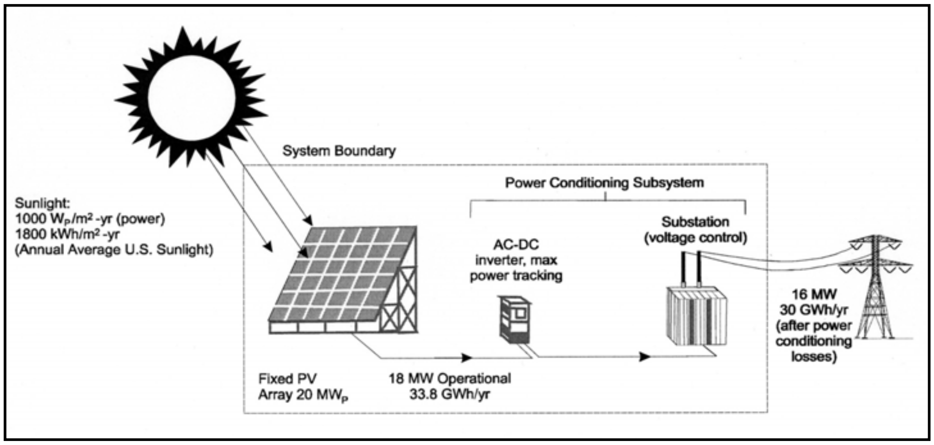
Photovoltaics

Technology Description

Photovoltaic (PV) arrays convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases (GHGs). Using solar PV for electricity and eventually transportation (from hydrogen production) will help reduce CO_2 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., see semi-transparent solar canopy, right). PV dc output can be conditioned into grid-quality ac electricity, or dc can be used to charge batteries or to split water to produce H_2.



Representative Technologies

- Flat-plate cells are either constructed from crystalline silicon cells, or from thin films using amorphous silicon. Other materials such as copper indium diselinide (CIS) and cadmium telluride also hold promise as thin-film materials. The vast majority of systems installed today are in flat-plate configurations where multiple cells are mounted together to form a module. These systems are generally fixed in a single position, but can be mounted on structures that tilt toward the sun on a seasonal basis, or on structures that roll east to west over the course of the day.
- Photovoltaic concentrator systems use optical concentrators to focus direct sunlight onto solar cells for conversion to electricity. A complete concentrating system includes concentrator modules, support and tracking structures, a power-processing center, and land. PV concentrator module components include solar cells, an electrically isolating and thermally conducting housing for mounting and interconnecting the cells, and optical concentrators. The solar cells in today's concentrators are predominantly silicon, although gallium arsenide-based (GaAs) solar cells may be used in the future because of their high-conversion efficiencies. The housing places the solar cells at the focus of the optical concentrator elements and provides means for dissipating excess heat generated in the solar cells. The optical concentrators are generally Fresnel lenses but also can be reflectors.

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 one 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

- The cost of PV-generated electricity has dropped 15- to 20-fold; and grid-connected PV systems currently sell for about \$5–\$8/W_p (20 to 32¢/kWh), including support structures, power conditioning, and land. They are highly reliable and last 20 years or longer.
- Crystalline silicon is widely used and the most commercially mature photovoltaic material. Thin-film PV modules currently in production include three based on amorphous silicon, cadmium telluride, and CIS alloys.
- About 288 MW of PV were sold in 2000 (more than \$2 billion worth) and 510 MW of PV were sold in 2002; total installed PV is more than 2 GW. The U.S. world market share is about 20%. Annual market growth for PV has been about 25% as a result of reduced prices and successful global marketing. Specifically, sales grew 36% in 2001 and 31% in 2002. Hundreds of applications are cost-effective for off-grid needs. Almost two-thirds of U.S.-manufactured PV is exported. However, the fastest growing segment of the market is grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California is subsidizing PV systems because it is considered cost-effective to reduce their dependence on natural gas, especially for peak daytime loads for air-conditioning, which matches PV output.
- Highest efficiency for wafers of single-crystal or polycrystalline silicon is 25%, and for commercial modules is 13%–17%. Silicon modules currently cost about \$2/W_p to manufacture.
- In the past few years, *world record* solar cell sunlight-to-electricity conversion efficiencies were set by federally funded universities, national laboratories, or industry in copper indium gallium diselenide (19% cells and 13% modules) and cadmium telluride (16% cells, 11% modules). Cell and module efficiencies for these technologies have increased more than 50% in the past decade. Efficiencies for commercial thin-film modules are 5%–11%, with the best cells offering 12-19% efficiency. 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.
- Highest efficiencies for single-crystal Si and multijunction gallium arsenide (GaAs)-alloy cells for concentrators are 25%–34%; and for commercial modules are 15%–17%. Prototype systems are being tested in the U.S. desert SW.
- Current leading PV companies in 2000 and associated production of cells/modules are listed below:

Top PV Producers (2002)

	U.S. Production	**World Production**
	MW	MW
Sharp	-	198.0
Shell Solar	52.0	73.0

Kyocera	-	72.0
BP Solar	13.4	70.2
RWE (ASE)	4.0	44.0
Mitsubishi	-	42.0
Isofoton	-	35.2
Sanyo	-	35.0
Q-Cells	-	28.0
Photowatt	-	20.0
AstroPower	17.0	17.0
USSC	7.0	
Global Solar	3.0	-
First Solar	3.0	-
Evergreen Solar	2.8	-
Other*	2.0	-
Total	104.22	632.4
World Total	-	744.1

Source: US: PV News, Vol. 23, No. 3, Page 2; World: PV News, Vol. 23, No. 4, Page 2

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 percent 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, rising 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 1997$/kWh) for PV are projected to be:

	2000	2010	2020
Utility-owned Residential (crystalline Si)	29.7	17.0	10.2
Utility-Scale Thin-Film	29.0	8.1	6.2
Concentrator	24.4	9.4	6.5

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.
(Note that this document is currently being updated by DOE, and the values most likely will change).

- Crystalline Silicon - Most PV systems installed to-date have used crystalline silicon cells. That technology is relatively mature. In the future, cost-effectiveness will be achieved through incremental efficiency improvements, enhanced yields, and advanced lower-cost manufacturing techniques.
- Even though some thin-film modules are now commercially available, their real commercial impact is only expected to become significant during the next three to 10 years. Beyond that, their general use should occur in the 2005-2015 time frame, depending on investment levels for technology development and manufacture.
- Thin films using amorphous silicon, which are a growing segment of the U.S. market, have several advantages over crystalline silicon. It can be manufactured at lower cost, is more responsive to indoor light, and can be manufactured on flexible or low-cost substrates. Improved semiconductor deposition rates will reduce manufacturing costs in the future. Other thin-film materials will become increasingly important in the future. In fact, the first commercial modules using indium gallium diselinide thin-film devices were produced in 2000. Improved manufacturing techniques and deposition processes will reduce costs and help improve efficiency.
- Substantial commercial interest exists in scaling-up production of thin films. As thin films are produced in larger quantity, and as they achieve expected performance gains, they will become more economical for the whole range of applications.
- Multijunction cells with efficiencies of 38% at very high concentrations are being developed.
- Manufacturing research and supporting technology development hold important keys to future cost reductions. Large-scale manufacturing processes will allow major cost reductions in cells and modules. Advanced power electronics and non-islanding inverters will lessen barriers to customer adoption and utility interface.
- A unique multijunction GaAs-alloy cell developed at NREL was spun off to the space power industry, leading to a record cell (34%) and a shared R&D100 Award for NREL/Spectrolab in 2001. This device configuration is expected to dominate future space power for commercial and military satellites.

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

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)*	Source: *Strategies Unlimited*								
	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

*Excludes indoor consumer (watches/calculators).

U.S. Shipments (MW) Source: *EIA, Annual Energy Review 2003,* DOE/EIA-0384(2003) (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	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Total		5.8	13.8	31.1	35.5	46.4	50.6	76.8	88.2	97.7	112.1	109.4
Imports		0.3	1.4	1.3	1.9	1.9	1.9	4.8	8.8	10.2	7.3	9.7
Exports		1.7	7.5	19.9	22.4	33.8	35.5	55.6	68.4	61.4	66.8	60.7
Domestic Total On-Grid*		0.4	0.2	1.7	1.8	2.2	4.2	6.9	4.9	10.1	13.7	NA
Domestic Total Off-Grid*		3.7	6.1	9.5	11.2	10.3	10.8	14.4	15.0	26.2	31.6	NA

Cumulative Shipments (since 1982)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Total		35.2	84.7	193.3	228.8	275.2	325.7	402.5	490.7	588.4	700.5	809.8
Imports		1.0	5.6	14.3	16.2	18	19.9	24.7	33.5	43.7	51.0	60.8
Exports		5.7	32.9	104	126.5	160.3	195.8	251.3	319.7	381.0	447.8	508.5
Domestic Total On-Grid*		2.9	4.7	8.2	10.0	12.2	16.5	23.3	28.2	38.3	52.0	NA
Domestic Total Off-Grid*		26.6	47.2	81.1	92.3	102.7	113.5	127.9	142.8	169.0	200.6	NA

* Domestic Totals include imports and exclude exports.

NA = Not Available; 2003 data not available at time of publication

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., Commercial			1		7	27	36	60	120	199	270
Central Station (>100kW)			1		2	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										0	-
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**	**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	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.										
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Single-Crystal Silicon				19.9	21.7	30	30.8	47.2	51.9	54.7	74.7
Cast and Ribbon Crystalline Silicon				9.9	12.3	14.3	16.4	26.2	33.2	29.9	29.4
Crystalline Silicon Total		5.5	12.5	29.8	34	44.3	47.2	73.5	85.2	84.7	104.1
Thin-Film Silicon	N/A	0.3	1.3	1.3	1.4	1.9	3.3	3.3	2.7	12.5	7.4
Concentrator Silicon				0.1	0.2	0.2	0.1	0.1	0.3	0.5	0.6
Other											
Total		5.8	13.8	31.2	35.6	46.3	50.6	76.8	88.2	97.7	112.1

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.											
	1980	**1985**	**1990**	**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.											
	1980	**1985**	**1990**	**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.										
	1980	**1985**	**1990**	**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: *Renewable Energy Technology Characterizations,* EPRI TR-109496, 1997.
(Note that this document is currently being updated by DOE, and the values most likely will change).

Efficiency		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Cell (%)	Crystalline Silicon			24.0	24.7				
	Thin Film			18.0	19.0	20.0	21.0	21.5	22.0
	Concentrator			20.0	23.0	26.0	33.0	35.0	37.0
Module (%)	Crystalline Silicon			14.0	16.0	17.0	18.0	18.5	19.0
	Thin Film	N/A	N/A	10.0	12.0	15.0	17.0	17.5	18.0
	Concentrator								
System (%)	Crystalline Silicon			11.3	13.1	14.1	15.1	15.6	16.1
	Thin Film			4.8	7.2	8.8	11.2	12.0	12.8
	Concentrator			13.8	15.1	17.1	21.7	23.0	24.3
Cost		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Module ($/Wp)	Crystalline Silicon			3.8	3.0	2.3	1.8	1.4	1.1
	Thin Film			3.8	2.2	1.0	0.5	0.4	0.4
	Concentrator			1.8	1.5	0.7	0.6	0.5	0.5
BOS ($/Wp)	Crystalline Silicon			2.7	2.1	1.6	1.2	0.9	0.7
	Thin Film			3.7	2.1	1.3	0.7	0.6	0.5
	Concentrator	N/A	N/A	3.6	2.7	1.2	1.0	0.8	0.7
Total ($/Wp)	Crystalline Silicon *			6.5	5.1	3.9	3.0	2.4	1.8
	Thin Film			7.5	4.3	2.3	1.2	1.1	0.9
	Concentrator			7.6	4.0	2.0	1.6	1.3	1.1
O&M ($/kWh)	Crystalline Silicon			0.008	0.007	0.006	0.006	0.006	0.005
	Thin Film			0.023	0.008	0.003	0.002	0.002	0.001
	Concentrator			0.047	0.020	0.010	0.008	0.007	0.006

* Range in total capital cost for crystalline silicon in 2000 is $5.1/Wp to $9.1/Wp depending on market supply and demand. (Source: John Mortensen, *Factors Associated with Photovoltaic System Costs*, June 2001, NREL/TP 620.29649, Page 3).