UTILITY-SCALE PHOTOVOLTAIC CONCENTRATORS

1.0 System Description

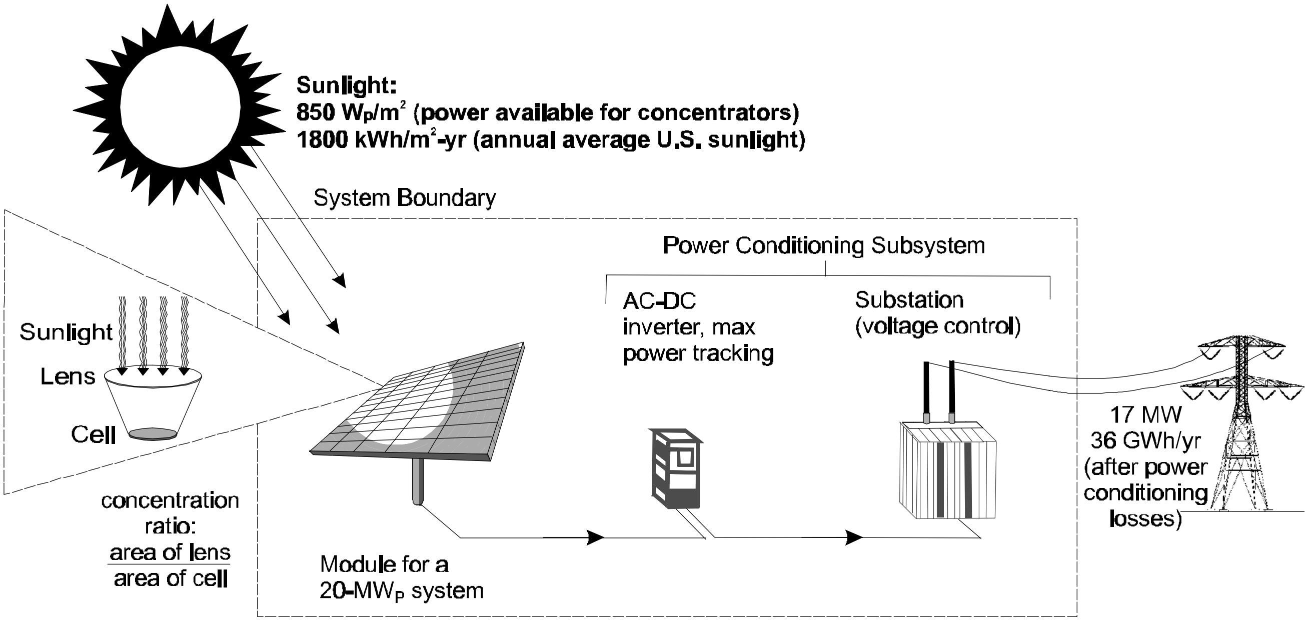

Figure 1. Grid-connected photovoltaic concentrator system schematic.

Photovoltaic concentrator systems use optical concentrators to focus direct sunlight onto solar cells for conversion to electricity. Figure 1 shows a PV concentrator system connected to a utility grid that eventually provides power to customers. The complete 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 (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 can also be reflectors. Except for low concentrations, below about 10 suns, optical concentrators can use only the direct normal, non-diffuse, portion of the incident solar radiation. The modules are mounted on a support structure and, during daylight hours, are oriented to face (or "track") the sun using motors, gears, and a controller. Tracking the sun is necessary for high concentration (above approximately 10 "suns" or 10x) and increases the amount of energy captured daily, more than compensating for the losses due to inability to convert diffuse radiation. The concentrator module output flows to a power-processing center that includes hardware to convert power from direct current (DC) to alternating current (AC), safety devices, and controls to interface properly with the utility grid or other load.

By using optical concentrators to focus direct sunlight onto solar cells, the cell area, and consequently cell cost, can be reduced by a factor of up to one thousand (a 1,000x concentration factor). The solar-cell cost constitutes between 5% and 10% of total concentrator system cost. More expensive cells, costing even hundreds or thousands of dollars more per unit area than 1-sun cells used in flat plate systems, can still be cost effective in concentrators. Moreover, because properly designed concentrator cells are already significantly more efficient than 1-sun cells, concentrators have always been a promising high-efficiency photovoltaic option.

2.0 System Application, Benefits, and Impacts

An important characteristic of concentrator technology is the potential for rapid scaleup. Except for the solar cells, the remaining concentrator components are readily available from metal, plastic, glass, and electrical fabricators and suppliers. Concentrators also offer the benefit of having no effluents or emissions during operation. The effluents resulting from cell manufacture are lower, by the concentration factor, than those of flat-plate (one-sun) solar cells. Further, if the availability of polysilicon feedstock becomes an issue for the crystalline-silicon photovoltaic industry, the fact that concentrators use one hundred to one thousand times less silicon than flat-plate systems may become important [1].

Sales of concentrating systems are less than 1 percent of all photovoltaic system sales. Concentrators are not well suited to small applications where most of these PV sales have been made, and the very large application of concentrators as utility power plants requires low cost from the beginning. Concentrators have additional burdens compared to flat-plate systems. Concerns over tracking-system reliability are added to concerns over their obtrusive appearance and more-restrictive mounting options. They are difficult to integrate into residential roofs, for example.

Knowing that concentrators cannot compete in certain markets amenable to small flat-plate PV systems does not mean they cannot compete in other markets. High-efficiency concentrators will be stiff competition for other PV technologies in medium-scale power applications in good solar-resource regions [2]. However, even though some applications favor PV concentrator over flat-plate systems, or vice versa, the most significant competition in the U.S. for either is natural gas.

3.0 Technology Assumptions and Issues

This characterization is based on the current state of worldwide concentrator development. There are at least 10 companies developing or manufacturing concentrator systems [3]. Three of the U.S. concentrator companies are actively marketing their systems. The variety of technologies is extensive, as shown in Table 1.

Given the variety of technologies shown in Table 1, the selection of a base-case concentrator for this characterization is somewhat arbitrary. A recent assessment included near-term estimates for a variety of concentrator technologies [2]. These include:

- <u>1-axis-tracking parabolic trough at 50x</u> A polar-axis tracking reflective trough with 50x concentration on a silicon photovoltaic receiver.
- <u>Static (non-tracking) concentrator</u> A static concentrator with concentration of 4x is assumed. It is mounted south-facing with latitude slope. This concept, although not part of this technology characterization, was found to be a low-cost option comparable with either flat-plate thin film or high concentration PV modules. The Japanese PV program recently started a new research effort into static concentrators.

Table 1. Current concentrator technology development efforts.

Concentrator Type	Concentration Factor	Cell Type	Comments
Linear Fresnel lens	20x	Silicon	Mature 4th generation design
Linear Fresnel lens	15x	1-sun Si	Collects some diffuse light and uses simple tracker
Point-focus Fresnel lens	250x	High efficiency Si	Uses reflective secondaries, projects less than \$2/W in high volume
Point-focus Fresnel lens	250x	High efficiency Si	Glass lens and advertises \$3/W for field larger than 500 kW
Point-focus Fresnel lens	300x	Si	Developed small 230 W module competitive with flat plate modules
Dish	2400x	Si or GaAs	Cogeneration approach produces thermal energy and electricity, 1 kW system completed
Dish	500x	Si	Cogeneration, demonstrated proof of concept
Reflecting Parabolic Trough	25x and 32x	Si	Two different manufacturers
Innovative Optics	10x	Si or Other	Spectrally selects light, non-tracking
Linear Focus	2-10x	$CuInSe_2$	Innovative solar cell filaments, tracking and nontracking

- <u>Point-focus or dish concentrator at 400x using Si</u> A reflective dish or a Fresnel lens using high-efficiency silicon concentrator cells operating at a concentration of 400x. The analysis is not accurate enough to distinguish between these two optical concentrators.

- <u>A point-focus or dish concentrator at 1,000x using GaAs</u> This is a system similar to the above, but the silicon cell is replaced with a very high-efficiency multijunction cell based on III-V (gallium arsenide-related) materials.

Of these approaches, the 1-axis-tracking parabolic trough at 50x is assumed for the baseline because it is the most similar to concentrators available in today's market. Today's cost for this generic base system, estimated at \$7.55 per DC watt (see Table 2), is clearly justifiable since some companies expect their systems would sell for considerably less under certain conditions (see Table 1). The point focus optical concentrator was chosen for future cost estimates because it shows some cost advantage over other concentrator technologies and it is under development by several of today's manufacturers (see Table 1). Projections for concentrator technologies beyond 2010 are highly uncertain, in part because both DOE and EPRI terminated concentrator development in the early 1990s. Some government funding opportunities are still available under such programs as Photovoltaic Manufacturing Technology (PVMaT) and Technology Experience to Accelerate Markets in Utility Photovoltaics (TEAM-UP) [3]. Nevertheless, an industry group (the PV Concentrator Alliance) pursuing the commercialization of concentrator components and systems, states that a role for the government in the development of their industry is necessary. The Alliance believes the government should provide technical support for improving system performance, system reliability, and standards. Furthermore, the Alliance believes the federal government should provide long-term support for R&D into higher-efficiency cells, better optics, more-robust modules, reliable sun-tracking arrays, novel concentrator applications, and new ideas for next-generation concentrators [4]. The Alliance also supports and encourages various government programs that promote renewable energy through tax incentives, market development, pollution credits, and green marketing.

In summary, this is a “best future” assessment of PV concentrator technologies, especially for the years following 2010. The performance (and costs) for these later years are subject to considerable uncertainty, especially in light of almost nonexistent government funding. Nevertheless, the existence of U.S. PV concentrator companies is evidence of their belief (and that of their investors) in the potential of this technology.

4.0 Performance and Cost

Table 2 summarizes the performance and cost indicators for the photovoltaic concentrator system being characterized in this report.

4.1 Evolution Overview

The concentrator systems characterized here evolve from a 1-axis trough using silicon cells and 50x concentration, to a two-axis tracking point focus system using silicon cells at 400x, and finally to using very-high-efficiency GaAs solar cells in a point focus optical concentrator at 1,000x. The base system is similar to products on the market, although it does not represent the design of a particular manufacturer.

4.2 Performance and Cost Discussion

The AC, grid-connected systems characterized here range in size from 20 kW to 80 MW. The systems and cells vary, just as they presently vary from company to company. The annual solar energy is that used in Reference 2 originally taken from the NREL Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors [5]. This manual provides annual solar energy available for various tracking and non-tracking modules in different U.S. locations. The high-sunlight case uses Albuquerque, New Mexico insolation data where the total horizontal (0^o tilt) value is 2,044 kWh/m^2-yr. The average sunlight case corresponds to a central U.S. location (e.g. Wichita, Kansas) where the total horizontal value is 1,680 kWh/m^2-yr. Table 2 shows the slight difference in annual solar energy available for 1-axis-tracking and 2-axis-tracking systems. The standard direct-normal incidence is 850 W/m^2 for concentrators and is the key factor in determining the module area in plant size. The AC capacity factors are therefore a direct result of system efficiency and annual solar energy for the particular concentrator technology. These capacity factors are consistent with those used in recent EPRI and DOE technology evaluations [6]. Note that the capacity factors depend on the site. Reference 2 used high-sunlight (Albuquerque) and low-sunlight (Boston ~ 1,300 kWh/m^2-yr), with the low-sunlight case resulting in AC capacity factors of 17% to 18%. Note also that the temperature-derating factor is important for concentrators because cells may be operating at temperatures as high as 65^oC (149^oF), whereas cell efficiencies are referenced to 25^oC (77^oF). The temperature-derating factors are from Reference 2.

Table 2. Performance and cost indicators.

INDICATOR NAME	UNITS	Base Case 1997	+/- %	2000	+/- %	2005	+/- %	2010	+/- %	2020	+/- %	2030	+/- %
PV Concentrator		Si 1-axis Trough		Si Point Focus		Si Point Focus		GaAs Point Focus		GaAs Point Focus		GaAs Point Focus	
Concentration	x suns	50		400		400		1,000		1,000		1,000	
Plant Size (DC Rating)	MW_p	0.02		3		10		20		40		80	
Plant Size (AC Rating)	MW	0.017		2.55		8.5		17		34		68	
Plant Size (Module Area)	1000 m^2	0.145		20		58.5		92.2		164.6		304.2	
Performance													
Cell Efficiency	%	20		23		26		33		37	5	40	5
BOS Efficiency	%	85		85		85		85		85		85	
Optical Efficiency	%	90		85		85		85		85		85	
Temperature Derating	%	90		91		91		91		91		91	
System Efficiency	%	13.8		15.1		17.1		21.7		24.3	5	26.3	5
Average Solar Energy Site (direct normal insolation)													
Annual Solar Energy	kWh/m^2-yr	1,674		1,800		1,800		1,800		1,800		1,800	
AC Capacity Factor	%	22.5		24.2		24.2		24.2		24.2		24.2	
System Annual Energy/Area	kWh/m^2-yr	231		272		308		391		437		473	
Total Annual Energy Delivery	GWh/yr	0.033		5.4		18		36		72		144	
High Solar Energy Site (direct normal insolation)													
Annual Solar Energy	kWh/m^2-yr	2,219		2,397		2,397		2,397		2,397		2,397	
AC Capacity Factor	%	29.5		32.2		32.2		32.2		32.2		32.2	
System Annual Energy/Area	kWh/m^2-yr	306		360		410		520		582		630	
Total Annual Energy Delivery	GWh/yr	0.044		7.2		24		47.9		95.8		191.6	

Table 2. Performance and cost indicators (cont.)

INDICATOR NAME	UNITS	Base Case 1997	+/- %	2000	+/- %	2005	+/- %	2010	+/- %	2020	+/- %	2030	+/- %
PV Concentrator		Si 1-axis Trough		Si Point Focus		Si Point Focus		GaAs Point Focus		GaAs Point Focus		GaAs Point Focus	
Capital Cost													
PV Module Cost	$\$/\mathrm{m}^2$	160		160		90		90		80		80	
Tracking Cost	$\$/\mathrm{m}^2$	40		67		35		35		25		25	
Power-Related BOS	$\$/\mathrm{W}_p$	.7		.6		.3		.3		.2		.15	
Area-Related BOS w/o Land Costs	$\$/\mathrm{m}^2$	200		140		70		70		50		50	
Cell Cost per Cell Area	$(\$1000)/\mathrm{m}^2$	15		20		15		30		20		15	
Indirect Cost on modules and systems (% added to above costs, not including land)	%	30		20		20		15		15		10	
Land Cost	$\$/\mathrm{m}^2$	0.5		0.5		0.5		0.5		0.5		0.5	
Total Capital Cost	$M	.151	10	12.2	10	20.1	20	31	30	44	40	71	50
Total Capital Cost per Peak Rated DC Power	$\$/\mathrm{W}_p$	7.55	10	4.01	10	2.01	20	1.55	30	1.1	40	.89	50
Total Capital Cost per Peak Rated AC Power	$\$/\mathrm{W}_p$	8.88		4.78		2.36		1.82		1.3		1.04	
Operation and Maintenance Cost													
Annual O&M	$/kWh	.047		.02		.01		.008		.006		.004	
Annual O&M	$\$/\mathrm{m}^2$-yr	14		7		4		4		3.5		2.5	
Annual O&M	($1000)/yr	2.03		140		234		369		576		761	
Unit Annual O&M (AC rating)	$/kW-yr (AC)	119		56		28		23		17		11	

Notes:

1. The columns for "+/-%" refer to the uncertainty associated with a given estimate.
2. Plant construction is assumed to require less than 1 year.

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One factor supporting the potential rapid evolution of concentrators is the existence of high-efficiency silicon solar cells, recently-developed very-high-efficiency gallium arsenide solar cells, and the prospect for continued increases in solar cell efficiency. Silicon-cell efficiencies of more than 26% have already been demonstrated by one U.S. concentrator manufacturer. DOE and EPRI concentrator programs have demonstrated stable, outdoor, module efficiencies of 18% from commercial production lines for high-concentration silicon cells [7, 8]. In 1994, NREL demonstrated a GaInP/GaAs monolithic two-terminal tandem cell with an efficiency greater than 30% at 140-180 suns, and greater than 29% at 400 suns [3]. The development of this device was the result of ten years' effort starting from an early 10% efficiency in 1985 to the 30% value in 1994 [9]. DOE’s Five Year Research Plan has a milestone in 1999 for a 32% monolithic device, and a four-terminal tandem cell has been measured at 34% under 100x [10,11]. Because theoretical upper limits are much higher, and there are several approaches for achieving efficiencies as high as 40% by 2030 or earlier [11], there is considerable expectation that higher efficiencies will be achieved. The primary ongoing obstacle for concentrators is a slowly developing market that impedes progress toward lower-cost systems. The uncertainties shown in Table 2 are 10 times larger for cost estimates in 2030 than they are for performance (efficiency). Nevertheless, all uncertainties in Table 2 are simply estimates since these technologies are not mature enough for more formalized engineering cost calculations.

Another factor that may affect the future evolution of concentrator cells and systems is the intense interest and investment of the space PV community. Space cell companies have recently installed large production facilities for GaInP/GaAs cells to be used in worldwide satellite telecommunications projects. The space PV community is looking at using PV concentrators, which show increased resistance to high-energy radiation damage because their cells are sheltered inside other components.

U.S. PV concentrator companies are pursuing a wide variety of technological approaches. Concentrating optics vary from static concentrators, to low concentration systems with one-axis or two-axis tracking, to high concentration systems that concentrate more than a thousand-fold [4]. Both reflective and refractive optics are used, and new approaches such as holographic and graded-index optics are under development. The potential of static concentrators has recently been identified, suggesting exploration is warranted to find a cost-effective, practical design [2]. Cell materials range from the industry standard—silicon—to new materials such as gallium arsenide or copper indium diselenide. These facts indicate that the technology is still evolving.

Another aspect of the future evolution of concentrators is that less capital is required for commercial scaleup because most of the system comprises readily available construction materials such as metal, glass, and plastic. PV concentrator technology could respond quickly to a drastic increase in demand for PV power plants—similar to the dramatic growth in the wind-energy industry in the 1980s. The cells are currently available at acceptable cost, and many system approaches are under development or in the marketplace, such as one producing both heat and electricity as well as a small concentrator system (230 W) beginning to compete in markets where certain flat-plate PV would previously have been the likely choice. These system developments may facilitate rapid commercialization into intermediate-sized applications, such as water pumping, island power, utility grid support, and remote housing.

Reference 2 assessed the various concentrator technologies over a time period ranging from a few years to a little over 10 years further out. Costs to 2010 are therefore based on the technology assessment in Reference 2. EPRI has conducted economic analyses for 2000–2005 that are consistent with the cost estimates in Table 2 [12]. Because of tremendous uncertainty in market projections for concentrators, no learning curve factors are used for the 2020 and 2030 estimates. The reductions that are shown are reasonably small decreases in module, tracking, BOS, and cell costs consistent with cost limits for materials.

Operation and maintenance costs begin with recent costs for early startup systems [13] and progress to those expected for future mature technologies [6]. The recent (base-case) O&M cost is adjusted slightly for the capacity factor difference between the test site and the high solar energy site used in this study.

5.0 Land, Water, and Critical Materials Requirements

Table 3. Resource requirements.

Indicator Name	Units	Base Year 1997	2000	2005	2010	2020	2030
Land	ha/MW	4.3	3.9	3.4	2.7	2.4	2.2
	ha	0.07	10	29.3	46.1	82.3	152.1
Silicon	kg/MW	245	28	25	-	-	-
GaAs	kg/MW	-	-	-	18	16	15
Water	m^3	0	0	0	0	0	0

The land requirement calculations shown in Table 3 assume the module area under plant size in Table 2 is 20% of land area, which corresponds to a 20% packing factor [14]. The module area is calculated using the AC rating under plant size, system efficiency, and the direct-normal insolation standard of 850 W/m^2. Silicon requirements are based on information in Reference 15, leading to 1.44 kg/m^2 of silicon feedstock needed per wafer area or 3.29 kg/m^2 of GaAs needed per wafer area. The difference between module area and cell-wafer area is, of course, the concentration that greatly reduces the amounts of expensive semiconductor material needed.

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