal Silicon Concentrators				0.3	0.7	0.7	0.2	0.5	0.5	0.5	0.5
Ribbon Silicon	N/A	N/A	N/A	2.0	3.0	4.0	4.0	4.2	5.0	6.9	6.9
Cadmium Telluride				0.1	0.4	0	0	0	0	0.6	1.6
Microcrystal SI/Single SI											-
SI on Low-Cost-Sub				0.1	0.3	0.5	1.0	2.0	2.0	1.7	1.7
A-SI on Cz Slice									0	0	-
Total				34.8	39.9	53.5	53.7	64.6	75	100.6	120.6

Annual World Shipments by Cell Type (MW)

Source: *PV News,* Vol. 15, No. 2, Feb. 1996; Vol. 16, No. 2, Feb. 1997; Vol. 17, No. 2, Feb. 1998; Vol. 18, No. 2, Feb. 1999; Vol. 19, No. 3, March 2000; Vol. 20, No. 3, March 2001; Vol. 21, No. 3, March 2002; Vol. 22, No. 5, May 2003; and *Renewable Energy World*, July-August 2003, Volume 6, Number 4.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998** 0	**1999**	**2000**	**2001**	**2002**
Single Crystal				46.7	48.5	62.8	59.8	73	89.7	150.41	162.31
Flat-Plate Polycrystal				20.1	24	43	66.3	88.4	140.6	278.9	306.55
Amorphous Silicon				9.1	11.7	15	19.2	23.9	27	28.01	32.51
Crystal Silicon Concentrators				0.3	0.7	0.2	0.2	0.5	0.5	0.5	0.5
Ribbon Silicon	N/A	N/A	N/A	2	3	4	4	4.2	14.7	16.9	16.9
Cadmium Telluride				1.3	1.6	1.2	1.2	1.2	1.2	2.1	4.6
Microcrystal SI/Single SI											3.7
SI on Low-Cost-Sub				0.1	0.3	0.5	1	2	2	1.7	1.7
A-SI on Cz Slice								8.1	12	30	30
Total				79.5	89.8	126.7	151.7	201.3	287.7	512.22	561.77

Annual U.S. Shipments by Cell Type (MW)

Source: EIA, Solar Collector Manufacturing Activity annual reports, 1982-1992; and EIA, *Renewable Energy Annual 1997,* Table 27; REA 2000, Table 26; REA 2002, Table 28; REA 2003, Table 28.

	1985	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Single-Crystal Silicon			19.9	21.7	30	30.8	47.2	51.9	54.7	74.7	59.4	94.9
Cast and Ribbon Crystalline Silicon			9.9	12.3	14.3	16.4	26.2	33.2	29.9	29.4	38.6	64.2
Crystalline Silicon Total	5.5	12.5	29.8	34	44.3	47.2	73.5	85.2	84.7	104.1	98.0	159.1
Thin-Film Silicon	0.3	1.3	1.3	1.4	1.9	3.3	3.3	2.7	12.5	7.4	11.0	22.0
Concentrator Silicon			0.1	0.2	0.2	0.1	0.1	0.3	0.5	0.6	0.5	0
Other												
Total	5.8	13.8	31.2	35.6	46.3	50.6	76.8	88.2	97.7	112.1	109.5	181.1

Annual Grid-Connected Capacity (MW)

Source: *The 2002 National Survey Report of Photovoltaic Power Applications in the United States*, prepared by Paul D. Maycock and Ward Bower, May 31, 2003, prepared for the IEA, derived from Table 1 http://www.oja-services.nl/iea-pvps/nsr02/usa2.htm. Japan data from *PV News*, Vol. 23, No. 1, January 2004.

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
U.S.		1.3	2.7	2.2	5.2	7.0	12.5		
Japan	3.9	7.5	19.5	24.1	57.7	74.4	91.0	155.0	168.0

Note: Japan data not necessarily grid-connected

Cumulative Grid-Connected Capacity (MW)

Source: *The 2002 National Survey Report of Photovoltaic Power Applications in the United States*, prepared by Paul D. Maycock and Ward Bower, May 31, 2003, prepared for the IEA, derived from Table 1 http://www.oja-services.nl/iea-pvps/nsr02/usa2.htm. Japan data from *PV News*, Vol. 23, No. 1, January 2004.

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
U.S.	21.7	23.0	25.7	27.9	33.1	40.1	52.6		
Japan	5.8	13.3	32.8	56.9	114.6	189.0	280.0	435.0	603.0

Japan Grid-Connected Capacity (MW)

Source: IEA Photovoltaic Power Systems Program, *National Survey Report of PV Power Applications in Japan* 2002, http://www.oja-services.nl/iea-pvps/nsr02/jpn2.htm Table 1.

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Annual	6.0	9.7	22.6	34.7	71.3	114.8	119.3	178.2
Cumulative	13.7	23.4	46.0	80.7	151.9	266.7	386.0	564.2

Annual U.S.-Installed Capacity (MW) Source: *Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.*

Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
California		0.034	0.016	0.720	0.900	0.606	0.577	2.993	5.833	7.236	16.072	7.452
Arizona		0.004		0.026	0.067	0.724	0.301	0.574	0.177	2.516	1.333	0.008
New York			0.013	0.067	0.425	0.021	0.246	0.041	0.377		1.078	
Ohio						0.001	0.001	0.010	0.144	0.004	1.986	
Hawaii				0.000	0.046	0.008	0.291	0.113	0.250	0.275		
Texas	0.006	0.015	0.002	0.008		0.010	0.133	0.248	0.089	0.028	0.020	
Colorado				0.018	0.100	0.006	0.132	0.344	0.137			
Georgia					0.352			0.019	0.221		0.003	0.032
Florida	0.009		0.008	0.018		0.036	0.047	0.106	0.202	0.031	0.050	
Illinois						0.002	0.005	0.034	0.043	0.449	0.044	
Total U.S.	0.015	0.078	0.049	1.029	2.131	1.670	1.899	5.140	8.244	10.807	21.251	8.008

2003 data not complete as REPiS database is updated through 2002.

Cumulative U.S.-Installed Capacity (MW) Source: *Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.*

Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
California	0.002	1.369	2.803	6.495	7.396	8.002	8.579	11.572	17.405	24.641	40.713	48.164
Arizona	0.008	0.032	0.048	0.097	0.164	0.888	1.190	1.764	1.941	4.457	5.790	5.798
New York	0	0	0.013	0.226	0.650	0.671	0.917	0.958	1.334	1.334	2.412	2.412
Ohio	0	0	0	0	0	0.001	0.002	0.012	0.155	0.159	2.145	2.145
Hawaii	0	0.014	0.033	0.033	0.079	0.087	0.378	0.491	0.741	1.016	1.016	1.016
Texas	0.006	0.021	0.366	0.437	0.437	0.446	0.579	0.828	0.917	0.945	0.965	0.965
Colorado	0	0	0.010	0.040	0.140	0.146	0.278	0.622	0.759	0.759	0.759	0.759
Georgia	0	0	0	0	0.352	0.352	0.352	0.371	0.592	0.592	0.595	0.627
Florida	0.009	0.093	0.117	0.135	0.135	0.171	0.218	0.325	0.527	0.558	0.609	0.609
Illinois	0	0	0.021	0.021	0.021	0.023	0.029	0.062	0.105	0.554	0.598	0.598
Total U.S. [1]	0.025	2.104	4.170	8.560	10.691	12.362	14.261	19.401	27.645	38.452	59.703	67.710

[1] There are an additional 3.4 MW of photovoltaic capacity that are not accounted for here because they have no specific online date.

2003 data not complete as REPiS database is updated through 2002.

Technology Performance

Source: *Solar Energy Technologies Program Multiyear Technical Plan,* NREL Report No. MP-520-33875; DOE/GO-102004-1775.

Efficiency		**2003**	**2007**	**2020**	**2025**
Cell (%)	Crystalline Silicon	NA	NA	NA	NA
	Concentrator	25	33	NA	40
Module (%)	Crystalline Silicon	14	15	15-20	NA
	Concentrator	NA	NA	NA	NA
System (%)	Crystalline Silicon	11.5	14	16	NA
	Concentrator	15	22	NA	33
Cost		**2003**	**2007**	**2020**	**2025**
Module ($/Wp)	Crystalline Silicon	4.80	2.50	1.00-1.50	NA
($/m^2)	Concentrator	160	90	NA	80
BOS ($/Wp)	Crystalline Silicon	0.85	0.60	0.40	NA
	Concentrator	0.60	0.30	NA	0.15
Total Installed System ($/Wp)	Crystalline Silicon *	6.20-9.50	5.20	2.30-2.80	NA
	Concentrator	NA	NA	NA	NA
O&M ($/kWh)	Crystalline Silicon	0.08	.0.02	0.005	NA
	Concentrator	0.02	0.01	NA	0.005

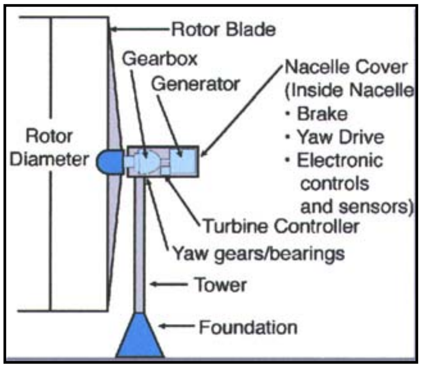
Wind Energy

Technology Description

Wind turbine technology converts the kinetic energy in wind to electricity. Grid-connected wind power reduces greenhouse gas emissions by displacing the need for natural gas and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially in developing countries.

System Concepts

- 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 and directly link to the grid, or at variable speed for better performance, using a power electronics system 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 stand-alone power applications.



Representative Technologies

- 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.

Technology Applications

- In the United States, the wind energy capacity exploded from 1,600 MW in 1994 to more than 9,200 MW by the end of 2005 – enough to serve more than 2.5 million households.
- Current performance is characterized by levelized costs of 3¢-5¢/kWh (depending on resource quality and financing terms), capacity factors of 30%-50%, availability of 95-98%, total installed costs of approximately $1,000-$1,300/kW, and efficiencies of 65%-75% of theoretical (Betz limit) maximum.

Current Status

- In 1989, the wind program set a goal of 5¢/kWh by 1995 and 4¢/kWh by 2000 for sites with average wind speeds of 16 mph. The program and the wind industry met the goals as part of dramatic cost reductions from 25¢-50¢/kWh in the early 1980s to 4¢-6¢/kWh today (2005).
- Wind power is the world's fastest-growing energy source. In the past decade, the global wind energy capacity has increased tenfold from 3,500 MW in 1994 to almost 50,000 MW by the end of 2004. During 2004, nearly 8,000 MW 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 National Wind Technology Center (operated by the National Renewable Energy Laboratory in Golden, Colorado) is recognized as a world-class center for wind energy R&D and has many facilities – such as blade structural test stands and a large gearbox test stand – not otherwise available to the domestic industry.

Technology History

- Prior to 1980, DOE sponsored (and NASA managed) large-scale turbine development – starting with hundred-kilowatt machines and culminating in the late 1980s with the 3.2-MW, DOE-supported Mod-5 machine built by Boeing.
- Small-scale (2-20 kW) turbine development efforts also were supported by DOE at the Rocky Flats test site. Numerous designs were available commercially for residential and farm uses.

- In 1981, the first wind farms were installed in California by a small group of entrepreneurial companies. PURPA provided substantial regulatory support for this initial surge.
- During the next five years, the market boomed, installing U.S., Danish, and Dutch turbines.
- By 1985, annual market growth had peaked at 400 MW. Following that, federal tax credits were abruptly ended, and California incentives weakened the following year.
- In 1988, European market exceeded the United States for the first time, spurred by ambitious national programs. A number of new companies emerged in the U.K. and Germany.
- In 1989, DOE's focus changed to supporting industry-driven research on components and systems. At the same time, many U.S. companies became proficient in operating the 1,600 MW of installed capacity in California. They launched into value engineering and incremental increases in turbine size.
- DOE program supported value-engineering efforts and other advanced turbine-development efforts.
- In 1992, Congress passed the Renewable Energy Production Tax Credit (REPI), which provided a 1.5 cent/kWh tax credit for wind-produced electricity. Coupled with several state programs and mandates, installations in the United States began to increase.
- In 1997, Enron purchased Zond Energy Systems, one of the value-engineered turbine manufacturers. In 2002, General Electric Co. purchased Enron Wind Corporation.
- In FY2001, DOE initiated a low wind-speed turbine development program to broaden the U.S. cost-competitive resource base.
- In 2004, Clipper Windpower began testing on its highly innovative, multiple-drive 2.5 MW Liberty prototype wind turbine.
- In 2005, the U.S. wind energy industry had a record-breaking year for new installations, adding more than 2,400 MW of new capacity to the nation's electric grid.
- In 2006, the U.S. Department of Energy signed a $27 million contract with General Electric to develop a multimegawatt offshore wind power system; and Clipper Windpower begins manufacturing its multiple-drive, 2.5 MW turbine.

Technology Future

The levelized cost of electricity (2002 $/MWh) for wind energy technology is projected to be:

	2005	2010	2020	2030	2040	2050
Class 4	5.5	4.0	3.1	2.9	2.9	2.8
Class 6	4.1	3.0	2.6	2.5	2.4	2.3

Source: *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs – FY 2006 Budget Request*, NREL/TP-620-37931, May 2005.

- Installed wind capacity in the United States expanded from 2,554 MW to 4,150 MW during the period of 2000 to 2005, but still make up less than 1% of total U.S. 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 – and in high-value niche applications or markets that recognize non-cost attributes. Its competitiveness is negatively affected by policies regarding ancillary services and transmission and distribution regulations.
- Continued cost reductions from low wind-speed technologies will increase the resource areas available for wind development by 20-fold and move wind generation five times closer to major load centers.
- Wind energy is often the least variable cost source of generation in grid supplied electricity and due to its less predictable (variable resource) supply; wind usually displaces natural gas and coal generated electricity as these sources adjust to hourly changes in demand and supply. Emerging markets for wind energy include providing energy for water purification, irrigation, and hydrogen production.

- Utility restructuring is a critical challenge to increased deployment in the near term because it emphasizes short-term, low-capital-cost alternatives – and lacks public policy to support deployment of sustainable technologies such as wind energy, leaving wind power at a disadvantage.
- In the United States, the wind industry is thinly capitalized, except for General Electric Wind Energy, which recently acquired wind technology and manufacturing assets in April 2002. About six manufacturers and six to 10 developers characterize the U.S. industry.
- In Europe, there are about 10 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market.
- Initial lower levels of wind deployment (up to 15%-20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. 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 onshore wind turbines. However, offshore resources are located close to major load centers.
- 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 include state renewable portfolio standards, incentive programs, and demand for community-owned wind applications.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Wind

Market Data

Grid-Connected Wind Capacity (MW)

Source: Reference IEA (data supplemented by *Windpower Monthly*, April 2001), 2001 data from *Windpower Monthly*, January 2002, 2002 data from AWEA "Global Wind Energy Market Report 2004".

Cumulative	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
U.S.	10	1,039	1,525	1,770	1,794	1,741	1,890	2,455	2,554	4,240	4,685	6,374
Germany	2	3	60	1,137	1,576	2,082	2,874	4,445	6,095	8,100	11,994	14,609
Spain	0	0	9	126	216	421	834	1,539	2,334	3,175	4,825	6,202
Denmark	3	50	310	630	785	1,100	1,400	1,752	2,338	2,417	2,889	3,110
Netherlands	0	0	49	255	305	325	364	416	447	483	693	912
Italy			3	22	70	103	180	282	427	682	788	904
UK	0	0	6	193	264	324	331	344	391	477	552	649
Europe	5	58	450	2,494	3,384	4,644	6,420	9,399	12,961	16,362	23,308	28,706
India	0	0	20	550	820	933	968	1,095	1,220	1,426	1,702	2110
Japan	0	0	1	10	14	7	32	75	121	250	415	686
Rest of World	0	0	6	63	106	254	315	574	797	992	1,270	1,418
World Total	15	1,097	2,002	4,887	6,118	7,579	9,625	13,598	17,653	23,270	31,128	39,294

Installed U.S. Wind Capacity (MW)

Source: *Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003** [2]
Annual	0.023	337	154	37	8	8	173	695	124	1,843	454	12
Cumulative[1]	0.060	674	1,569	1,773	1,781	1,788	1,961	2,656	2,780	4,623	5,078	5,090

[1] There are an additional 48 MW of wind capacity that are not accounted for here because they have no specific online date.

[2] 2003 data not complete as REPiS database is updated through 2002.

Annual Market Shares

Source: *US DOE- 1982-87 wind turbine shipment database; 1988-94. DOE Wind Program Data Sheets; 1996-2000 American Wind Energy Association*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S. Mfg Share of U.S. Market	98%	44%	36%	67%	NA	38%	78%	44%	0%
U.S. Mfg Share of World Market	65%	42%	20%	5%	2%	4%	13%	9%	6%

State-Installed Capacity Source: *American Wind Energy Association and Global Energy Concepts.*

Annual State-Installed Capacity (MW)

Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
California*		N/A	N/A	3.0	0.0	8.4	0.7	250.0	0.0	67.1	108.0	206.3	99.7	61.9
Texas		0	0	41.0	0.0	0.0	0.0	139.2	0.0	915.2	0.0	203.5	0.0	701.8
Minnesota		0	0	0.0	0.0	0.2	109.2	137.6	17.8	28.6	17.9	239.8	52.1	145.3
Iowa		0	0	0.1	0.0	1.2	3.1	237.5	0.0	81.8	98.5	49.2	310.7	202.3
Wyoming		0	0	0.0	0.1	0.0	1.2	71.3	18.1	50.0	0.0	144.0	0.0	3.8
Oregon		0	0	0.0	0.0	0.0	25.1	0.0	0.0	131.8	64.8	41.0	0.0	75.0
Washington		0	0	0.0	0.0	0.0	0.0	0.0	0.0	176.9	48.0	15.6	0.0	149.4
Colorado		0	0	0.0	0.0	0.0	0.0	21.6	0.0	39.6	0.0	162.0	6.0	0.1
New Mexico		0	0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	205.3	60.0	140.0
Oklahoma		0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	176.3	0.0	298.3
Total of 10 States		N/A	N/A	44.1	0.1	9.8	139.3	858.5	35.9	1491.0	337.2	1443.0	528.5	1,777.8
Total U.S.		N/A	N/A	44.0	1.0	16.0	142.0	884.0	67.0	1694.0	449.7	1694.5	559.9	2,431.4

Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
California*		N/A	N/A	1,387.0	1,387.0	1,396.0	1,396.0	1,646.0	1,646.0	1,714.0	1,822.0	2,042.6	2,142.3	2,204.2
Texas		0	0	41.0	41.0	41.0	41.0	180.2	180.2	1,095.5	1,095.5	1,293.0	1,293.0	1,994.8
Minnesota		0	0	25.7	25.7	25.9	135.1	272.7	290.5	319.1	335.9	562.7	614.8	760.1
Iowa		0	0	0.7	0.8	2.0	5.0	242.5	242.5	324.2	422.7	471.2	781.9	984.2
Wyoming		0	0	0.0	0.1	0.1	1.3	72.5	90.6	140.6	140.6	284.6	284.6	288.4
Oregon		0	0	0.0	0.0	0.0	25.1	25.1	25.1	157.5	218.4	259.4	259.4	334.4
Washington		0	0	0.0	0.0	0.0	0.0	0.0	0.0	178.2	228.2	243.8	243.8	393.2
Colorado		0	0	0.0	0.0	0.0	0.0	21.6	21.6	61.2	61.2	223.2	229.2	229.3
New Mexico		0	0	0.0	0.0	0.0	0.0	1.3	1.3	1.3	1.3	206.6	266.6	406.6
Oklahoma			0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	176.3	176.3	474.6
Total of 10 states		N/A	N/A	1,454.4	1,454.6	1,465.0	1,603.5	2,461.9	2,497.8	3,991.6	4,325.8	5,763.4	6,291.9	8,069.7
Total U.S.	10.00	1039.0	1525.0	1,697.0	1,698.0	1,706.0	1,848.0	2,511.0	2,578.0	4,275.0	4,686.0	6,353.0	6,912.9	9,344.3

* The data set includes 1,193.53 MW of wind in California that is not given a specific installation year, but rather a range of years (1072.36 MW in 1981-1995, 87.98 in 1982-1987, and 33.19 MW in "mid-1980's"), this has led to the "Not Available" values for 1985 and 1990 for California and the totals, and this data is not listed in the annual installations, but has been added to the cumulative totals for 1995 and later.

Cumulative Installed Capacity (MW)	Source: U.S. - EIA, *Annual Energy Review 2004*, DOE/EIA-0384(2004) (Washington, D.C., August 2005), Table 8.11a; IEA R&D Wind Countries - IEA Wind Energy Annual Reports, 1995-2003. IEA Total - "Renewables Information 2002," IEA, 2002.											
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**[1]	**2003**	**2004**
U.S.		17.5	1,799	1,731	1,678	1,610	1,720	2,252	2,377	3,864	4,417	5,995	6,190
IEA R&D Wind Countries[2]								10,040	15,440	21,553	27,935	35,275	
IEA Total	N/A		2,386	4,235	5,124	6,228	8,001	11,390	16,103				

1. Wind capacity in 2002 will be revised upward to at least 4.4 million kilowatts, as the Energy Information Administration continues to identify new wind facilities.
2. Data for IEA R&D Wind Countries through 2001 included 16 IEA countries. Ireland and Switzerland were added in 2002 and Portugal was added in 2003.

Annual Generation from Cumulative Installed Capacity (Billion kWh)	Source: U.S. - EIA, *Annual Energy Review 2004*, DOE/EIA-0384(2004) (Washington, D.C., August 2005),Table 8.2a; IEA R&D Wind Countries - IEA Wind Energy Annual Reports, 1995-2003. IEA Total - "Renewables Information 2002", IEA, 2002.												
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
U.S.	N/A	0.006	2.8	3.2	3.2	3.3	3.0	4.5	5.6	6.7	10.4	11.2	14.2
IEA R&D Wind Countries[2]				7.1	8.4	10.9	11.3	22.0	26.4	37.2	49.0	69.0	
IEA Total			3.8	7.3	8.4	10.7	14.4	19.1	28.9				

2. Data for International Energy Agency R&D Wind Countries through 2001 included 16 IEA countries. Ireland and Switzerland were added in 2002 and Portugal was added in 2003.

Annual Wind Energy Consumption for Electric Generation (Trillion Btu)	Source: EIA, *Annual Energy Review 2004,* DOE/EIA-0384(2003) (Washington, D.C., September 2004), Table 8.4a												
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
U.S. Total	N/A	(s)	29.0	32.6	33.4	33.6	30.9	45.9	57.1	68.4	104.8	114.6	143.0
(s)=Less than 0.5 trillion Btu.													

Technology Performance

Energy Production

Source: *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs – FY 2006 Budget Request,* NREL/TP-620-37931, May 2005.

		2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Capacity Factor (%)	Class 4	33.8	40.4	46.3	46.9	47.2	48.0	48.2	48.2	48.2	48.3
	Class 6	43.6	49.5	50.7	51.4	51.7	51.9	52.1	52.2	52.3	52.5

Cost
(2002 dollars)

Source: *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs – FY 2006 Budget Request,* NREL/TP-620-37931, May 2005.

		2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Capital Cost ($/kW)	Class 4	1103	982	919	893	866	866	861	856	851	840
	Class 6	1050	893	840	819	814	788	777	767	756	746
O&M ($/kW)	Onshore	25.0	20.0	16.0	15.0	14.2	13.8	13.5	13.2	12.8	12.8

Levelized Cost of Energy* ($/kWh)

(2002 dollars)

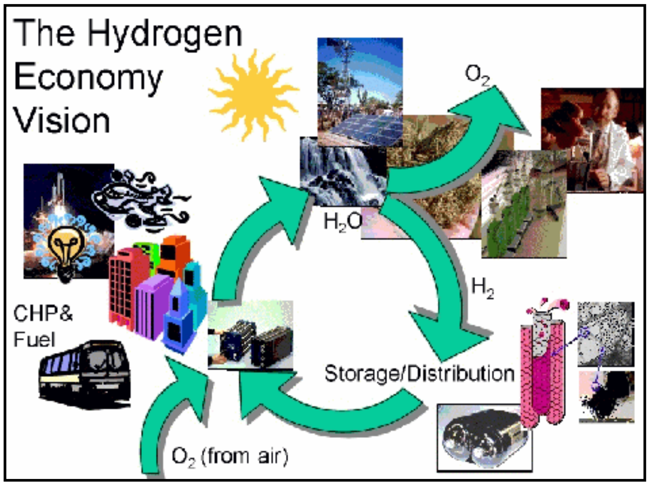
Source: *Projected Benefits of Federal Energy Efficiency and Renewable Energy Programs – FY 2006 Budget Request,* NREL/TP-620-37931, May 2005.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Class 4	55.1	40.3	32.3	30.8	29.6	29.0	28.7	28.5	28.2	27.8
Class 6	40.9	30.3	27.2	26.1	25.6	24.7	24.3	23.8	23.4	23.1

Hydrogen

Technology Description

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.

System Concepts

- 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 production, storage, distribution, and use.
- A fuel cell works like a battery but does not run down or need recharging. It will produce electricity and heat as long as fuel (hydrogen) is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte. Hydrogen is fed to the anode, and oxygen is fed to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat. Fuel cells can be used to power vehicles, or to provide electricity and heat to buildings.

Representative Technologies

Hydrogen production

- 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)
- 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)
- Photoelectrochemical and photobiological processes for direct production of hydrogen from sunlight and water.

Hydrogen storage

- Pressurized gas and cryogenic liquid (commercial today)

- Higher pressure (10,000 psi), carbon-wrapped conformable gas cylinders
- Cryogenic gas
- Chemically bound as metal or chemical hydrides or physically adsorbed on carbon nanostructures

Hydrogen distribution

- By pipeline (relatively significant pipeline networks exist in industrial areas of the Gulf Coast region, and near Chicago)
- By decentralized or point-of-use production using natural gas or electricity
- By truck (liquid and compressed hydrogen delivery is practiced commercially)

Hydrogen use

- 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
- Industrial sector: ammonia production, reductant in metal production, hydrotreating of crude oils, hydrogenation of oils in the food industry, reducing agent in electronics industry.
- Buildings sector: combined heat, power, and fuel applications using fuel cells
- Power sector: fuel cells, gas turbines, generators for distributed power generation

Technology Applications

- In the United States, nearly all of the hydrogen used as a chemical (i.e. for petroleum refining and upgrading, ammonia production) is produced from natural gas. The current main use of hydrogen as a fuel 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.

The primary fuel cell technologies under development are:

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. 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 fluorocarbon ion exchange with a polymeric membrane as the electrolyte. The PEM cell appears to be more adaptable to automobile use than the PAFC type of cell. These cells operate at relatively low temperatures and can vary their output to meet shifting power demands. These cells are the best candidates for light-duty vehicles, for buildings, and much smaller applications.

Solid oxide fuel cells (SOFC) - Solid oxide fuel cells (SOFC) currently under development use a thin layer of zirconium oxide as a solid ceramic electrolyte, and include a lanthanum manganate cathode and a nickel-zirconia anode. 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. It has the potential to be fueled with coal-derived fuel gases or natural gas.

Alkaline fuel cell - 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.

Regenerative or Reversible 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.

Current Status

- Currently, 48% of the worldwide production of hydrogen is via large-scale steam reforming of natural gas. Today, we safely use about 90 billion cubic meters (3.2 trillion cubic feet) of hydrogen yearly.
- Hydrogen technologies are in various stages of development across the system:

Production - 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 and require R&D. 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.

Storage - 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.

Use - 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. The United States is conducting a major five-year learning demonstration of fuel cell vehicles and hydrogen infrastructure. Four teams comprised of automobile manufacturers and energy companies are conducting the study.

- Major industrial companies are pursuing R&D in fuel cells and hydrogen production technologies with a mid-term time frame for deployment for both stationary and vehicular applications.

Technology History

- From the early 1800s to the mid-1900s, a gaseous product called town gas (manufactured from coal) supplied lighting and heating for America and Europe. Town gas is 50% hydrogen, with the rest comprised of mostly methane and carbon dioxide, with 3% to 6% carbon monoxide. Then, large natural gas fields were discovered, and networks of natural gas pipelines displaced town gas. (Town gas is still found in limited use today in Europe and Asia.)
- From 1958 to present, the National Aeronautics and Space Administration (NASA) has continued work on using hydrogen as a rocket fuel and electricity source via fuel cells. NASA became the worldwide largest user of liquid hydrogen and is renowned for its safe handling of hydrogen.
- During the 20th century, hydrogen was used extensively as a key component in the manufacture of ammonia, methanol, gasoline, and heating oil. It was – and still is – also used to make fertilizers, glass, refined metals, vitamins, cosmetics, semiconductor circuits, soaps, lubricants, cleaners, margarine, and peanut butter.
- Recently, (in the late 20th century/dawn of 21st century) many industries worldwide have begun producing hydrogen, hydrogen-powered vehicles, hydrogen fuel cells, and other hydrogen products. From Japan's hydrogen delivery trucks to BMW's liquid-hydrogen passenger cars; to Ballard's fuel cell transit buses in Chicago and Vancouver, B.C.; to Palm Desert's Renewable Transportation Project; to Iceland's commitment to be the first hydrogen economy by 2030; to the forward-thinking work of many hydrogen organizations worldwide; to Hydrogen Now!'s public education work; the dynamic progress in Germany, Europe, Japan, Canada, the United States, Australia, Iceland, and several other countries launch hydrogen onto the main stage of the world's energy scene. Specific U.S.-based examples of hydrogen production and uses are as follows:

- A fully functional integrated renewable hydrogen utility system for the generation of hydrogen using concentrated solar power was demonstrated by cooperative project between industry and an Arizona utility company.

- A renewable energy fuel cell system in Reno, Nevada, produced hydrogen via electrolysis using intermittent renewable resources such as wind and solar energy.
- An industry-led project has developed fueling systems for small fleets and home refueling of passenger vehicles. The refueling systems deliver gaseous hydrogen up to 5,000 psi to the vehicle.

A transit agency in California installed an autothermal reformer, generating hydrogen for buses and other vehicles. This facility also operates a PV-powered electrolysis system to provide renewable hydrogen to their fleet.

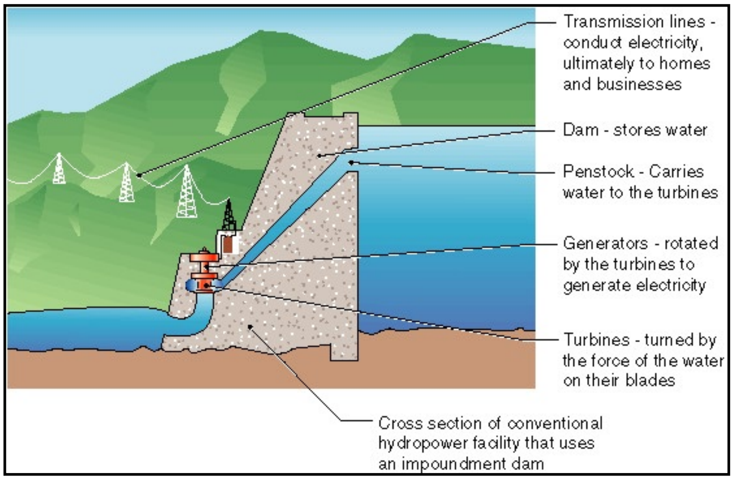
Technology Future

- 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. 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. The RD&D target for 2010 is $45/kW for internal combustion engines operating on hydrogen; the cost goal is $30/kW by 2015.
- 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.
- In summary, future fuel cell technology will be characterized by reduced costs and increased reliability for transportation and stationary (power) applications.
- To enable the transition to a hydrogen economy, the cost of hydrogen energy is targeted to be equivalent to gasoline market prices ($2-3/gallon in 2001 dollars).
- 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.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005); and National Renewable Energy Laboratory. *Gas-Fired Distributed Energy Resource Technology Characterizations.* NREL/TP-620/34783. November 2003.

Advanced Hydropower

Technology Description



Hydroelectric power generates no greenhouse gas. To the extent that existing hydropower can be maintained or expanded through advances in technology, it can 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. 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.

System Concepts

- 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.

Representative Technologies

- New turbine designs that improve survivability of fish that pass through the power plant.
- Autoventing 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.

Technology Applications

- Hydropower provides about 78,000 MW of the nation’s electrical-generating capability. This is about 80 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 (deregulation, etc.); 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.
- DOE's Advanced Hydropower Turbine System (AHTS) program will be completing public-private partnerships with industry to demonstrate the feasibility of new turbine designs (e.g., aerating turbines at the Osage Dam, and a Minimum Gap Runner turbine at the Wanapum Dam).

Current Status

- 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 of the Kaplan turbine Minimum Gap Runner design indicates that fish survival can be significantly increased, if conventional turbines are modified. The full complement of Minimum Gap Runner design features will be tested at the Wanapum Dam in FY 2005.

Technology History

- Since the time of ancient Egypt, people have used the energy in flowing water to operate machinery and grind grain and corn. However, hydropower had a greater influence on people's lives during the 20th century than at any other time in history. Hydropower played a major role in making the wonders of electricity a part of everyday life and helped spur industrial development. Hydropower continues to produce 24% of the world's electricity and supply more than 1 billion people with power.
- The first hydroelectric power plant was built in 1882 in Appleton, Wisconsin, to provide 12.5 kilowatts to light two paper mills and a home. Today's hydropower plants generally range in size from several hundred kilowatts to several hundred megawatts, but a few mammoth plants have capacities up to 10,000 megawatts and supply electricity to millions of people.
- By 1920, 25% of electrical generation in the United States was from hydropower; and, by 1940, it increased to 40%.
- Most hydropower plants are built through federal or local agencies as part of a multipurpose project. In addition to generating electricity, dams and reservoirs provide flood control, water supply, irrigation, transportation, recreation, and refuges for fish and birds. Private utilities also build hydropower plants, although not as many as government agencies.

Technology Future

- Voith Siemens Hydro Power and the TVA have established a partnership to market environmentally friendly technology at hydropower facilities. Their products were developed partly by funding provided by DOE and the Corps of Engineers, as well as private sources.
- In a competitive solicitation, DOE accepted proposals for advanced turbine designs from Voith Siemens, Alstom, American Hydro, and General Electric Co. Field verification and testing is underway with some of these designs to demonstrate improved environmental performance.
- Flash Technology is developing strobe lighting systems 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.

Market Context

- Advanced hydropower products can be applied at more than 80% of existing hydropower projects (installed conventional capacity is now 94 GW); the potential market also includes 15-20 GW at existing dams (i.e. no new dams required for development) and 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 – if fully implemented, this would equate to 5 GW and 18,600 GWh of new, clean energy production.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Hydroelectric Power

Market Data

U.S. Installed Capacity (MW)* Source: *Renewable Electric Plant Information System (REPiS)*, Version 7, NREL, 2003.

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003
Annual	1,391	3,237	862	1,054	19.9	64.0	7.6	179.3	1.1	11	0.002	21.0
Cumulative	80,491	87,839	90,955	94,052	94,072	94,136	94,143	94,323	94,324	94,335	94,335	94,356

* There are an additional 21 MW of hydroelectric capacity that are not accounted for here because they have no specific online date.
2003 data not complete as REPiS database is updated through 2002.

Cumulative Grid-Connected Hydro Capacity (MW)[1]

Source: U.S. data from EIA, AER 2004, Table 8.11a; World Total from EIA, International Energy Annual, 1996-2003, Table 6.4. International data from International Energy Agency, Electricity Information 2004.

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
U.S.													
Conventional and other Hydro	81,700	88,900	73,923	78,562	76,437	79,415	79,151	79,393	79,359	79,484	79,354	78,694	78,703
Pumped Storage[2]	N/A	N/A	19,462	21,387	21,110	19,310	19,518	19,565	19,522	19,096	20,373	20,522	20,522
U.S. Hydro Total	81,700	88,900	93,385	99,948	97,548	98,725	98,669	98,958	98,881	98,580	99,727	99,216	99,225
OECD Europe[3]	124,184	124,577	130,886	132,893	134,902	135,939	133,307	136,251	140,779	141,913	147,580	NA	NA
IEA Europe[4]	123,960	124,357	130,663	132,666	134,038	135,074	132,315	135,254	138,093	138,912	144,010	NA	NA
Japan	21,377	19,980	20,825	21,171	21,222	21,277	21,477	21,555	22,019	22,081	21,690	NA	NA
OECD Total	286,969	300,725	316,291	340,259	342,893	346,342	342,673	346,446	351,513	352,564	338,130	NA	NA
IEA Total	286,745	300,505	316,068	330,703	331,947	335,395	331,930	335,768	339,145	339,880	324,920	NA	NA
World Total	470,669	537,734	600,206	650,936	661,237	673,797	680,610	697,749	712,689	723,581	NA	NA	NA

1. Excludes pumped storage, except for specific U.S. pumped storage capacity listed.
2. Pumped storage values for 1980-1985 are included in "Conventional and other Hydro"
3. OECD included 24 countries as of 1980. Mexico, Czech Republic, Hungary, Poland, South Korea, Slovak Republic joined after 1980. Countries' data are included only after the year they joined.
4. IEA included 26 countries as of 2003. Countries' data are included only after the year they joined the OECD.

NA = Not Available; Updated international data not available at time of publication

Annual Generation from Cumulative Installed Capacity (Billion kWh)	Source: EIA, *International Energy Annual 2003*, DOE/EIA-0219(02), Table 1.5.											
		1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
United States		279	284	289	308	344	352	319	313	270	208	255
Canada		251	301	294	332	352	347	329	342	355	330	315
Mexico		17	26	23	27	31	26	24	32	33	28	25
Brazil			177	205	251	263	276	289	290	302	265	282
Western Europe			453	453	506	491	506	523	531	555	553	503
Former U.S.S.R.	128		205	231	238	215	216	225	227	228	239	243
Eastern Europe	432		26	23	34	34	36	35	35	31	30	32
China	184		91	125	184	185	193	203	211	241	258	309
Japan			82	88	81	80	89	92	86	86	83	81
Rest of World	27	273	328	435	504	515	522	533	541	558	571	581
	58											
World Total	88	1,736	1,973	2,167	2,466	2,511	2,564	2,571	2,609	2,658	2,565	2,627

State Generating Capability* (MW)	Source: EIA, Electric Power Annual 2004 – Spreadsheets, "1990 - 2002 Existing Nameplate and Net Summer Capacity by Energy Source and Producer Type (EIA-860)" http://www.eia.doe.gov/cneaf/electricity/epa/existing_capacity_state.xls									
Top 10 States	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Washington	19,935	20,487	20,431	20,923	21,012	21,011	21,011	21,006	21,016	21,018	20,941
California	12,687	13,519	13,500	13,475	13,383	13,445	13,475	13,471	13,523	13,306	13,323
Oregon	8,221	8,268	8,267	8,264	8,265	8,249	8,261	8,240	8,211	8,235	8,236
New York	5,345	5,545	5,557	5,565	5,668	5,662	5,659	5,712	5,804	5,842	5,891
Tennessee	3,717	3,818	3,818	3,937	3,950	3,950	3,950	3,948	3,948	3,948	3,948
Georgia	2,453	3,287	3,005	3,305	3,314	3,314	3,313	3,313	3,613	3,414	3,566
South Carolina	2,367	3,468	3,468	3,442	3,442	3,452	3,455	3,453	3,453	3,459	3,499
Virginia	3,072	3,126	3,149	3,082	3,093	3,090	3,091	3,088	3,088	3,088	3,088
Alabama	2,857	2,868	2,864	2,904	2,961	2,961	2,961	2,959	2,959	3,159	3,261
Arizona	2,685	2,885	2,885	2,893	2,893	2,890	2,890	2,890	2,893	2,899	2,903
U.S. Total	89,828	94,513	94,372	95,222	95,496	95,802	95,879	95,844	96,343	96,353	96,699

* Values are nameplate capacity for total electric industry

State Annual Generation from Cumulative Installed Capacity* (Billion kWh)	Source: EIA, *Electric Power Annual 2002* – Spreadsheets, “1990 - 2002 Net Generation by State by Type of Producer by Energy Source (EIA-906)” http://www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls									
Top 10 States	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Washington	87.5	82.5	98.5	104.2	79.8	97.0	80.3	54.7	78.2	71.8	71.6
Oregon	41.2	40.8	44.9	46.7	39.9	45.6	38.1	28.6	34.4	33.3	33.1
California	24.8	50.5	46.9	42.1	50.8	40.4	39.3	25.2	30.9	36.4	34.1
New York	27.1	24.8	27.8	29.5	28.2	23.6	23.9	22.2	24.1	24.3	24.0
Montana	10.7	10.7	13.8	13.4	11.1	13.8	9.6	6.6	9.6	8.7	8.9
Alabama	10.4	9.5	11.1	11.5	10.6	7.8	5.8	8.4	8.8	12.7	10.6
Idaho	9.1	11.0	13.3	14.7	12.9	13.5	11.0	7.2	8.8	8.4	8.5
Arizona	7.7	8.5	9.5	12.4	11.2	10.1	8.6	7.9	7.6	7.1	7.0
Tennessee	9.5	9.0	10.8	10.4	10.2	7.2	5.7	6.2	7.3	12.0	10.4
South Dakota	3.9	6.0	8.0	9.0	5.8	6.7	5.7	3.4	4.4	4.3	3.6
U.S. Total	289.4	308.1	344.1	352.4	318.9	313.4	270.0	208.1	255.6	275.8	268.4

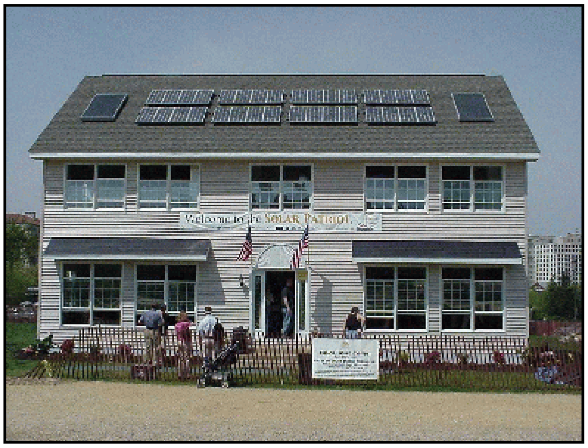
* Values are for total electric industry. Years before 1998 do not include nonutility generation.

Annual Hydroelectric Consumption for Electric Generation (Trillion Btu)	Source: *EIA, Annual Energy Review 2004, DOE/EIA-0384(2004) (Washington, D.C., August 2005) Table 8.4a*												
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
U.S. Total	2,900	2,970	3,046	3,205	3,590	3,640	3,297	3,268	2,811	2,201	2,689	2,825	2,725
Note: Conventional hydroelectric power only, for all sectors.													
Hydroelectric data through 1988 include industrial plants as well as electric utilities. Beginning in 1989, data are for electric utilities, independent power producers, commercial plants, and industrial plants.													

Building Technologies

Technology Description

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.

Building envelope

The building envelope is the interface between the interior of a building and the outdoor environment. In most buildings, the envelope – along with the outdoor weather – 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.

Whole building integration

Whole building integration uses data from design (together with sensed data) to automatically configure controls and commission (i.e., start-up and check out) and operate buildings. Control systems use advanced, robust 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 recommissioning 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 were met at the lowest possible cost.

System Concepts

Building equipment

- 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 crosscutting opportunities for efficiency include improved materials, efficient low-emissions combustion and heat transfer, advanced refrigerants and cycles, electrodeless 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.

Building envelope

- Control of envelope characteristics provides control over 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.

Whole building integration

- The system consists of design tools, automated diagnostics, interoperable control-system components, abundant wireless sensors and controls, and highly integrated operation of energy-using and producing systems.
- These components would 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 would ensure that essential information – especially the design intent and construction implementation data – would be preserved and shared across many applications throughout the lifetime of the building.
- Equipment and system performance records would be stored as part of a networked building performance knowledge base, which would grow over time and provide feedback to designers, equipment manufacturers, and building operators and owners.
- Optimally integrate on-site power production with building energy needs and the electric-power grid by applying intelligent control to building cooling, heating, and power.

Representative Technologies

Building equipment

- Residential gas-fired absorption heat pumps, centrifugal chillers, desiccant preconditioners for treating ventilation air, heat-pump water heaters, proton exchange membrane fuel cells, heat pump water heaters, solid-state lighting, and lighting controls.
- Specialized HVAC (heating, ventilating, and air-conditioning) systems for research laboratories, server/data systems, and other buildings housing high-technology processes.

Building envelope

- *Superinsulation*: 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.
- *Advanced window systems*: Krypton-filled, triple-glazed, low-E windows; electrochromic glazing; and hybrid electrochromic/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.
- *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.

Whole building integration

- DOE is developing computer-based building commissioning and operation tools to improve the energy efficiency of “existing” buildings. It is also investing in the next generation of building-simulation programs that could be integrated into design tools.
- DOE, in collaboration with industry, also is developing and testing technologies for combined cooling, heating, and power; and wireless sensor and control systems for buildings.

Technology Applications

Building equipment

- Technology improvements during the past 20 years – through quality engineering, new materials, and better controls – 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; H-axis clothes washers are 50% more efficient than current minimum standards. Electronic equipment has achieved order-of-magnitude efficiency gains, at the microchip level, every two to three years.

Building envelope

- Building insulations have progressed 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. Superinsulations of more than 25 ºF ft^2/Btu/in. will be available for niche markets soon. Improvements in window performance have been even more spectacular. In the 1970s, window thermal resistance was 1 to 2 ºF ft^2/Btu. Now, new windows have thermal resistance of up to 6 ºF ft^2/Btu (whole window performance). 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.

Whole building integration

- Savings from improved operation and maintenance procedures could save more than 30% of the annual energy costs of existing commercial buildings, even in many of those buildings thought to be working properly by their owners/operators. These technologies would have very short paybacks, because they would ensure that technologies were performing as promised, for a fraction of the cost of the installed technology.
- Savings for new buildings could exceed 70%, using integration of building systems; and, with combined cooling, heating and power, buildings could become net electricity producers and distributed suppliers to the electric power grid.

Current Status

Building equipment

- Recent DOE-sponsored R&D, often with industry participation, includes an improved air-conditioning cycle to reduce oversizing and improve efficiency; a replacement for inefficient, high-temperature halogen up-lights (torchieres), which use only 25% of the power, last longer, and eliminate potential fire hazards; ozone-safe refrigerants, where supported R&D was directed toward lubrication materials problems associated with novel refrigerants and ground-source heat pumps.

Building envelope

- A DOE-sponsored RD&D partnership with the Polyisocyanurate Insulation Manufacturers Association, the National Roofing Contractors Association, the Society of the Plastics Industry, and Environmental Protection Agency (EPA) helped the industry find a replacement for chloroflurocarbons (CFCs) in polyisocyanurate foam insulation. This effort enabled the buildings industry to transition from CFC-11 to HCFC-141b by the deadline required by the Montreal protocol.
- Spectrally selective window glazings – which reduce solar heat gain and lower cooling loads – and high-performance insulating materials for demanding thermal applications are available.

Whole building integration

- Energy 10 models passive solar systems in buildings.
- DOE-2: international standard for whole building energy performance simulation has thousands of users. DOE released Energy Plus, new standard for building energy simulation and DOE-2 successor.
- The International Alliance for Interoperability is setting international standards for interoperability of computer tools and components for buildings.
- DOE-BESTEST is the basis for ANSI/ASHRAE Standard 140, Method of Test for the Evaluation of Building Energy Simulation Programs.

Technology History

- 1890s – First commercially available solar water heaters produced in southern California. Initial designs were roof-mounted tanks and later glazed tubular solar collectors in thermosiphon configuration. Several thousand systems were sold to homeowners.
- 1900s – Solar water-heating technology advanced to roughly its present design in 1908 when William J. Bailey of the Carnegie Steel Company, invented a collector with an insulated box and copper coils.
- 1940s – Bailey sold 4,000 units by the end of WWI, and a Florida businessperson who bought the patent rights sold nearly 60,000 units by 1941.
- 1950s – Industry virtually expires due to inability to compete against cheap and available natural gas and electric service.
- 1970s – The modern solar industry began in response to the OPEC oil embargo in 1973-74, with a number of federal and state incentives established to promote solar energy. President Jimmy Carter put solar water-heating panels on the White House. FAFCO, a California company specializing in solar pool heating; and Solaron, a Colorado company that specialized in solar space and water heating, became the first national solar manufacturers in the United States. In 1974, more than 20 companies started production of flat-plate solar collectors, most using active systems with antifreeze capabilities. Sales in 1979 were estimated at 50,000 systems. In Israel, Japan, and Australia, commercial markets and manufacturing had developed with fairly widespread use.
- 1980s – In 1980, the Solar Rating and Certification Corp (SRCC) was established for testing and certification of solar equipment to meet set standards. In 1984, the year before solar tax credits expired, an estimated 100,000-plus solar hot-water systems were sold. Incentives from the 1970s helped create the 150-business manufacturing industry for solar systems with more than $800 million in annual sales by 1985. When the tax credits expired in 1985, the industry declined significantly. During the Gulf War, sales again increased by about 10% to 20% to its peak level, more than 11,000 square feet per year (sq.ft./yr) in 1989 and 1990.
- 1990s – Solar water-heating collector manufacturing activity declined slightly, but has hovered around 6,000 to 8,000 sq.ft./yr. Today's industry represents the few strong survivors: More than 1.2 million buildings in the United States have solar water-heating systems, and 250,000 solar-heated swimming pools exist. Unglazed, low-temperature solar water heaters for swimming pools have been a real success story, with more than a doubling of growth in square footage of collectors shipped from 1995 to 2001.

Reference: American Solar Energy Society and Solar Energy Industry Association

Technology Future

Building equipment

- 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 stock and energy intensity of homes are growing faster than the building stock itself, as manufacturers introduce – and consumers and businesses eagerly accept – 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 nonresidential 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. Certain technologies, such as office and home electronics, compete in global markets with little or no change in performance specifications.

Building envelope

- 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. Exporting is not an important factor in the sales of most building structure products.

Whole building integration

- The future vision of buildings 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.
- 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 (e.g., Trane Intellipack

System) and the recently announced air-conditioning diagnostic hand-held service tool by Honeywell (i.e. Honeywell HVAC Service Assistant).

- The Department of Energy – in concert with the California Energy Commission – is testing a number of automated diagnostic tools and techniques with commercial building owners, operators, and service providers in an effort to promote commercial use. About 12 software vendors develop, support, and maintain energy design tools; most are small businesses. Another 15 to 20 building automation and control vendors exist in the marketplace – the major players include Johnson Controls, Honeywell, and Siemens.
- 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 (not only energy efficiency).
- 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.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

For more data on the Buildings sector, please refer to the "**Buildings Energy Data Book**" which is a comprehensive collection of buildings- and energy-related data. The Buildings Energy Data Book is available online at http://buildingsdatabook.eren.doe.gov/

Solar Buildings

Market Data

U.S. Installations (Thousands of Sq. Ft.)

Source: EIA, *Renewable Energy Annual 2004,* Table 38, REA 2003 Table 18 and Table 10; REA 2002, Table 18; REA 1997- 2000, Table 16; REA 1996, Table 18.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Annual													
Hot Water				755	765	595	463	373	367	274	423	511	452
Pool Heaters					6,787	7,528	7,201	8,141	7,863	10,797	11,073	10,800	13,634
Total Solar Thermal 1	18,283	19,166	11,164	7,136 6,763	7,162	7,759	7,396	8,046	7,857	10,349	11,004	10,926	14,114
Cumulative													
Hot Water				755	1,520	2,115	2,578	2,951	3,318	3,592	4,015	4,526	4,978
Pool Heaters				6,763	13,550	21,078	28,279	36,420	44,283	55,080	66,153	76,953	90,587
Total Solar Thermal 1	62,829	153,035	199,459	233,386	240,548	248,307	255,703	263,749	271,606	281,955	292,959	303,885	317,999

1. Domestic shipments - total shipments minus export shipments

U.S. Annual Shipments (Thousand Sq. Ft.)

Source: EIA, *Renewable Energy Annual 2003,* Table 11; and REA 1999, Table 11.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Total	19,398	N/A	11,409	7,666	7,616	8,138	7,756	8,583	8,354	11,189	11,663	11,444	14,114
Imports		N/A	1,562	2,037	1,930	2,102	2,206	2,352	2,201	3,502	3,068	2,986	3,723
Exports	1,115	N/A	245	530	454	379	360	537	496	840	659	518	813

U.S. Shipments by Cell Type (Thousand sq. ft.)

Source: EIA *Annual Energy Review 2004,* Table 10.3; and *Renewable Energy Annual 2003,* Table 12.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Low-Temperature Collectors	12,233	N/A	3,645	6,813	6,821	7,524	7,292	8,152	7,948	10,919	11,126	10,877	13,608
Medium-Temperature Collectors	7,165	N/A	2,527	840	785	606	443	427	400	268	535	560	506
High-Temperature Collectors	N/A	N/A	5,237	13	10	7	21	4	5	2	2	7	0
Total	19,398	N/A	11,409	7,666	7,616	8,137	7,756	8,583	8,353	11,189	11,661	11,444	14,114

U.S. Shipments of High-Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)

Source: EIA, *Renewable Energy Annual 2003,* Table 18; REA 2002, Table 18; REA 1996, Table F9; REA 1997, 1999-2000, Table 16; and REA 1998, Table 19.

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Market Sector	0	0	0	0	0		0	0	0	0
Residential	1	7	7	18	0		1	2	7	0
Commercial	0	2	0	0	0		0	0	0	0
Industrial	9	0	0	2	4		1	0	0	0
Utility	3	0	0	1	0		0	0	0	0
Other	13	10	7	21	4		2	2	7	0
Total										
End Use	0	0	0	0	0		0	0	0	0
Pool Heating	0	7	7	18	0		0	0	0	0
Hot Water	0	0	0	0	0		0	0	0	0
Space Heating	1	0	0	0	0		0	0	0	0
Space Cooling	0	0	0	0	0		0	2	7	0
Combined Space and Water Heating	0	2	0	0	0		0	0	0	0
Process Heating	9	0	0	2	4		2	0	0	0
Electricity Generation	2	0	0	1	0		0	0	0	0
Other	13	10	7	21	4		2	2	7	0
Total	0	0	0	0	0		0	0	0	0

2000 data not published by EIA

U.S. Shipments of Medium- Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)	Source: EIA, *Renewable Energy Annual 2003,* Table 18; REA 2002, Table 18; REA 1996, Table F9; REA 1997, 1999-2000, Table 16; and REA 1998, Table 19.									
	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Market Sector										
Residential	774	728	569	355	366		238	481	507	478
Commercial	51	50	35	70	59		23	69	44	0
Industrial	12	1	0	18	0		5	60	0	26
Utility	0	0	0	0			0	4	0	0
Other	3	7	2	0			1	1	2	3
Total	839	786	606	443	426		268	614	553	507
					0					
					2					
End Use										
Pool Heating	32	21	11	36	12		16	28	22	33
Hot Water	743	754	588	384	373		231	421	510	452
Space Heating	62	6	2	13	24		9	145	4	6
Space Cooling	0	0	0	0			0	0	0	0
Combined Space and Water Heating	2	2	3	8	16		12	15	16	16
Process Heating	0	1	0	0			0	4	0	0
					0					
Electricity Generation	0	0	0	0			0	0	0	0
Other	0	0	1	1			0	0	0	0
					0					
Total	839	784	605	442	427		268	614	553	507
					0					

2000 data not published by EIA

2

U.S. Shipments of Low- Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)

Source: EIA, *Renewable Energy Annual 2003,* Table 18; REA 2002, Table 18; REA 1996, Table F9; REA 1997, 1999-2000, Table 16; and REA 1998, Table 19.

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Market Sector										
Residential	6,192	6,146	6,791	6,810	7,408		9,885	10,519	9,993	12,386
Commercial	552	625	726	429	726		987	524	813	1,178
Industrial	69	51	7	44	18		12	2	71	44
Utility	0	0	0	0	0		0	0	0	0
Other	0	0	0	2	0		34	0	0	0
Total	6,813	6,822	7,524	7,285	8,152		10,919	11,046	10,877	13,608
End Use										
Pool Heating	6,731	6,766	7,517	7,164	8,129		10,782	11,045	10,778	13,600
Hot Water	11	4	0	60	0		42	1	0	0
Space Heating	70	51	7	53	18		61	0	65	8
Space Cooling	0	0	0	0	0		0	0	0	0
Combined Space and Water Heating										0
Process Heating	0	0	0	0	5		34	0	34	0
Electricity Generation	0	0	0	0	0		0	0	0	0
Other	0	0	0	0	0		0	0	0	0
Total	6,813	6,821	7,524	7,285	8,152		10,919	11,046	10,877	13,608

2000 data not published by EIA

Technology Performance

Energy Production	Source: Arthur D. Little, *Review of FY 2001 Office of Power Technology's Solar Buildings Program Planning Unit Summary*, December 1999.								
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Energy Savings									
DHW (kWh/yr)					2,750				
Pool Heater (therms/yr)					1,600				

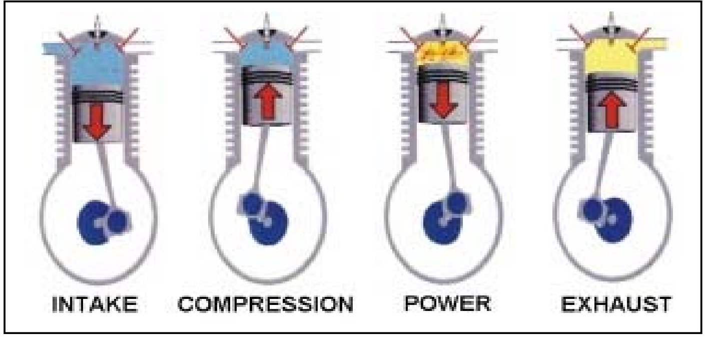
Cost	Source: Hot-Water Heater data from Arthur D. Little, *Water-Heating Situation Analysis*, November 1996, page 53, and Pool-Heater data from Ken Sheinkopf, *Solar Today,* Nov/Dec 1997, pp. 22-25.								
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capital Cost* ($/System)									
Domestic Hot-Water Heater					1,900 - 2,500				
Pool Heater					3,300 - 4,000				
O&M ($/System-yr)									
Domestic Hot-Water Heater					25 - 30				
Pool Heater					0				

* Costs represent a range of technologies, with the lower bounds representing advanced technologies, such as a low-cost polymer integral collector for domestic hot-water heaters, which are expected to become commercially available after 2010.

For more data on the Buildings sector, please refer to the "**Buildings Energy Data Book**" which is a comprehensive collection of buildings- and energy-related data. The Buildings Energy Data Book is available online at http://buildingsdatabook.eren.doe.gov/

Reciprocating Engines

Technology Description



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.

System Concepts

- 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), 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.

Representative Technologies

- 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, igniting 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.

Technology Applications

- 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. Utility substations and small municipalities 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 (energy/demand charges).
- 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.

Current Status

- Commercially available engines have efficiencies (LHV) 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. CHP engines achieve efficiencies (LHV) of 70-80%.

- Installed cost for reciprocating engines range between $695 and $1,350/ kW depending on size and whether the unit is for a straight generation or cogeneration application. Operating and maintenance costs range 0.8 -1.8 ¢/kWh. Production costs are generally lowest for high-speed engines.
- Exhaust temperature for most reciprocating engines is 700-1,200° F in non-CHP mode and 350-500°F 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 (engine), emission controls, waste recovery (CHP systems) and rejections (radiators), and electrical switchgear.
- Annual shipments of reciprocating engines (sized 10MW or less) have almost doubled to 18 GW between 1997 and 2000. The growth is overwhelming in the diesel market, which represented 16 GW shipments compared with 2 GW of natural gas reciprocating engine shipments in 2000.
- The cost of full maintenance contracts range from 0.7 to 2.0 cents/kWh. Remote monitoring is now available as a part of service contracts.

(**Source**: Diesel and Gas Turbine Worldwide, 2003).

Key indicators for stationary reciprocating engines:

Installed Worldwide Capacity	Installed US Capacity	Number of CHP sites using Recips in the U.S. in 2000
146 GW	52 GW	1,055

Sources: Distributed Generation: The Power Paradigm for the New Millenium, 2001; “Gas-Fired Distributed Energy Resource Technology Characterizations (2003).”

Technology History

- Natural gas-reciprocating engines have been used for power generation since the 1940s. The earliest engines were derived from diesel blocks and incorporated the same components of the diesel engine. Spark plugs and carburetors replaced fuel injectors, and lower compression-ratio pistons were substituted to run the engine on gaseous fuels. These engines were designed to run without regard to fuel efficiency or emission levels. They were used mainly to produce power at local utilities and to drive pumps and compressors.
- In the mid-1980s, manufacturers were facing pressure to lower NOx emissions and increase fuel economy. Leaner air-fuel mixtures were developed using turbochargers and charge air coolers, and in combination with lower in-cylinder fire temperatures, the engines reduced NOx from 20 to 5 g/bhp-hr. The lower in-cylinder fire temperatures also meant that the BMEP (Brake Mean Effective Pressure) could increase without damaging the valves and manifolds.
- Reciprocating-engine sales have grown more then fivefold from 1988 (2 GW) to 1998 (11.5 GW). Gas-fired engine sales in 1990 were 4% compared to 14% in 1998. The trend is likely to continue for gas-fired reciprocating engines due to strict air-emission regulations and because performance has been steadily improving for the past 15 years.
- More than 35 million reciprocating engine units are produced in North America annually for automobiles, trucks, construction and mining equipment, marine propulsion, lawn care and a diverse range of power-generation applications.

Technology Future

In 1998, The U.S. Department of Energy – in partnership with the Gas Technology Institute, the Southwest Research Institute, and equipment manufacturers – joined the Advanced Reciprocating Engines Systems (ARES) consortium, aimed at further advancing the performance of the engine. Performance targets include:

High Efficiency- Target fuel-to-electricity conversion efficiency (LHV) 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 for the ARES program is 0.1 g/hp-hr, a 90% decrease from today's NOx emissions rate.

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.

Other R&D directions 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.

Source: National Renewable Energy Laboratory. *Gas-Fired Distributed Energy Resource Technology Characterizations.* NREL/TP-620-34783. November 2003.

Reciprocating Engines

Technology Performance

Power Ranges (kW) of Selected Manufacturers

Source: Manufacturer Specs

	Low	High
Caterpillar	150	3,350
Waukesha	200	2,800
Cummins	5	1,750
Jenbacher	200	2,600
Wartsila	500	5,000

Market Data

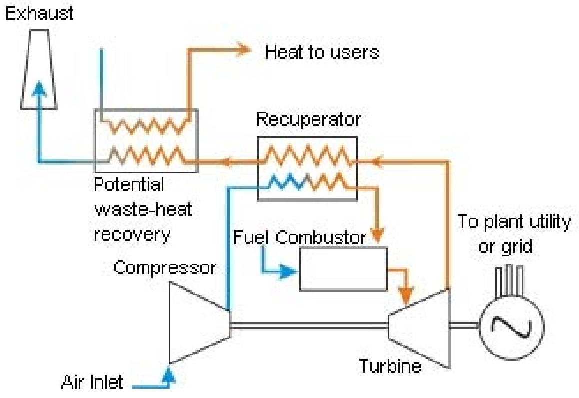
Source: Debbie Haught, DOE, communication 2/26/02 - from Diesel and Gas Turbine Worldwide.

Market Shipments
(GW of units under 10 MW in size)

	1996	1997	1998	1999	2000
Diesel Recips	7.96	7.51	8.23	10.02	16.46
Gas Recips	0.73	1.35	1.19	1.63	2.07

Microturbines

Technology Description



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%.

System Concepts

- 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.

Representative Technologies

- Microturbines in a simple-cycle, or unrecuperated, 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 unrecuperated units, and yield 30%-40% fuel savings from preheating.

Technology Applications

- Microturbines can be used in a wide range of applications in the commercial, industrial, and institutional sectors; microgrid power parks; remote off-grid locations; and premium power markets.
- 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.

Current Status

- 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 to date is the 30-kW system manufactured by Capstone. Microturbine efficiencies are 25-29% (LHV).

- The typical 30 kW unit package cost averages \$1,100/kW. For gas-fired microturbines, the present installation cost (site preparation and natural gas hookup) for a typical 30 kW commercial unit averages \$2,263/kW for power only systems and \$2,636 for CHP systems. Service contracts are available at 1 to 2 cents/kWh

Technology History

- Microturbines represent a relatively new technology, which entered the commercial market in 1999-2000. The technology used in microturbines is derived from aircraft auxiliary power systems, diesel-engine turbochargers, and automotive designs.
- In 1988, Capstone Turbine Corporation began developing the microturbine concept; and, in 1998, Capstone was the first manufacturer to offer commercial power products using microturbine technology.

Technology Future

- The acceptable cost target for microturbine energy is \$0.05/kWh, which would present a cost advantage over most nonbaseload utility power.
- "Ultra-clean, high-efficiency" microturbine product designs focus on the following DOE 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 alternatives (including grid) for market applications by 2005 (for units in the 30-60 kW range)
  - Fuel Flexibility — Options for using multiple fuels including diesel, ethanol, landfill gas, and biofuels.

Source: National Renewable Energy Laboratory. *Gas-Fired Distributed Energy Resource Technology Characterizations.* NREL/TP-620-34783. November 2003.

Microturbines

Market Data

Microturbine Shipments	Source: Debbie Haught, communications 2/26/02. Capstone sales reported in Quarterly SEC filings, others estimated.			
No. of units	**1998**	**1999**	**2000**	**2001**
Capstone	2	211	790	1,033
Other Manufacturers				120
MW				
Capstone		6	23.7	38.1
Other Manufacturers				10.2

Technology Performance

Source: Manufacturer Surveys, Arthur D. Little (ADL) estimates.

Current System Efficiency (%)	LHV: 17-20% unrecuperated, 25-30%+ recuperated	
Lifetime (years)	5-10 years, depending on duty cycle	
Emissions (natural gas fuel)	Current	Future (2010
CO_2	670 - 1,180 g/kWh (17-30% efficiency)	
SO_2	Negligible (natural gas)	Negligible
NO_x	9-25 ppm	<9 ppm
CO	25-50 ppm	<9 ppm
PM	Negligible	Negligible
Typical System Size	Current Products: 25-100 kW Units can be bundled or "ganged" to produce power in larger increments	Future Products: up to 1 MW
Maintenance Requirements (Expected)	10,000-12,000 hr before major overhaul (rotor replacement)	
Footprint [ft^2/kW]	0.2-0.4	

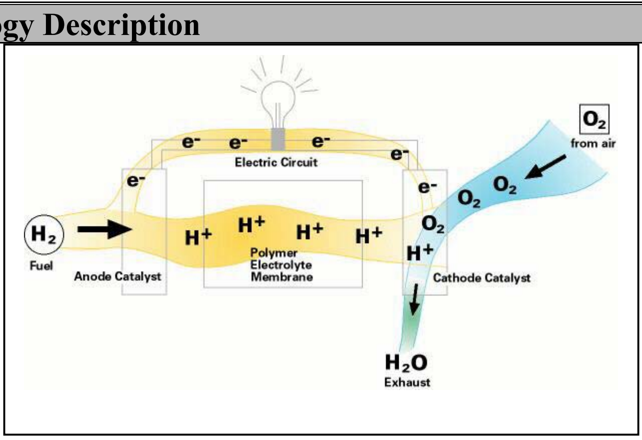
Technology Performance

Sources: Debbie Haught, DOE, communication 2/26/02 and Energetics Inc. *Distributed Energy Technology Simulator: Microturbine Validation*, July 12 2001.

	Capstone Turbine Corporation		Elliot Energy Systems	Ingersoll-Rand Energy Services		Turbec	DTE Energy Technologies
Model Name	Model 330	Capstone 60	TA-80	PowerWorks			ENT 400 recuperated
Size	30 kW	60 kW	80 kW	70 kW		100 kW	300 kW
Voltage	400-480 VAC					400 VAC	480/277 VAC
Fuel Flexibility	natural gas, medium Btu gas, diesel, kerosene		natural gas	natural gas		natural gas, biogas, ethanol, diesel	natural gas (diesel, propane future)
Fuel Efficiency (cf/kWh)	13.73	14.23				11.2	
Efficiency	26% (+/-2%)	28% (+/- 2%)	28%	30-33%		30%	28% (+/- 2%)
	70-90% CHP	70-90% CHP	80% CHP			80% CHP	74% CHP
Emissions	NO_x <9ppmV @15% O_2		NO_x diesel <60ppm, NO_x NG <25ppm, CO diesel <400ppm, CO NG <85ppm	NO_x <9ppmV @15% O_2, CO <9ppmV @15% O_2		NO_x <15ppmV @15% O_2, CO <15ppm, UHC <10ppm	NOx <9ppmV @15% O_2
Units Sold	1999: 211 units			2000: 2 precommercial units, expected commercial in 2001		2000: 20 units in the European market	Available late 2001
	2000: 790 units						
	2001: 1,033 units		2001: 100 units				
Unit Cost	$1000/kW					$75,000	
Cold Start-Up Time	3 min						3 min emergency, 7 min normal
Web site	www.capstone.com		www.elliott-turbo.com/new/products_microtubines.html	www.irco.com/energysystems/powerworks.html		www.turbec.com	www.dtetech.com/energynow/portfolio/2_1_4.asp

Fuel Cells

Technology Description



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.

System Concepts

- 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. The ions and electrons then recombine, with water and heat as the only byproducts.
- Fuel cell systems today 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.

Representative Technologies

Fuel cells are categorized by the kind of electrolyte they use:

- Alkaline Fuel Cells (AFCs) were the first type of fuel cell to be used in space applications. AFCs contain a potassium hydroxide (KOH) solution as the electrolyte and operate at temperatures between 60 and 260°C (140 to 500°F). 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.
- Phosphoric Acid Fuel Cells (PAFCs) were the first fuel cells to be commercialized. These fuel cells operate at 190-210°C (374-410°F) and achieve 35 to 45% fuel-to-electricity efficiencies LHV. Commercially-validated reliabilities are 90-95%.
- Proton Exchange Membrane Fuel Cells (PEMFCs) operate at relatively low temperatures of 70-100°C (150-180°F), 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). The PEM is 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.
- Molten Carbonate Fuel Cell (MCFC) technology has the potential to reach fuel-to-electricity efficiencies of 45% to 60% on a higher heating value basis (HHV). Operating temperatures for MCFCs are around 650° C (1,200°F), which allows total system thermal efficiencies up to 50% HHV in combined-cycle applications. MCFCs have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products.
- Solid Oxide Fuel Cells (SOFCs) operate at temperatures up to 1,000°C (1,800°F), which further enhances combined-cycle performance. A solid oxide system usually uses a hard ceramic material instead

of a liquid electrolyte. The solid-state ceramic construction enables the high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability. As with MCFCs, SOFCs are capable of fuel-to-electricity efficiencies of 45% to 55% LHV and total system thermal efficiencies up to 85% LHV in combined-cycle applications.

Technology Applications

- 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 (most likely SOFC and MCFC), 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 (more then six-nines) 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, small-footprint portable power.

Current Status

- The cost of fuel cells hinders competition in widespread domestic and international markets without significant subsidies.
- PAFC – More than 250 PAFC systems are in service worldwide, with those installed by ONSI having surpassed 2 million total operating hours with excellent operational characteristics and high availability.

Economic Specifications of the PAFC (200 kW)

Expense	Description	Cost
Capital Cost	1 complete PAFC power plant	$850,000
Installation	Electrical, plumbing, and foundation	$40,000
Operation	Natural gas costs	$5.35/MMcf
Minor Maintenance	Service events, semiannual and annual maintenance	$20,000/yr
Major Overhaul	Replacement of the cell stack	$320,000/5 yrs

Source: Energetics, *Distributed Energy Technology Simulator: Phosphoric Acid Fuel Cell Validatio*n, May 2001.

- PEMFC – Ballard's first 250 kW commercial unit is under test. PEM systems up to 200 kW are also operating in several hydrogen-powered buses. Most units are small (<10 kW). PEMFCs currently cost several thousand dollars per kW.
- SOFC – 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.
- MCFC – 50 kW and 2 MW systems have been field-tested. Commercial offerings are in the 250 kW-2 MW range.

Fuel Cell Type	Electrolyte	Operating Temp (°C)	Electrical Efficiency (% HHV)	Commercial Availability	Typical Unit Size Range	Start-up time (hours)
AFC	KOH	260	32-40	1960s		
PEMFC	Nafion	65-85	30-40	2000-2001	5-250 kW	< 0.1
PAFC	Phosphoric Acid	190-210	35-45	1992	200 kW	1-4

MCFC	Lithium, potassium, carbonate salt	650-700	40-50	Post 2003	250 kW-2 MW	5-10
SOFC	Yttrium & zirconium oxides	750-1000	45-55	Post 2003	5-250 kW	5-10

Sources: Anne Marie Borbely and Jan F. Kreider. *Distributed Generation: The Power Paradigm for the New Millennium*, CRC Press, 2001, and Arthur D. Little, Distributed Generation Primer: Building the Factual Foundation (multiclient study), February 2000

Technology History

- In 1839, William Grove, a British jurist and amateur physicist, first discovered the principle of the fuel cell. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell into hydrogen and oxygen.
- In the 1960s, alkaline fuel cells were developed for space applications that required strict environmental and efficiency performance. The successful demonstration of the fuel cells in space led to their serious consideration for terrestrial applications in the 1970s.
- In the early 1970s, DuPont introduced the Nafion® membrane, which has traditionally become the electrolyte for PEMFC.
- In 1993, ONSI introduced the first commercially available PAFC. Its collaborative agreement with the U.S. Department of Defense enabled more than 100 PAFCs to be installed and operated at military installations.
- The emergence of new fuel cell types (SOFC, MCFC) in the past decade can lead to technology applications where high temperature heat recovery has value.

Technology Future

- According to the Business Communications Company, the market for fuel cells was about $218 million in 2000 and will reach $7 billion by 2009.
- Fuel cells are being developed for stationary power generation through a partnership of the U.S DOE and the private sector.
- 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 also working with industry to test and validate the PEM technology at the 1–kW level and to transfer technology to the Department of Defense. 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.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005); and National Renewable Energy Laboratory. Gas-Fired Distributed Energy Resource Technology Characterizations. NREL/TP-620/34783. November 2003.

Fuel Cells

Technology Performance

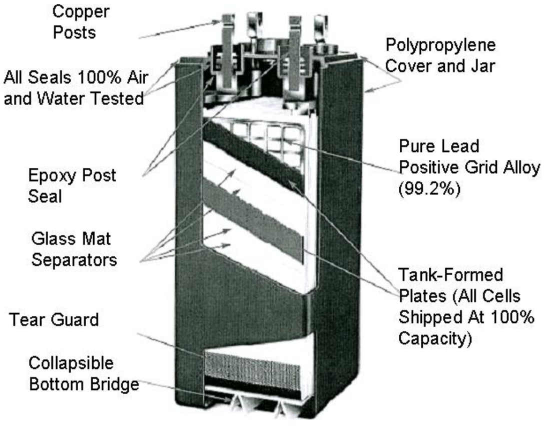
		Source: *Hydrogen, Fuel Cells & Infrastructure Technologies Program Multiyear Research, Development and Demonstration Plan,* February 2005					
		Small (3-25 kW)			**Large (50-250kW)**		
Characteristic	Units	2004 Status	2005	2010	2004 Status	2005	2010
Electrical Energy Efficiency @ rated power	%	30	32	35	30	32	40
CHP Energy Efficiency @ rated power	%	75	75	80	75	75	80
Cost	$/kW		1500	1000	2500	1500	750
Transient Response Time (from 10% to 90% power)	msec	<3	<3	<3	<3	<3	<3
	3000						
Cold Start-up Time (to rated power @ -20 degrees C ambient) Continuous-use application	min	<90	<60	<30	<90	<60	<30
Survivability (min and max ambient temperature)	C degrees	-25 +40	-30 +40	-35 +40	-25 +40	-30 +40	-35 +40
Durability @ <10% rated power degradation	hour	>8,000	16,000	40,000	15,000	20,000	40,000

Noise	dB(A)	<70 @ 1m	<65 @ 1m	<60 @ 1m	<65 @ 1m	<60 @ 1m	<55 @ 1m
Emissions (Combined NOX, CO, SOX, Hydrocarbon, Particulates)	g/ 1,000 kW	<15	<10	<9	<8	<2	<1.5

a Includes fuel processor, stack, and all ancillaries.
b Ratio of DC output energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant.
c For LPG, efficiencies are 1.5 percentage points lower than natural gas because the reforming process is more complex.
d Ratio of DC output energy plus recovered thermal energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant
e Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for black start.
f Not applicable to backup power because this application does not use a fuel processor.

Batteries

Technology Description



Batteries are likely the most widely known type of energy storage. They all 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.

System Concepts

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.

Representative Technologies

- 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.

Technology Applications

- 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. The largest system to date is 20 MW. 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 microporous 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 a 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.

Current Status

- Energy storage systems for large-scale power quality applications (~10 MW) are economically viable now, with sales from one manufacturer doubling from 2000 to 2001.
- Lead-acid battery annual sales tripled between 1993 and 2000. The relative importance of battery sales for switchgear and UPS applications shrunk during this period from 45% to 26% of annual sales by 2000. VRLA and flooded battery sales were $5.34 million and $1.71 million, respectively, in 2000.
- Lead-acid battery manufacturers saw sales drop with the collapse of the telecommunications bubble in 2001. They saw significant growth in sales in 2000, due to the demand from communications firms, and invested in production and marketing in anticipation of further growth.
- Many manufacturers have been subject to mergers and acquisitions. A few dozen manufacturers in the United States and abroad still make batteries.
- Government and private industry are currently developing a variety of advanced batteries for transportation and defense applications: lithium-ion, lithium polymer, nickel metal hydride, sodium metal chloride, sodium sulfur, and zinc bromine.
- Rechargeable lithium batteries already have been introduced in the market for consumer electronics and other portable equipment.
- There are two demonstration sites of ZBB’s Zinc Bromine batteries in Michigan and two additional ones in Australia.
- 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.
- Batteries are the most common energy storage device.
- About 150 MW of utility peak-shaving batteries were in use in Japan in 2003.
- In 2003, construction began on two 10-MW flow battery systems – one in the U.K. and the other in the United States.

Technology History

- Most historians date the invention of batteries to about 1800, when experiments by Alessandro Volta resulted in the generation of electrical current from chemical reactions between dissimilar metals.
- Secondary batteries date back to 1860, when Raymond Gaston Planté invented the lead-acid battery. His cell used two thin lead plates separated by rubber sheets. He rolled the combination up and immersed it in a dilute sulfuric acid solution. Initial capacity was extremely limited because the positive plate had little active material available for reaction.
- Others developed batteries using a paste of lead oxides for the positive plate active materials. This allowed much quicker formation and better plate efficiency than the solid Planté plate. Although the rudiments of the flooded lead-acid battery date back to the 1880s, there has been a continuing stream of improvements in the materials of construction and the manufacturing and formation processes.
- Because many of the problems with flooded lead-acid batteries involved electrolyte leakage, many attempts have been made to eliminate free acid in the battery. German researchers developed the gelled-electrolyte lead-acid battery (a type of VRLA) in the early 1960s. Working from a different approach, Gates Energy Products developed a spiral-wound VRLA cell, which represents the state of the art today.

Technology Future
• 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. • Energy storage and battery systems, in particular, will play a significant role in the Distributed Energy Resource environment of the future. Local energy management and reliability are emerging as important economic incentives for companies. • The growing market for hybrid vehicles and the potential for "plug-in hybrid" vehicles--that could supply power to the grid as well as draw power from the grid—may increase future demand for batteries. • A contraction in sales of lead-acid batteries that began in 2001 was expected to continue over the next few years until "9/11" occurred. Military demand for batteries may drastically alter the forecast for battery sales. • 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. • A 10 MW-120 MWh sodium bromide system is under construction by the Tennessee Valley Authority. A 40 MW nickel cadmium system is being built for transmission-line support and stabilization in Alaska.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Batteries

Market Data

Recent Battery Sales Source: Battery Council International, Annual Sales Summary, October 2001.

	1993	**2000**	Growth
Flooded Batteries (Million $)	156.9	533.5	340%
VRLA Batteries (Million $)	79.6	170.6	214%
Total Lead-Acid Batteries (Million $)	236.5	704.1	298%

Percent Communications	58%	69%
Percent Switchgear/UPS	45%	26%

Market Predictions Source: Sandia National Laboratories, Battery Energy Storage Market Feasibility Study, September 1997.

Year	MW	($ Million)
2000	496	372
2005	805	443
2010	965	434

Technology Performance

Grid-Connected Energy Storage Technologies Costs and Efficiencies

Source: Sandia National Laboratories, *Characteristics and Technologies for Long- vs. Short-Term Energy Storage,* March 2001.

Energy-Storage System	Energy Related Cost ($/kWh)	Power Related Cost ($/kW)	Balance of Plant ($/kWh)	Discharge Efficiency
Lead-acid Batteries				
low	175	200	50	0.85
average	225	250	50	0.85
high	250	300	50	0.85
Power-Quality Batteries	100	250	40	0.85
Advanced Batteries	245	300	40	0.70

Technology Performance

Off-Grid Storage Applications, Their Requirements, and Potential Markets to 2010 According to Boeing

Source: Sandia National Laboratories, Energy Storage Systems Program Report for FY99, June 2000.

Application	Single Home: Developing Community	Developing Community: No Industry	Developing Community: Light Industry	Developing Community: Moderate Industry	Advanced Community or Military Base
Storage-System Attributes					
Power (kW)	0.5	8	40	400	1 MW
Energy (kWh)	3	45	240	3,600	1.5 MWh
Power					
Base (kW)	0.5	5	10	100	100
Peak (kW)		< 8	< 40	< 400	< 1000
Discharge Duration	5 to 72 hrs	5 to 72 hrs	5 to 24 hrs	5 to 24 hrs	0.5 to 1 hr
Total Projected Number of Systems	47 Million	137,000	40,000	84,000	131,000
Fraction of Market Captured by Storage	> 50	> 50	~ 30	~ 10	< 5
Total Number of Storage Systems to Capture Market Share	24 Million	69,000	12,000	8,000	< 7,000

Technology Performance

Advanced Batteries Characteristics

Source: DOE Energy Storage Systems Program Annual Peer Review FY01, Boulder City Battery Energy Storage, November 2001.

Energy Storage System	Sodium Sulfur	Vanadium Redox	Zinc Bromine
Field Experience	Over 30 Projects, 25 kW to 6 MW, Largest 48 MW	Several Projects 100kW to 3 MW (pulse power), Largest 1.15 MWh	Several Projects, 50 kW to 250 kW, Largest 400 kWh
Production Capacity	160 MWh/yr	30 MWh/yr	40 to 70 MWh/yr
Actual Production	50 MWh/yr	10 MWh/yr	4.5 MWh/yr
Life	15 yrs	7 to 15 yrs	10 to 20 yrs
Efficiency	72%	70to 80 %	65 to 70%
O&M Costs	$32.5k/yr	$50k/yr	$30 to $150k/yr

Advanced Energy Storage

Technology Description

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:* Electric demand falls at night, providing an opportunity for the most cost effective electric generators 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. 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, 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. 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. 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.

Technology Applications

- 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.

- 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 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 apps
Batteries	70–84	30-50	0.2-0.4	17-40	most common
Flywheels	90+	15-30	1-3	0.1-20 kWh	US & foreign dev.
Ultracapacitors	90+	2-10	high	0.1-0.5 kWh	high-power dens

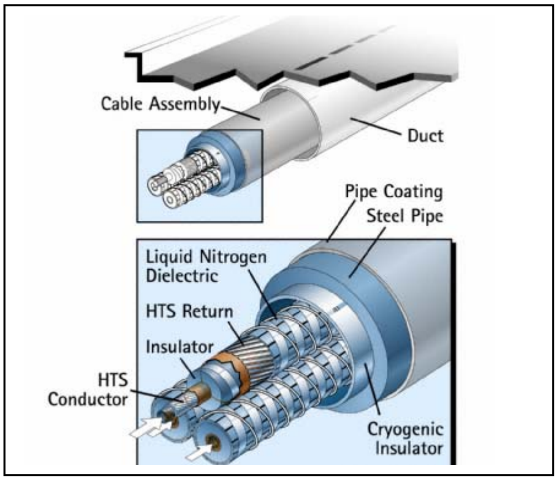
Technology Future

- For utilities, only pumped hydro has made a significant penetration with approximately 21 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.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Superconducting Power Technology

Technology Description



Source: American Superconductor

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, 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.

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, may 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 rated at 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 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 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 with Industry (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 underway 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 is 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 is 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 researching motor components with improved performance characteristics.

Current Status

- The development at the national laboratories of ion-beam assisted deposition and rolling-assisted, biaxially textured substrate (RABiTS$^{\text{TM}}$) 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.

Technology History

- In 1911, after technology allowed liquid helium to be produced, Dutch physicist Heike Kammerlingh Onnes found that at 4.2 K, the electrical resistance of mercury decreased to almost zero. This marked the first discovery of superconducting materials.
- Until 1986, superconductivity applications were highly limited due to the high cost of cooling to such low temperatures, which resulted in costs higher than the benefits of using the new technology.

In 1986, two IBM scientists, J. George Bednorz and Karl Müller achieved superconductivity on lanthanum copper oxides doped with barium or strontium at temperatures as high as 38 K.

- In 1987, the compound $Y_1Ba_2Cu_3O_7$ (YBCO) was given considerable attention, as it possessed the highest critical temperature at that time, at 93 K. In the following years, other copper oxide variations were found, such as bismuth lead strontium calcium copper oxide (110 K), and thallium barium calcium copper oxide (125 K).
- In 1990, the first (dc) HTS motor was demonstrated.
- In 1992, a 1-meter-long HTS cable was demonstrated.
- By 1996, a 200-horsepower HTS motor was tested and exceeded its design goals by 60%.

A Pirelli Cable team installed a 120m HTS cable in Detroit, Michigan under the DOE Superconductivity Partnership Initiative. Since February 2000, Southwire's 30m prototype cable has been powering three manufacturing plants in Carrollton, Georgia.

- HTS transformers have seen increased interest, as Waukesha Electric Systems demonstrated a 1-MVA prototype transformer in 1999. This team is also leading the development of a 5/10-MVA, 26.4-kV/4.2-kV three-phase prototype.
- A 750 kW HTS motor was demonstrated by Rockwell Automation. This team is now (in 2006) researching motor components.

Technology Future

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. The Power Delivery Research Initiative, authorized in the 2005 Energy Policy Act, would help enable broad utility involvement in the technology.

Source: National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003 (draft update, September 2005).

Superconducting Power Technology

Market Data

Projected Market for HTS devices
(Thousands of Dollars)

Source: *Oak Ridge National Laboratory - High Temperature Superconductivity: The Products and Their Benefits*, 2002 Edition, Total Market Benefits, p 40.

	2004	**2006**	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
Motors	0	0	27.29	169.24	527.03	1310.49	3103.37	6360.31	11322.83
Transformers	0	3.8	14.22	37.47	90.63	197.73	371.87	605.23	877.71
Generators	0	0	0	4.09	15.56	41.12	101.16	224.26	426.61
Cables	0	0.17	0.59	1.44	2.81	4.86	7.7	11.21	15.17
Total	0	3.97	42.1	212.24	636.03	1554.2	3584.1	7201.01	12642.32

The report assumes electrical generation and equipment market growth averaging 2.5% per year through 2020. This number was chosen based on historic figures (the past fifteen years) and the assumption that electric demand will drive electric supply.

Projected Market for HTS devices
(Thousands of Dollars)

Source: *Analysis of Future Prices and Markets for High-Temperature Superconductors,* September 2001, DOE.

	2011	**2013**	**2015**	**2017**	**2019**	**2021**	**2023**	**2025**
Motors	225	956	4,025	15,399	50,968	108,429	148,770	164,072
Transformers	0	0	243	1,451	9,353	56,081	222,277	390,964
Generators	6,926	24,710	83,634	227,535	445,693	592,904	656,499	675,656
Cables	4,117	14,405	48,335	135,001	318,844	488,783	570,326	586,284
Total	11,270	40,071	136,236	379,386	824,857	1,246,196	1,597,872	1,816,975

Technology Performance

Source: *Oak Ridge National Laboratory – High-Temperature Superconductivity: The Products and Their Benefits*, 2002 Edition, Tables M-2, T-1, G-1, C-2

HTS Energy Savings (GWh)	**2004**	**2006**	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
Motors	0	0	0.4	3	8	21	48	98	172
Transformers	0	0.1	0.2	1	1	3	6	9	14
Generators	0	0	0	0.1	0.2	1	2	3	6
Cables	0	3	18	56	133	270	488	806	1,236
Total	0	4	19	60	143	294	544	916	1,428

Source: *Analysis of Future Prices and Markets for High-Temperature Superconductors,* September 2001, DOE.

HTS Energy Savings (GWh)	**2009**	**2011**	**2013**	**2015**	**2017**	**2019**	**2021**	**2023**	**2025**
Motors	0	0	1	4	15	57	154	300	468
Transformers	0	0	0	0	2	15	94	449	1,194
Generators	2	11	44	171	556	1,417	2,699	4,196	5,785
Cables	1	3	13	55	196	598	1,336	2,289	3,326
Total	3	14	58	231	769	2,086	4,283	7,235	10,774

Thermally Activated Technologies

Technology Description

Thermally Activated Technologies (TATs), 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.

System Concepts

- TATs 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.

Representative Technologies

- Thermally activated heat pumps can revolutionize the way residential and commercial buildings are heated and cooled. This technology enables highly efficient heat pump cycles to replace the best natural gas furnaces, reducing energy use as much as 50%. 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.
- 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 refrigerative 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. The desiccant is usually formed in a wheel made up of lightweight honeycomb or corrugated material (see figure). Commercially available desiccants include silica gel, activated alumina, natural and synthetic zeolites, 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.

Technology Applications

- Thermally activated heat pumps are a new generation of advanced absorption cycle heat pumps that can efficiently condition residential and commercial space. 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. Facilities with stringent indoor air-quality needs (schools, hospitals, grocery stores, hotels) have adapted desiccant technology.
- CHP applications are well suited for TATs. 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.

Current Status

- Thermally activated heat pump technology can replace the best natural gas furnace and reduce energy use by as much as 50%, while also providing gas-fired technology.
- Desiccant technology may be used in pharmaceutical manufacturing to extend the shelf life of products; refrigerated warehouses to prevent water vapor from forming on the walls, floors, and ceilings; operating rooms to remove moisture form the air, keeping duct work and sterile surfaces dry; and hotels, to prevent buildup of mold and mildew.

Technology History

- In the 1930s, the concept of dehumidifying air by scrubbing it with lithium chloride was introduced, paving the way for development of the first desiccant unit.
- In 1970, Trane introduced a mass-produced, steam-fired, double-effect LiBr/H2O absorption chiller.
- In 1987, the National Appliance Energy Conversion Act instituted minimum efficiency standards for central air-conditioners and heat pumps.

Technology Future

- Expand the residential market of the second-generation Hi-Cool residential absorption heat pump technology to include markets in southern states; the targeted 30% improvement in cooling performance can only be achieved with major new advancements in absorption technology or with an engine-driven system.
- Work in parallel with the first-generation GAX effort to determine the most attractive second-generation Hi-Cool technology.
- Fabricate and test the 8-ton advanced cycle VX GAX ammonia/water heat pump.
- Fabricate and test the 3-ton complex compound heat pump and chiller.
- Develop, test, and market an advanced Double Condenser Coupled commercial chiller, which is expected to be 50% more efficient than conventional chillers.
- Assess new equipment designs and concepts for desiccants using diagnostic techniques, such as infrared thermal performance mapping and advanced tracer gas-leak detection.