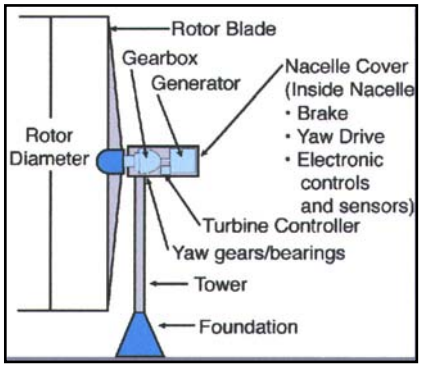
Wind Energy

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.	10.0	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