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Photovoltaics Program
Program Analysis and Integration Center

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Relative Potentials of Concentrating and Two-Axis Tracking Flat-Plate Photovoltaic Arrays for Central-Station Applications

Issue Study

Chester S. Borden
Diane L. Schwartz

December 31, 1984

Prepared for
U.S. Department of Energy
Through an Agreement with
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ABSTRACT

The purpose of this study is to assess the relative economic potentials of concentrating and two-axis tracking flat-plate photovoltaic arrays for central-station applications in the mid-1990's. Specific objectives of this study are to provide information on concentrator photovoltaic collector probabilistic price and efficiency levels to illustrate critical areas of R&D for concentrator cells and collectors, and to compare concentrator and flat-plate PV price and efficiency alternatives for several locations, based on their implied costs of energy. To deal with the uncertainties surrounding research and development activities in general, a probabilistic assessment of commercially achievable concentrator photovoltaic collector efficiencies and prices (at the factory loading dock) is performed. The results of this projection of concentrator photovoltaic technology are then compared with a previous flat-plate module price analysis (performed early in 1983). To focus this analysis on specific collector alternatives and their implied energy costs for different locations, similar two-axis tracking designs are assumed for both concentrator and flat-plate options. The results of this study provide the first comprehensive assessment of PV concentrator collector manufacturing costs in combination with those of flat-plate modules, both projected to their commercial potentials in the mid-1990's.

ADVISEMENT

This study presents an assessment of the future cost and efficiency potential of concentrator photovoltaic collectors in the mid-1990's and a comparison of these results with those of a previous assessment of flat-plate technology conducted early in 1983. Although there is a high level of confidence in the concentrator collector price projections determined in this study, at least two cautions are required in interpreting the results of the concentrator and flat-plate technology comparison.

This study is based on subjective assessments of the probabilities of technology potentials. In interpreting the probabilistic results, it is entirely possible that one technology with an assessed lower probability of achieving a given cost target may ultimately succeed in achieving that target, whereas a second technology with a higher assessed probability of success may fail. Probabilistic results display uncertainties in the technology projections, but do not necessarily provide conclusive forecasts of achievements.

Another caution is that the flat-plate study is now almost two years old. Based on flat-plate technology progress over the past two years and on the current funding environment, subjective probabilities of flat-plate technology commercial potential in the mid 1990's may have changed. An update of the previous flat-plate study is recommended for improved insight into the relative potentials for concentrating and two-axis tracking flat-plate photovoltaic arrays.

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SECTION I

INTRODUCTION AND SUMMARY

A. STUDY OBJECTIVES

The purpose of this study is to assess the relative economic potentials of concentrating and two-axis tracking flat-plate photovoltaic (PV) arrays for central-station applications in the mid-1990's. Its specific objectives are to provide information on concentrator PV collector probabilistic price and efficiency levels to illustrate critical areas of research and development (R&D) for concentrator cells and collectors, and to compare concentrator and flat-plate PV price and efficiency alternatives for several locations, based on their implied cost of energy.

To deal with the uncertainty surrounding research and development activities in general, a probabilistic assessment of commercially achievable concentrator PV collector efficiencies and prices (at the factory loading dock) is performed. The results of this projection are then compared with those of a previous flat-plate module price analysis from a systems-level perspective (Reference 1). To focus this analysis on specific collector alternatives and their implied energy costs for different locations, similar two-axis tracking designs are assumed for both concentrator and flat-plate options.

The results of this study provide the first comprehensive assessment of PV concentrator collector manufacturing costs in combination with those of flat-plate modules, both projected to their commercial potentials in the mid-1990's. It is expected that technical progress through R&D will be made over the years and that both absolute and relative costs will vary over time from levels projected in this study.

This study is designed to investigate future concentrator PV technology price potentials, given a probabilistic assessment of the manufacturing cost at each step in the production process, the attainable commercial component efficiency levels, and the probability of success of each production process alternative. Experts in various phases of concentrator photovoltaic collector R&D and manufacturing were interviewed about their probabilistic projections of the technology.

Using this analytical approach, several key concentrator module R&D issues are addressed, such as the value of high concentration ($\geq$500X), the relative potentials of different cell materials and structures, and the prospects for alternative lens production techniques. The results of this study are compared with the flat-plate PV price results in Reference 1. This comparison provides information that is expected to be useful to research centers in evaluating their concentrator R&D activities and in determining which technology options should be emphasized through R&D funding.

To the greatest extent practicable, the ground rules underlying the previous flat-plate collector analysis and the present concentrator analysis have been held constant. By using (1) a broad spectrum of experts in PV concentrator technologies as data sources, (2) a probabilistic structure for accepting and processing projections of technical and economic potential, (3) a model that has been validated in several previous analyses of research and development projects, and (4) a procedure in which equations and data developed during this study have been reviewed by other organizations, there is a high level of confidence in the concentrator collector price results presented here.

B. SCOPE

This study provides a look into the future prospects for PV concentrator collector prices, based on the insights of experts working with the technology. Probabilistic cost and efficiency projections are made for passively cooled, point-focus Fresnel lens collectors, assuming a commercial product in the mid-1990's. Component technology development activities are assumed to be completed by 1990-1992 to allow time for commercial process development and scale-up.

Concentrator collectors are evaluated at concentration levels of 200X, 500X, and 1000X. Lower concentration ratios (<200X) are assumed to be relevant for near-term applications rather than the longer-term central-station applications evaluated in this report. All of the major cell-device, cell-assembly, lens-assembly, and module-assembly technologies currently being investigated are included in the study. Cost estimates include all the capital, labor, and material costs relevant to a manufactured product f.o.b. the factory loading dock, including return on investment. Probabilistic collector prices, in dollars per peak watt, rated at a standard set of conditions, are the primary output of the first part of this study.

It is assumed that there is a sufficiently large demand for concentrator PV systems that the most critical economies of scale in manufacturing are captured. However, the potential market for concentrator PV technology is not addressed in this study.

A comparison of concentrator collector prices and efficiencies to previously projected prices and efficiencies of flat-plate collectors in 1995 is then made. The comparison assumes that both module technologies are placed on similar two-axis tracking structures. Other fixed and tracking flat-plate structures are not addressed here. Concentrator and flat-plate technologies in central-station applications are compared for several U.S. locations on the basis of delivered energy cost, assuming equivalent balance-of-system costs and efficiencies. For the purpose of this report, cell, module, and system reliability and lifetimes for all flat-plate and concentrator alternatives are assumed to be identical. The effect of different levels of module reliability are identified but not quantified in this study.

C. REPORT ORGANIZATION

The approach, assumptions and limitations of the analysis presented in this report are discussed in Section II. Section III presents a brief model description and a discussion of the selected concentrator module technology alternatives, input variables, and new input-data-related issues arising during the course of this study. The results of the concentrator module price analysis are displayed in Section IV. PV system prices are compared in Section V, based on the concentrator module price results shown in Section IV and previous flat-plate module price projections. Overall study conclusions are reviewed and recommendations for productive R&D efforts are made in Section VI.

Appendix A describes the SIMRAND model used in this analysis. Appendix B, describes input data distributions and constants. Results of the earlier flat-plate module price analysis shown in Appendix C are used in the system comparison (Section V).

D. SUMMARY OF RESULTS AND CONCLUSIONS

This study derives a number of research and development-related insights into concentrating PV collector and system technical and economic potential in the mid-1990's. Results of the concentrator collector price projections are summarized in this subsection, and associated energy costs for various locations are compared with the energy costs for two-axis tracking flat-plate collectors. Recommendations for future technology development and analysis based on the findings of this study are presented.

Concentrator PV collectors are projected to be able to achieve f.o.b. prices in the range of \$0.70 to \$1.50/W_p assuming large-scale manufacturing production in the mid-1990's. Figure 1 displays the cumulative PV concentrator collector price probabilities for 200X, 500X and 1000X concentration levels. High concentration alternatives (500X to 1000X) are shown to have significantly lower achievable costs than lower-concentration (200X) collectors. The lower-concentration modules are estimated to be approximately 50% more expensive (per peak watt) than their high-concentration counterparts. The primary savings for high-concentration collectors are in the cell and cell assembly value-added costs due to lower cell material requirements and higher cell efficiencies. The reliability of the high-concentration collector designs is still to be established.

Different cell technologies are shown to affect collector price significantly. Figure 2 displays the mean module prices for 1000X modules using the alternative cell technologies considered. Advanced silicon (e.g., point contact) and gallium arsenide cells are projected to be of lower cost per watt than either the mechanically stacked or monolithic multijunction cells. Although the multijunction cells have a higher efficiency potential, today's preliminary estimates of their future costs (in \$/cm^2) imply significantly higher module prices.

Concentrator systems with collector concentration ratios of 1000X, 500X and 200X are compared with two-axis tracking flat-plate systems in Southwestern (Phoenix), Southeastern (Miami) and Northeastern (Boston) locations, based on their respective costs of energy generated (see Figure 3) in levelized nominal dollars, assuming a 1982 base year. Due to the low levels of annual direct normal insolation falling in Northeastern and Southeastern locations, concentrators are calculated to have relatively high energy costs. They are, therefore, not well suited to applications in those

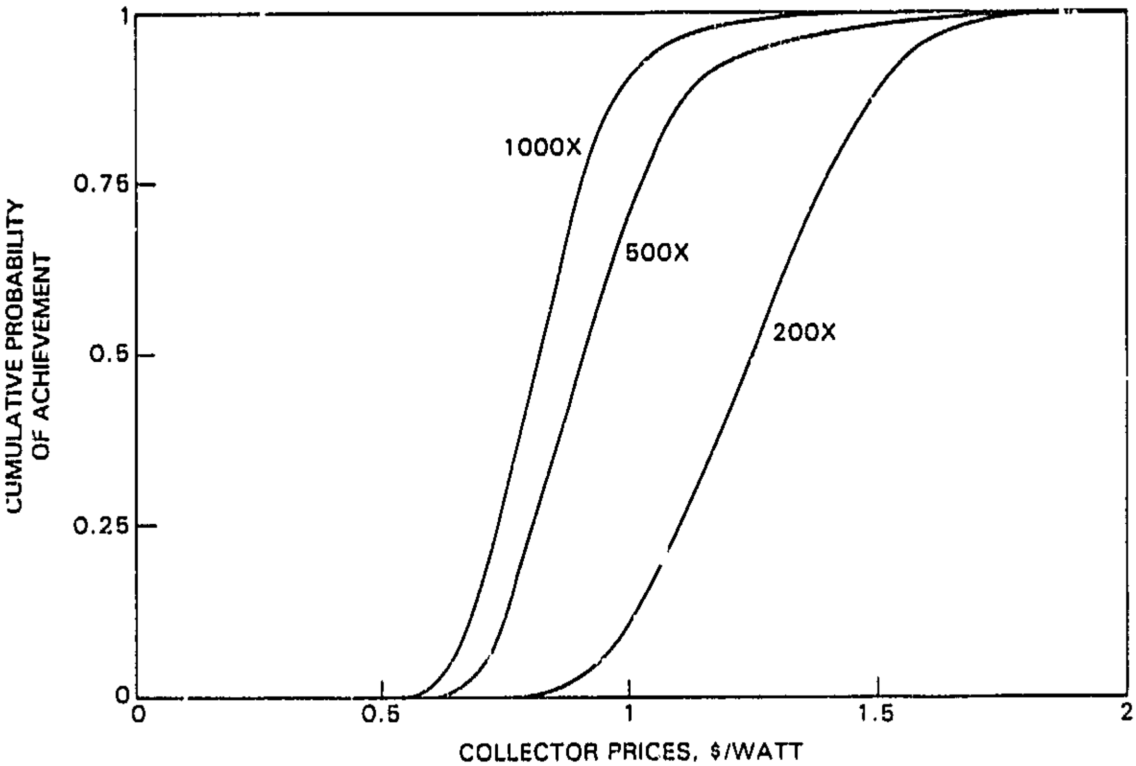


Figure 1. Concentrator Photovoltaic Collector Price Projections

geographic regions. Flat-plate collectors fare relatively better in these locations (i.e. they have lower energy costs) due to their ability to take advantage of diffuse as well as direct insolation.

Energy costs for all PV technologies are lowest in the Southwest due to the high levels of annual insolation, both total and direct normal. Two-axis tracking flat-plate systems are projected to be of uniformly lower cost than all concentrator alternatives in Phoenix across all percentile rankings. Flat-plate system energy costs are on the order of $0.05/kWh cheaper than the lowest-costing concentrator (1000X) alternative (approximately $0.02/kWh, expressed in real 1982 dollars).

A result consistently demonstrated by this analysis is the lower cost potential for high-concentration collectors (1000X and 500X) than for the lower-concentration (200X) alternatives. Therefore, it is recommended that concentrator technology research activities focus on developing highly reliable, low-cost, high-concentration collectors. Module reliability testing and analysis is an important complement to high concentration technology development activities. Development efforts for low-concentration ($\leq$200X) designs that can simultaneously provide information benefiting high-concentration alternatives may also be worthwhile.

Continued analysis of PV concentrator collector technical capability and manufacturing cost is strongly recommended. Extension and continued application of the methodology developed during this study is encouraged.

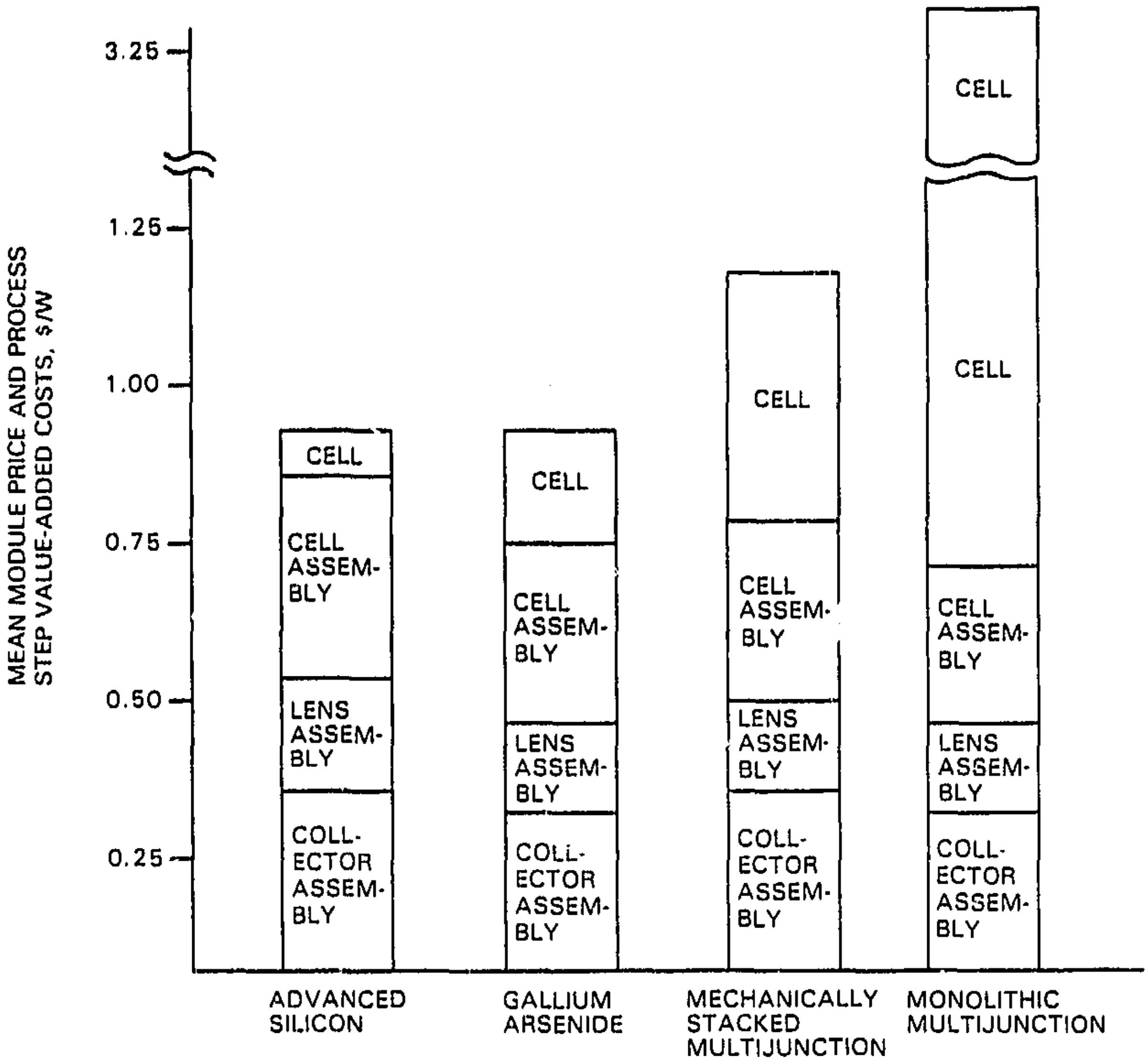
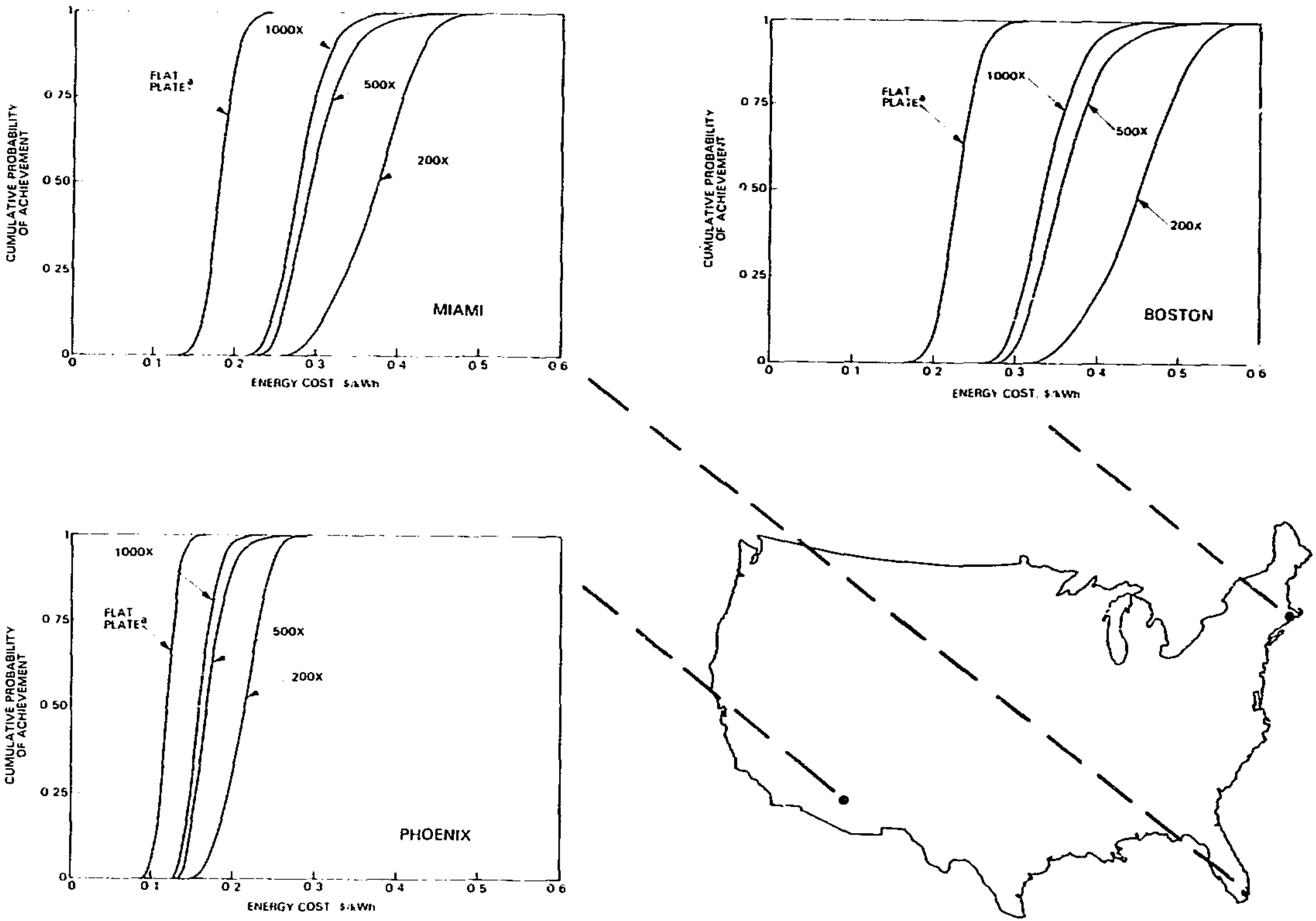


Figure 2. Mean Module Price and Breakdown for Mean Process Step Value-Added Cost per Watt for 1000X Concentrator



[a]Cumulative probabilities for flat-plate system energy costs from Reference 1 (note caveats in Advisement on p. iv).

Figure 3. Concentrator and Two-Axis Tracking Flat-Plate Energy Cost Comparison ($/kWh)

SECTION II

APPROACH, ASSUMPTIONS AND LIMITATIONS

A. APPROACH AND ASSUMPTIONS

This study is composed of two separate, sequential analyses. The first analysis is the projection of PV concentrator collector price and efficiency distributions in the mid-1990's; the second is a system-level comparison of PV concentrator collector results with previously reported flat-plate projections. Approaches and assumptions relevant for each analysis are summarized below.

1. Photovoltaic Concentrator Collector Projections

The assessment of PV concentrator collector prices projected to the mid-1990's is based on cumulative probability distributions of cost and efficiency, and on probability-of-success estimates. The distributions are supplied by technical experts in concentrator PV technology during an individual-interview process. Projections are made for each step in the concentrator module manufacturing process. Concentrator module price projections (f.o.b. the factory loading dock) include, to the extent possible, all relevant expenditures on capital, labor, and materials, as well as return on investment, general and administrative expenses, and income tax considerations. Technology development is assumed to proceed until approximately 1990-1992, at which time it is frozen and development of scaled-up commercial production processes begins for products to be available in the mid-1990's. For the purpose of this study, a concentrator collector is defined as the complete unit that fits onto a tracking-array support structure for a generic two-axis tracking array support structure that can alternatively accommodate a flat-plate PV module. In this report, the terms "module" and "collector" are synonymous.

The mid-1990's were selected as the basis for concentrator PV cost analysis for several reasons. Of primary importance is that high-concentration technologies are allowed time to reach a state of development sufficient for adoption and scale-up by industry. The 1990's are not, however, so far in the future that visibility of the technical path to that period is lost. It is assumed that funding for each technology option (by the National Photovoltaics Program and/or private industry) continues such that adequate financial resources are available for the orderly progression of technology development. In addition, a sufficiently large market size is assumed in that period that concentrator module manufacturers will be able to capture all important economies of scale in production. Due to the selection of the mid-1990's, many promising near-term, low-concentration (<200X) alternatives are excluded from the set of alternatives considered in this report because their costs are dominated by (i.e., higher than) the projected cost of longer-term high-efficiency modules. Long-term reliability of high concentration PV arrays is the subject of much debate. Lacking empirical data, this study assumes that all concentrator collectors have 30-year lifetimes and reliability equal to that of flat-plate collectors.

Concentrator module price projections are derived from the subjective estimates of probabilities made by technical experts for component costs and efficiencies from each step in the production process. Therefore, the analysis begins by decomposing the manufacturing process for point-focus Fresnel lens collectors at 200X, 500X, and 1000X concentration levels into a sequence of detailed production steps. The set of steps, cost and efficiency elements, and technology alternatives is shown in Table 1.

Each step in the manufacturing process is described by its unique set of parameters that influence the cost of production. Cumulative probability distributions of costs and component efficiencies, where appropriate, are collected for each technology alternative in the production step. Each expert's input distributions were accepted at face value. The only modifications of the raw input distributions were the use of standard financial parameters for comparability with the flat-plate study. It was not possible in the course of this study to achieve consensus on several parameter value distributions. Future analyses of this type should include such a consensus.

A Monte Carlo simulation is then performed to estimate the value-added cost distribution for each process step using the governing equation for that step (see III D). The governing equation for the total module price includes all relevant financial attributes (e.g., return on investment) as well as functional relationships that are dependent on concentration level, cell type and process yields. Total module price for a given process sequence is the sum of the value-added costs for each production step.

To take into account technological alternatives for each processing step, a network of feasible production paths is created. For each iteration of the Monte Carlo simulation, module prices are determined for all paths in the network. A mathematical screen is then used to select the most cost-effective PV concentrator module alternative path for that iteration. The screen combines module cost, module efficiency, and area-related balance-of-system (BOS), e.g., tracking structure, costs such that the module alternative that minimizes system cost per watt of installed capacity is selected. The price of the "winning" module is then entered into the cumulative module price distribution. This process is repeated for each iteration (typically 500) of the Monte Carlo simulation. The output of the Monte Carlo run is the cumulative probability distribution of module price. Module prices are expressed in 1982 dollars per peak watt (rated at 900 watts per square meter direct normal insolation and Nominal Operating Cell Temperature) f.o.b. the factory loading dock.

In many cases, there is less than a 100% certainty that a technology alternative will succeed by the mid-1990's. When the technology fails, a default value for the attribute (cost or efficiency) is required. Options for the default value for each technology alternative of each process step are: present-day values for the alternative, present-day values for a competing technology, or extremely high cost or low efficiency values depicting failure. If a failure occurs, the model will never select the technology as a "winner." For the purpose of this study, each technology option is judged independently (i.e., cross-benefits to one option resulting from research on competing options is not included as a benefit to the first option).

Table 1. Photovoltaic Concentrator Collector Production Steps and Technology Alternatives

Step	Cost and Efficiency Elements	Technology Alternatives
Cell	cell cost cell efficiency	baseline silicon advanced silicon gallium arsenide mechanically stacked multijunction monolithic multijunction
Cell Assembly	secondary optical element cost	glass, total internal reflection
	substrate cost	alumina or loaded alumina
	heat spreader cost	for 500X and 1000X only
	heat sink cost	for plastic housing for steel housing for aluminum housing (none)
	cell packaging cost	see note a
Lens Assembly	lens cost lens efficiency	compression-molded injection-molded lens film direct bond, polymer/glass
	antireflective coating cost	see note a
Collector Assembly	housing cost	plastic steel aluminum
	interconnects and bypass diodes cost	see note a
	collector assembly cost	see note a
	balance-of-module efficiency	including secondary optical elements, interconnects, etc.

Note a: includes capital, labor, and materials.

Although the governing equations and input data were developed specifically for this study, an existing model, Simulation of Research and Development Projects (SIMRAND), was used to perform the Monte Carlo simulation, process the data through the production paths, and generate the value-added and total price distributions. (Reference 2; see Section II.) This same model was used in the previous analysis of flat-plate PV module costs (Reference 1).

2. Comparison of Concentrator and Flat-Plate Photovoltaic Costs

Concentrator and flat-plate PV energy costs are compared for central-station applications for a number of locations in the United States. The approach is to use the results of the concentrator module study from this report and the flat-plate module study (Reference 1) in a systems-level comparison. It is assumed that a generic two-axis tracking system design exists and the per-unit cost and efficiency of all non-module components (both area-related and power-related BOS) are identical.

Two comparisons are performed. In the first, module price and efficiency projections are used in combination with the equal BOS cost assumption and the best available insolation data to estimate system energy costs (cents per kilowatt hour). Values for the remaining parameters in the energy cost equation will come from the values recommended for use in the National Photovoltaic Program Five-Year Research Plan (Reference 3). A second analysis that determines allowable concentrator collector cost and efficiency combinations based on projected flat-plate module costs and efficiencies is then performed. This analysis is consistent with the comparison technique devised by Sandia National Laboratories (Reference 4).

B. LIMITATIONS

This study provides a first detailed analysis of concentrator module prices in the mid-1990's in which the manufacturing environment is explicitly considered. Since this is a first study of the manufacturing environment, several limitations are placed on the study results. In many cases, adequate manufacturing process and capital equipment descriptions and/or costs were not available. This precluded the use of a standardized manufacturing cost model, based on capital, labor, materials, energy, and floorspace attributes (IPEG, Reference 5), as used previously in the flat-plate study. In place of direct use of the IPEG model for concentrator module pricing, typical values resulting from model calibration exercises with empirical data for flat-plate module technologies are used. Furthermore, some process steps were not separately costed, as the information was unavailable. In these cases (e.g., optical alignment and cell testing upon receipt from manufacturer), optimistic (i.e., low-cost) estimates of value added at the appropriate process steps are included. In addition, technology processes and innovative materials selected for incorporation in this study are based on current expectations, although future innovations in materials and production processes are also considered likely.

A major limitation of this study is the assumption of highly reliable, 30-year-lifetime modules across all cell alternatives and concentration levels. For some of the technology options, stable long-life multijunction cells have not been demonstrated in the laboratory. There are also potential reliability problems associated with metallization and encapsulation. Additionally, it has been shown that cell operating temperature can significantly affect module lifetime (Reference 6). This study makes no effort to quantify the effects of the differential cell temperatures on lifetime or cost of flat-plate and 200X, 500X and 1000X concentrator technologies; however the study did take cell temperature differentials into account in determining module efficiency. Also, concentrator module reliability is affected by condensation inside the module; the module price analysis does not treat these reliability differences in module housing design. Concentrator module reliability testing and analysis is an important subject for future work.

Several limitations are associated with the approach and methodology selected for this study. In particular, estimates of some concentrator technologies and production processes expected to be commercially available in the mid-1990's are highly speculative. The methodology uses subjective probability distributions from technical experts projecting today's laboratory and developmental technologies several years into the future. Although using probability distributions rather than single-point estimates provides more insight into the technical possibilities, an objective standard for calibrating inputs does not exist. Some experts are simply more optimistic, and some are more conservative, than others. One technique for attempting to calibrate inputs is by subjecting the distributions to a consensus process. Although a consensus process involving all of the experts in concentrator technology was not attempted in this study, this should be a goal of future efforts. In addition, the relative degrees of optimism among experts in concentrator and flat-plate technologies should be evaluated.

A number of technology-related limitations are also present. Only three concentration levels (200X, 500X, and 1000X) have been evaluated in this study, rather than all conceivable levels. Concentrator cell efficiency is assumed to be constant across all concentration levels. Furthermore, lens cost ($\$/m^2$ aperture), secondary optical-element cost, and bypass-diode cost are assumed not to vary by concentration level.

Another limitation concerns the definition of the module price that is determined. The calculated module price is a minimum required price to cover all costs of production, return on investment and taxes. It is not a projection of market price. Furthermore, the module price is estimated up to the factory loading dock. No costs are included for marketing and distribution expenses in the module price estimate. These expenses are included in the energy cost analysis.

In the comparison between concentrator and two-axis tracking flat-plate PV system energy costs, a number of issues are not addressed. For example, it is assumed, without restriction, that there are no differences in operations and maintenance costs, BOS efficiencies, tracker and control costs, and time-of-day value of energy output. Another limitation is the use of only three sites, one each for the Southwest, Southeast, and Northeast, for the system comparison. Finally, only a two-axis tracking flat-plate system design is considered in this comparison though one-axis tracking and fixed arrays are also viable technical alternatives for flat-plate collector systems.

SECTION III

SIMRAND MODEL DESCRIPTION AND TECHNOLOGY ALTERNATIVES

In this study the Simulation of Research and Development Projects (SIMRAND) methodology (Reference 2) is used to predict the mid-1990's price of concentrator photovoltaic modules. The module production process is decomposed into production steps: solar concentrator cell, cell assembly, lens assembly and collector assembly. These steps are further characterized by major cost and efficiency elements. Within each production step, alternative technologies are considered (Table 1). A network of alternative production paths is created in which a production path corresponds to a choice of a technology at each production step and a specification of a concentration level (Figure 4).

A. METHODOLOGY

The SIMRAND model is a general methodology that can be used to predict the cost of a product based on a probabilistic assessment of the costs of the processing steps needed to produce that product. If there are alternative ways to implement any or all of the production processing steps, a network of alternative production paths is created; SIMRAND then uses a Monte Carlo simulation to identify the most cost-effective production paths and to produce a cumulative distribution function of the cost of the product based on these paths. The inputs to the simulation are distributions of the costs of the production processing steps. In cases where the cost of a processing step is derived from several variables, distributions for these variables are input instead.

To describe the general SIMRAND computation in this study more fully, let $X_1,\ldots,X_m$ be the input variables (i.e., cost and efficiencies of the production processing steps); let P = number of alternative production paths; let $f_i(X_1,\ldots,X_m)$, $i = 1,\ldots,P$ be the cost of the product when the ith alternative production path is used. Let $g_i(X_1,\ldots X_m)$, $i = 1,\ldots,P$ be the balance of system cost when the ith alternative production path is used. Each Monte Carlo trial randomly chooses values for $X_1,\ldots X_m$ based on their input distributions and uses these values to compute $f_i(X_1,\ldots,X_m)$ and $g_i(X_1,\ldots,X_m)$ for $i = 1,\ldots,P$. The distribution from which the values for X_k are chosen may depend on i.

Then

$$T = \min \quad [f_i(X_1,\ldots,X_m) + g_i(X_1,\ldots,X_m)] \text{ for } i = 1,\ldots,P$$

is computed. T is by definition the system cost of the most cost-effective production path for that random choice of values for $X_1,\ldots,X_m$. The value of product cost (i.e., f_i for some i) corresponding to the most cost-effective path is added to a cumulative distribution function being tallied. The output of SIMRAND is the tallied cumulative distribution function. (See Appendix A for further details of SIMRAND pertinent to this study.)

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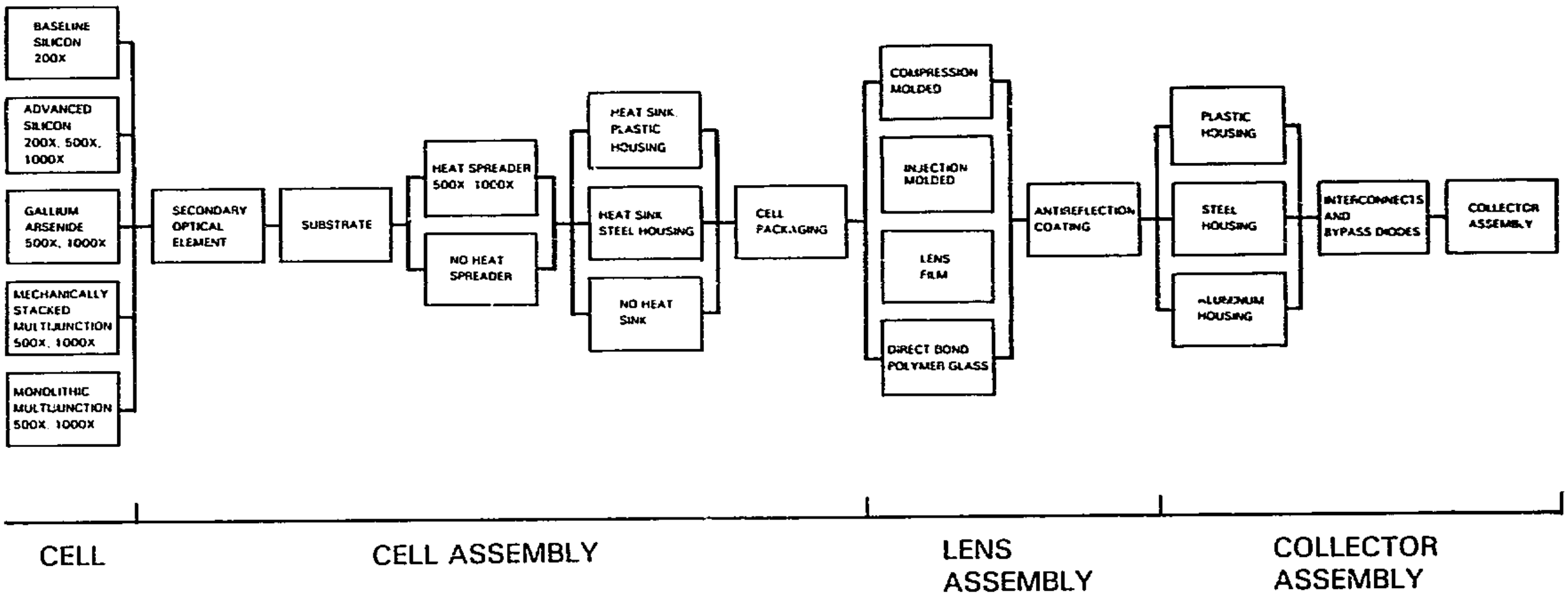


Figure 4. Concentrator Collector Production Network

B. CONCENTRATOR COLLECTOR MANUFACTURING NETWORK AND TECHNOLOGY ALTERNATIVES

The manufacturing process for concentrator PV collectors can be described by means of a series of production steps. Each technology alternative available for a given production step forms a node in an overall production network. Technology alternatives and the production network are described below.

In this study, technologies used in two-axis tracking, point-focus Fresnel lens concentrator collector designs at 200X, 500X, and 1000X concentration levels are evaluated. The assessment of concentrator collector prices begins with a description of the manufacturing process. Concentrator collector production process steps include concentrator cell, cell assembly, lens assembly, and collector assembly. Consistent with standard industry practice, this study allows components made more cheaply by other manufacturers to be procured by the collector manufacturer. In today's, and the projected mid-1990's, concentrator PV collector industry, these components typically include the concentrator cell, secondary optical element, and Fresnel lens.

Concentrator Cell Step: Concentrator cells are described by their cost and efficiency. Baseline silicon cells represent the cells available in present-day commercial modules projected to the mid-1990's. Advanced silicon cells are high-concentration cells having a point-contact geometry of multiple p-n junctions. Gallium arsenide cells and two types of multijunction cells, mechanically stacked and monolithic, are also included. In this study, module manufacturers are assumed to purchase cells from cell suppliers. Cell manufacturing process steps are, therefore, not included in this analysis.

Cell Assembly Step: In this step components, either purchased or produced, are assembled into a complete cell. A secondary optical element (SOE) is projected to be used in all cases for concentration levels of 200X or greater. Total-internal-reflection and reflective secondaries are both being used in today's R&D efforts. In this analysis, a cost projection to the mid-1990's for SOE devices is used. Substrate costs reflect alumina or loaded alumina. A heat spreader is required for both the 500X and 1000X collector designs.

Heat sinks are required, but their cost is dependent on the housing material selected. For equivalent heat-rejection capability, the heat sink for a plastic housing would be larger, and thus more expensive, than for a steel housing. If an aluminum housing is used, the aluminum pan provides the function of the heat sink; thus the heat sink is not separately identified and costed. The cost of cell assembly fabrication includes the capital equipment, labor, and miscellaneous materials required.

Lens Assembly Step: Lens types are differentiated by their cost and optical efficiency. Lens production alternatives include compression molding, injection molding, lens film, and direct molding of polymer to glass. An antireflective coating is assumed to be applied to the back surface of the lens to increase transmittance efficiency.

Collector Assembly Step: Concentrator module housing options include plastic, steel, and aluminum. Plastic housings are used in today's point-focus Fresnel lens modules and are a design option for high-concentration collectors as well. Steel housings are another design alternative. Though more expensive than plastic, cost savings are expected from reduced heat-sink requirements for steel housings. Aluminum housings, which do not require additional heat sinks, are the final alternative considered. Other components of the module include interconnects and bypass diodes. Assembly of the completed module proceeds with cost estimates for required capital equipment, labor, and miscellaneous materials and an estimate of any power (efficiency) losses within the module not identified in any of the previous production steps.

The collection of these steps and technology alternatives is displayed in the PV concentrator collector production network shown in Figure 4. Feasible paths through the production network are determined by concentration level and explicit linkages. Given these dependencies, there is a total of 120 allowable paths through the network (see Appendix A).

Cell and cell assembly steps have elements dependent on the chosen concentration level. For the 200X concentrator alternative, only baseline silicon and advanced silicon cell alternatives are considered. In addition, the 200X cell assembly design does not require a heat spreader. For the 500X and 1000X concentrators, advanced silicon, gallium arsenide, mechanically stacked multijunction and monolithic multijunction cells are included. A heat spreader is required for the 500X and 1000X concentrator modules. Each concentration level also has its own unique set of variables describing the physical and thermal properties of the cell and cell assembly.

The choice of the heat sink is linked to the module housing material type. The alternative heat-sink designs are for plastic and steel housings.

C. MODEL INPUT DESCRIPTIONS

The input parameters used to determine concentrator PV module prices are discussed in this section. These inputs are supplied by experts in concentrator PV technology and reflect their opinions regarding the potential costs and efficiencies of various concentrator collector components, assuming high volume production in the mid-1990's. Input variable distributions are collected in the most natural units for each step in the production process (e.g., cell costs are in $\$/cm^2$ and lens costs are in $\$/m^2$ of aperture). Actual values for variables and constants used in this analysis are shown in Appendix B.

List 1 below displays the input variables used in this study. Each of these variables has one or more probability distributions associated with it (List 2). For example, cell cost (X_1) and cell efficiency (X_2) have separate distributions for each type of cell technology considered (baseline silicon, advanced silicon, gallium arsenide, mechanically stacked multijunction, monolithic multijunction). On the other hand, SOE costs are expected to be independent of the alternative technologies considered, so there is only one probability distribution for the SOE. Cumulative probability distributions for each variable were collected from experts in

List 1. SIMRAND Input Variables

X_1	Cell cost ($\$/cm^2$)
X_2	Cell efficiency (fraction)
X_3	Secondary optical element ($, each)
X_4	Substrate for cell assembly ($\$/cm^2$ of cell)
X_5	Heat spreader ($, each)
X_6	Heat sink ($\$/m^2$ of aperture)
X_7	Cell packaging ($/cell assembly)
X_8	Lens cost ($\$/m^2$ of aperture)
X_9	Lens efficiency (fraction)
X_{10}	Housing fabrication ($\$/m^2$ of aperture)
X_{11}	Interconnects and bypass diodes cost ($/cell assembly)
X_{12}	Module construction cost ($\$/m^2$ of aperture)
X_{13}	Balance of module efficiency (fraction)
X_{14}	Antireflective (AR) coating for lens back ($\$/m^2$ of aperture)
X_{15}	Lens efficiency increase due to AR coating (fraction)

List 2. SIMRAND Distributions

D_1	Baseline silicon cell cost ($\$/cm^2$)
D_2	Baseline cell efficiency
D_3	Advanced silicon cell cost ($\$/cm^2$)
D_4	Advanced silicon cell efficiency
D_5	Gallium arsenide cell cost ($\$/cm^2$)
D_6	Gallium arsenide cell efficiency
D_7	Mechanically stacked multijunction cell cost ($\$/cm^2$)
D_8	Mechanically stacked multijunction cell efficiency
D_9	Monolithic multijunction cell cost ($\$/cm^2$)
D_{10}	Monolithic multijunction cell efficiency
D_{11}	Secondary optical element costs ($, each)
D_{12}	Substrate ($\$/cm^2$)
D_{13}	Heat spreader ($, each)
D_{14}	No heat spreader (200X)
D_{15}	Heat sink for plastic housing ($\$/m^2$ of aperture)
D_{16}	No heat sink
D_{17}	Cell packaging costs ($/cell assembly)
D_{18}	Compression-molded lens cost ($\$/m^2$)
D_{19}	Compression-molded lens efficiency
D_{20}	Injection-molded lens cost ($\$/m^2$)
D_{21}	Injection-molded lens efficiency
D_{22}	Lens film cost ($\$/m^2$)
D_{23}	Lens film efficiency
D_{24}	Direct-bond polymer/glass lens cost ($\$/m^2$)
D_{25}	Direct-bond polymer/glass lens efficiency
D_{26}	Plastic housing ($\$/m^2$)
D_{27}	Aluminum housing ($\$/m^2$)
D_{28}	Interconnects and bypass diodes ($/cell assembly)
D_{29}	Module assembly ($\$/m^2$ of aperture)
D_{30}	Balance-of-module efficiency
D_{31}	Steel housing ($\$/m^2$ of aperture)
D_{32}	Heat sink for steel housing ($\$/m^2$ of aperture)
D_{33}	Antireflective coating for lens back ($\$/m^2$ of aperture)
D_{34}	Antireflective coat, lens efficiency increase

concentrator module technology. A single cumulative distribution for each variable was obtained by combining the collected distributions so that each expert's opinion was given equal weight.

It is assumed that module manufacturers buy cells, secondary optical elements and lenses from suppliers. Thus, cumulative probability distributions for cell cost (X_1), secondary optical element cost (X_3), and lens cost (X_8) reflect the purchase price available to module manufacturers plus a 20% add-on to cover the module manufacturer's general and administrative expenses and profit. The cell efficiencies (X_2) projected for each technology are held constant across the 200X, 500X and 1000X concentration levels. Cost projections for the substrate (X_4), heat spreader (X_5), heat sink (X_6), cell packaging (X_7), housing (X_{10}), interconnects and bypass diodes (X_{11}), module construction (X_{12}), and antireflective coating (X_{14}) include the cost of capital equipment and return on investment in addition to the cost of materials and labor. In cases where only materials and labor costs were supplied for these variables, a manufacturing cost multiplier of 1.5 is used based on IPEG (Reference 5) calibrations with other manufacturing cost analyses. The cost of the the antireflective coating on the back of the lens (X_{14}) reflects an IPEG analysis of magnesium fluoride deposited on acrylic lens material (PMMA) using an evaporative deposition process. Lens efficiency (X_9) and the incremental efficiency supplied by the antireflective coating (X_{15}) are supplied separately. Any losses internal to the module that are not included in the efficiency variables discussed above (e.g., internal wiring or secondary optical element efficiency) are aggregated in the balance-of-module efficiency variable (X_{13}).

Each input variable also has an associated probability of the related technology failing. A technology is considered failed if a repeatable commercial manufacturing process is not foreseen for the mid-1990s. If the failure probability is greater than zero, then a default value for the attribute is required. Default values for a failed technology in any process step reflect either present-day values for the technology, present-day values for a competing technology, or very high cost or low ficiency values depicting failure. If a failure occurs, the technology will not appear as the most cost-effective production path in the model.

D. PROCESS STEP EQUATIONS

The SIMRAND process step equations are used to aggregate process step costs and efficiencies to a total product price and are shown below. The value-added cost at each step in the production process is determined by normalizing the various inputs to a common unit of \$/watt. To the extent possible, value-added costs and total module price include the required capital equipment, labor and materials cost, and return on investment. Cost inputs are converted to \$/watt for each cost element by means of the appropriate cost factor C_1, C_2, or C_3.

SIMRAND PROCESS STEP EQUATIONS

$$\text{Cell cost} = (X_1 \times 10000) / (C_1 \times \text{ACTIVE} \times Y_1 \times Y_2 \times \text{DEFL}) \quad (1)$$

Cell assembly cost (excludes cell cost)

$$\begin{aligned} &= X_3 / (C_3 \times Y_3 \times \text{DEFL}) \\ &\quad + (X_4 \times 10000 \times SC) / (C_1 \times \text{ACTIVE} \times Y_6 \times \text{DEFL}) \\ &\quad + X_5 / (C_3 \times Y_4 \times \text{DEFL}) \\ &\quad + X_6 / (C_2 \times Y_5 \times \text{DEFL}) \\ &\quad + X_7 / (C_3 \times Y_7 \times Y_8 \times \text{DEFL}) \end{aligned} \quad (2)$$

$$\text{Lens assembly cost} = (X_8 + X_{14}) / (C_2 \times Y_9 \times Y_{10} \times \text{DEFL}) \quad (3)$$

$$\begin{aligned} \text{Module assembly cost} &= X_{10} / (C_2 \times Y_{11} \times Y_{12} \times \text{DEFL}) \\ &\quad + X_{11} / (C_3 \times Y_{13} \times \text{DEFL}) \\ &\quad + X_{12} / (C_2 \times Y_{14} \times \text{DEFL}) \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Total module price} &= \text{Cell cost} \\ &\quad + \text{Cell assembly cost} \\ &\quad + \text{Lens assembly cost} \\ &\quad + \text{Module assembly cost} \end{aligned} \quad (5)$$

where ACTIVE = the fraction of the cell area that is active
SC = the required ratio of substrate area to cell area
DEFL = appropriate Gross National Product Implicit Price Deflator

CONVERSION FACTORS

C_1 = watts/m^2 of cell area
= DNSI x module efficiency x concentration ratio (6)

C_2 = watts/m^2 of lens aperture area
= DNSI x module efficiency (7)

C_3 = watts/cell assembly
= DNSI x module efficiency x lens area (8)

where

DNSI = direct normal solar irradiance = 900 W/m^2

module efficiency
$= X_2 \times (X_9 + X_{15}) \times X_{13} \times$ (1 + temperature coefficient x temperature difference) x LC (9)

LC = laboratory-to-commercialization cell efficiency correction factor
(1 + temperature coefficient x temperature difference) = temperature correction factor to correct cell efficiencies to SOC

Costs that are given in $/cm^2 of cell area are multiplied by 10,000 and then divided by C_1; costs given in $/m^2 of lens aperture are divided by C_2; costs given in $/cell assembly are divided by C_3. The resulting $/watt amounts reflect a module rated at 900 watts/m^2 of direct normal insolation and Nominal Operating Cell Temperature (Reference 7).

To account for the effects of yield rates on the cost of a production step, each equation is divided by one or more of the yield terms, $Y_1,\ldots,Y_{14}$ (List 3). Multiple yields for a single production process step indicate the potential for downstream processes affecting the cost of a previous process step (e.g., cell assembly yield affects the amount, and thus the cost, of cells used). If cost inputs are based on a different year's dollar than the required output prices, they must be inflated or deflated by the appropriate Gross National Product Implicit Price Deflator. In this analysis, cost inputs are in 1984 dollars and are deflated to the required 1982 dollars. The value-added cost and resulting module price equations used to aggregate the input variables are in the SIMRAND process step equations above. The resulting sum, total module price, is the final price at the factory loading dock including all production costs and return on investment.

A number of constants are used in this analysis to calculate the size and cost of concentrator module components (see List 3). Several constants depend on the concentration level being evaluated. These constants relate to the cell and cell assembly as either sizing parameters (cell active-area ratio and ratio of substrate area to cell area) or thermal parameters (cell operating temperature above ambient and coefficient of cell efficiency with respect to cell temperature). Manufacturing-related parameters have also been included. In particular, a cell-type-specific correction for potential laboratory efficiency to achievable efficiency in a manufacturing environment and a manufacturing yield for each step in the production process are included.

Appendix B contains the input values for all cost and efficiency distributions and technology constants. In some cases, there was no consensus on technology potential. When this occurred, the data were not smoothed; multimodal distributions were used. Historically, wide variances in the perception of a technology's potential are reduced as the technology moves from laboratory research toward commercial product.

E. CONCENTRATOR PV COLLECTOR PRICE OPTIMIZATION

The SIMRAND methodology will identify the most cost-effective production paths in a network of alternative production paths. In this study, a production path corresponds to a collector design, i.e., a choice of cell type, cell assembly type, lens type, housing type, and concentration level. For example, a 500X GaAs module in a plastic housing with a compression-molded lens is a production path. The most cost-effective path is the path that achieves the lowest system-level cost where

system-level cost = total module price + area-related balance-of-system cost.

List 3. Model Constants

Concentration level (200X, 500X, 1000X)
  Cell and cell assembly sizing
    Substrate-to-cell area ratio, fraction
    Cell active area ratio, fraction
  Cell thermal parameters
    Cell temperature above ambient, ^{o}C
    Cell efficiency coefficient vs cell temperature, fraction/^{o}C

Manufacturing parameters
  Laboratory-to-commercialization cell efficiency correction, fraction
  Manufacturing yields

Y_1	Cell yield due to cell assembly step
Y_2	Cell yield due to module assembly step
Y_3	SOE yield due to cell assembly step
Y_4	Heatspreader yield due to cell assembly step
Y_5	Heatsink yield due to cell assembly step
Y_6	Substrate yield due to cell assembly step
Y_7	Cell packaging yield due to cell assembly step
Y_8	Cell packaging yield due to module assembly step
Y_9	Lens yield due to lens assembly step
Y_{10}	Lens yield due to module assembly step
Y_{11}	Housing fabrication yield
Y_{12}	Housing fabrication yield due to module assembly step
Y_{13}	Interconnects and diodes yield due to module assembly step
Y_{14}	Module assembly yield due to module assembly step

A system-level cost minimization was selected in preference to a module-level cost minimization because the system-level costs more accurately reflect the trade-offs between the module technologies. The reason for this is that the area-related BOS cost ($/watt) depends on the module efficiency. In this equation, BOS costs not affected by module efficiency are not considered. The value selected for the area-related balance of system cost term is shown in Appendix B.

Each run of the SIMRAND computer program consists of 500 Monte Carlo trials. In each trial the total module cost and the cost of each production step is computed for each production path. The result of each trial is the determination of the optimal production path from a set of alternative production paths, and the computation of the total module price and the value-added cost of each production step for the optimal production path. The total module price and the production-step costs for the optimal production path are accumulated for each trial.

The output of a SIMRAND run is the cumulative distribution function for the price of an optimal-path concentrator module and the histogram of the frequency of selection of each of the alternative paths as the optimal path. For example, if the set of alternative paths is restricted to considering only those paths that use an advanced-silicon-cell technology, the resulting module price cumulative distribution function is the distribution of the total module price of an advanced-silicon module given that one always prefers the advanced-silicon module that will minimize system costs.

SECTION IV

CONCENTRATOR COLLECTOR PRICE ANALYSIS

A. AGGREGATE COLLECTOR PRICE RESULTS

Probabilistic concentrator collector price estimates (1982 $\$/W_p$) for commercial modules in the mid-1990's, assuming large-scale production, are displayed and evaluated in this section. A range of cell, lens, and module types and concentration levels are included. Results are based on the equations and data described above and the Monte Carlo simulation that selects the most cost-effective collector design from each of 500 iterations. The total prices generated by the SIMRAND computer program runs with 500 Monte Carlo trials vary by approximately ± \$0.01 due to the statistical error introduced by using only a finite number of Monte Carlo trials. Energy costs associated with the projected collector prices and efficiencies are evaluated in Section V.

Figure 1 presents the aggregate concentrator collector price results for all technologies at concentration levels of 1000X, 500X and 200X. The cost-reduction potentials of high (1000X and 500X) concentrations when compared with 200X concentration is clearly displayed. For any potentially achievable module price (<\$1.80/W_p) the cumulative probability of attaining that price is greater for higher levels of concentration, and highest at 1000X. For example, the cumulative probability of achieving a module price of \$1.00/W_p or less (in 1982 dollars) is approximately 90% for 1000X, 67% for 500X, and 10% for 200X. At a lower collector price (e.g., \$0.75/W_p), the cumulative probabilities are 25% for 1000X, 10% for 500X, and 0% (not attainable) for 200X. Reading Figure 1 in the opposite direction, the collector price associated with a specified percentile ranking is reduced for increasing concentration level. For example, at the median (50th percentile, 50% cumulative probability) the cost-reduction potentials for 1000X and 500X concentration levels over the 200X level are \$0.45/W_p and \$0.35/W_p, respectively.

B. PRICE RESULTS, 1000X COLLECTORS

Value-added costs for each manufacturing process step in the production of 1000X concentrators, as well as total collector prices and efficiencies, are summarized in Table 2. The table displays the values resulting from the Monte Carlo simulation at the 10th, 25th, 50th, 75th and 90th percentiles, and also, for the mean, standard deviation, minimum and maximum amounts. The mean 1000X collector price is \$0.85/W_p, the mean module efficiency is 18.4% at SOC, and each production step contributes the following mean value-added costs:

Production Step	1982 $\$/W_p$	Percentage of Total
Cell	0.10	12
Cell Assembly	0.26	31
Lens Assembly	0.15	18
Collector Assembly	0.33	39
Mean Total Collector Price	0.85	100

Table 2. Prices and Value-Added Costs by Production Process Step (1982 $\$/W_p$) for 1000X Collectors

	Cell Value-Added	Cell Assembly Value-Added	Lens Assembly Value-Added	Collector Assembly Value-Added	Total Collector Price	Collector Efficiency at SOC
Mean	0.104	0.263	0.152	0.328	0.848	0.184
Std. Deviation	0.091	0.071	0.051	0.062	0.141	0.016
Minimum	0.011	0.087	0.064	0.201	0.579	0.136
10th percentile	0.034	0.175	0.102	0.249	0.690	0.162
25th percentile	0.058	0.212	0.122	0.283	0.756	0.173
50th percentile	0.082	0.263	0.141	0.325	0.823	0.186
75th percentile	0.106	0.322	0.179	0.373	0.934	0.196
90th percentile	0.236	0.351	0.208	0.414	1.022	0.201
Maximum	0.603	0.454	0.544	0.545	1.687	0.229

Figure 4 displays the elements of each process step. For the 1000X concentrator, collector assembly costs contribute the largest amount to mean total collector price, followed by the cell assembly lens assembly and then the cell. Table 2 also shows that the process step having the greatest variance in value-added cost, in both absolute and relative terms, is the concentrator cell step. Note that the percentile rankings of value-added costs for the process steps shown in Table 2 do not add to total collector price, as the percentiles are determined independently. Similarly, module efficiency at SOC is ranked independently of price in this table. (See Equation 9 for functional relationship of module efficiency components. Collector prices and efficiency in combination are discussed below).

Table 3 displays the winning paths from the Monte Carlo simulation using the production network for 1000X collectors. (Refer to Appendix A and Tables A-1 and Lists 1 and 2 for explanation and coding of path numbers).

The results in Table 3 provide the following summary of technologies (Table 4) based on the number of winning paths using the specified cell, lens or housing technological alternative (500 winners per Monte Carlo simulation).

The dominant paths through the network are concentrator collector designs using gallium arsenide cells and plastic housing with injection-molded, lens film and direct-bonded polymer/glass lenses (paths 78, 79, and 80

Table 3. Path Selection Histogram for 1000X Collectors

Path No.	No. of Selections	Path No.	No. of Selections	Path No.	No. of Selections	Path No.	No. of Selections
73	0	85	0	97	0	109	4
74	33	86	0	98	4	110	29
75	23	87	0	99	6	111	18
76	16	88	0	100	7	112	27
77	0	89	1	101	0	113	0
78	64	90	29	102	0	114	8
79	44	91	11	103	0	115	3
80	36	92	15	104	0	116	3
81	0	93	0	105	0	117	0
82	10	94	28	106	14	118	0
83	8	95	14	107	8	119	0
84	4	96	21	108	12	120	0

respectively), collector designs using advanced silicon cells and injection-molded lenses with plastic and aluminum housings (paths 74 and 90, respectively) and collector designs using gallium arsenide cells and injection-molded lenses, with steel housings (path 110). The ordinal ranking of any path can be inferred from Table 3. It should be noted that at no time is the collector design with the monolithic multijunction cell technology selected, as the module cost is so much greater than for those using alternative cells. This will be explored in greater depth below.

Cumulative probability distributions of prices for 1000X concentrator collectors, disaggregated by cell technology, are shown in Figure 5. A number of insights from this figure are obvious:

(1) Cumulative price probabilities for modules with advanced silicon and gallium arsenide cells are virtually identical, though there is a higher probability that gallium arsenide technologies will cost more than $\$1.00/W_p$.

Table 4. Summary of Technologies, 1000X Collectors

Technological Alternative	Number of Winners	Path Numbers
Cell		
Advanced Si	162	73-76, 89-92, 105-108
GaAs	285	77-80, 93-96, 109-112
Mechanically Stacked Multijunction	53	81-84, 97-100, 113-116
Monolithic Multijunction	0	85-88, 101-104, 117-120
Lens		
Compression-Molded	5	73,77,81,85,89,93,97,101, 105,109,113,117
Injection-Molded	219	74,78,82,86,90,94,98,102, 106,110,114,118
Lens Film	135	75,79,83,87,91,95,99,103, 107,111,115,119
Direct-Bond Polymer/Glass	141	76,80,84,88,92,96,100,104, 108,112,116,120
Housing		
Plastic	238	73-88
Aluminum	136	89-104
Steel	126	105-120

(2) Mechanically stacked multijunction cell technologies appear to have only a small potential to surpass gallium arsenide and advanced silicon alternatives. Mean module price differences between these options are about $0.30/W_p$. In addition, the flatter slope of this multijunction cell technology reflects greater uncertainty in the price projection.

(3) Monolithic multijunction cell technologies are conspicuously absent from the figure. The price range is $2.78/W_p$ (minimum) to $4.00/W_p$ (maximum), with a mean collector price of $3.32/W_p$. Although monolithic multijunction cells have the highest median efficiency of all cells considered, their projected high cost of cell material ($25/m^2$ plus 20% for general and administrative expenses and profit) overwhelms their efficiency advantage.

Figure 2 presents the mean 1000X concentrator collector prices and process step value-added costs for the different cell technologies. Although advanced silicon and gallium arsenide total collector prices are the same, the costs associated with each production step are seen to vary in a consistent manner. Gallium arsenide cell costs (in $/W_p$) are more than 2.5 times as expensive as advanced silicon cell costs, but this cost advantage is cancelled

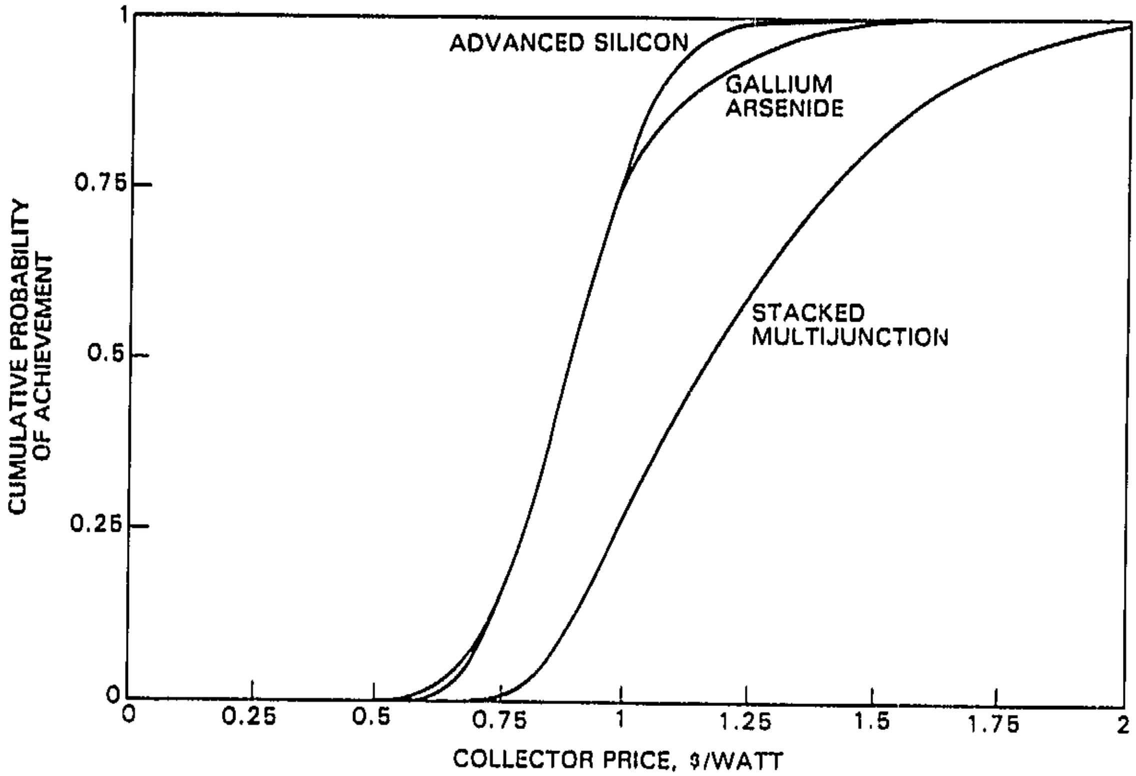


Figure 5. Prices, 1000X Collectors

by the higher efficiency of gallium arsenide, which reduces cell assembly, lens assembly, and collector assembly costs (in $\$/W_p$). Monolithic multijunction cell costs are shown to be an unacceptable $\$2.60/W_p$. Allowable costs for monolithic multijunction cells are evaluated below. In general, the multijunction cell material cost projections are of a high level of uncertainty.

Monolithic multijunction cell costs must be reduced dramatically for the price of 1000X concentrator collectors having such cells to be competitive with alternative 1000X technologies. The cumulative module price probabilities parameterized by monolithic multijunction cell cost are shown in Figure 6. Superimposed is the 1000X curve from Figure 1. By requiring the median module price for the 1000X monolithic multijunction cell collector to equal to the median module price on the 1000X curve, an allowable cost for the cell can be determined. Using this criterion, the allowable cost of a monolithic cell to be competitive with the other cell technologies is approximately $\$1.30/cm^2$. Any module price curve to the left of the 1000X curve would make the monolithic multijunction cell a preferred (i.e., more cost-effective) technology for 1000X collectors.

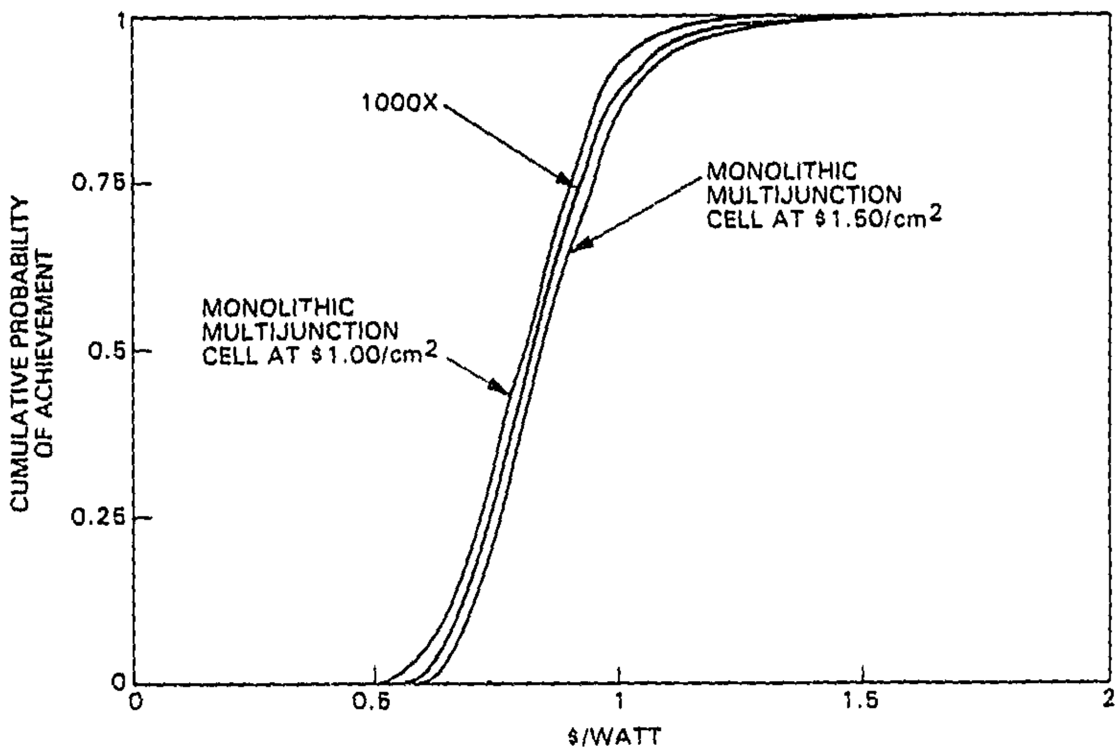
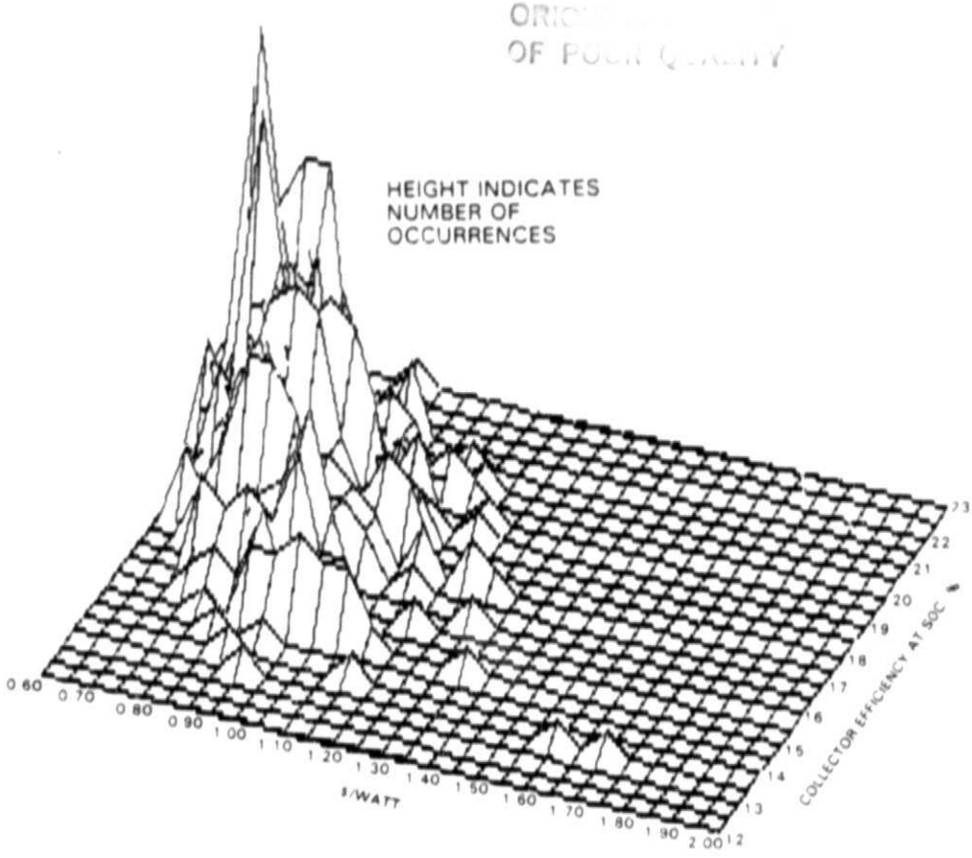


Figure 6. Cumulative Probability Curves of the Price of Concentrator Collectors Using Monolithic Multijunction Cell Technology, Compared with 1000X-Module Prices for Advanced Si, GaAs, or Mechanically Stacked Multijunction Technologies

Thus far, collector prices and efficiencies have been presented as independent cumulative probability distributions. The analysis procedure also allows prices and efficiencies to be displayed in combination. For each iteration of the Monte Carlo simulation, a single projected price and efficiency are calculated. These values are collected into a histogram. Figure 7 displays this histogram graphically and numerically for 1000X collectors. As discussed above, collector efficiencies at Standard Operating Conditions (SOC) (900 W/m^2, NOCT, Reference 7) are determined from the cell efficiency at Standard Test Conditions (STC) (1000 W/m^2, 25^{o}C cell temperature, AM1.5), lens efficiency, antireflective (AR) coating efficiency, balance-of-module efficiency, cell temperature-related efficiency correction to SOC, and a laboratory-to-commercial cell efficiency correction factor (see Equation 9).

Figure 7 indicates that the largest grouping of 1000X collector price and efficiency pairs is clustered between \$0.70 and \$0.85/W_p and 0.18 and 0.195 module efficiency at SOC (900 W/m^2 direct normal insolation and 20^{o}C ambient air temperature).



Collector Price, $/W_p$	Collector Module Efficiency at SOC, %																					
	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23
0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	1	3	0	0	0	0	0
0.65	0	0	0	0	0	0	0	0	0	0	3	2	6	3	5	6	4	2	0	1	0	0
0.70	0	0	0	0	0	0	0	0	0	2	1	6	4	6	18	6	3	3	0	0	2	0
0.75	0	0	0	0	0	0	1	4	1	4	6	4	16	11	11	8	2	0	0	3	2	0
0.80	0	0	0	0	0	1	2	3	1	8	8	9	10	5	13	7	2	2	0	0	0	0
0.85	0	0	0	0	1	0	1	4	3	8	5	10	5	10	13	8	4	1	0	0	0	0
0.90	0	0	0	1	0	3	4	3	4	6	4	9	9	3	5	5	2	1	0	0	1	1
0.95	0	0	1	0	1	3	1	6	7	3	4	4	8	4	4	0	3	0	3	0	0	0
1.00	0	0	0	0	0	4	1	2	3	3	3	2	5	2	1	2	2	0	0	0	0	0
1.05	0	0	0	0	0	3	0	2	0	2	2	4	0	1	3	1	0	0	0	0	0	0
1.10	0	0	0	0	0	3	0	0	0	0	0	3	2	1	0	2	0	1	0	0	0	0
1.15	0	0	0	1	0	1	0	0	0	1	2	0	0	0	0	1	1	0	0	0	0	0
1.20	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0
1.25	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
1.30	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
1.35	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7. Price and Efficiency Combinations, 1000X Collectors

C. PRICE RESULTS, 500X COLLECTORS

Collectors at 500X concentration level include all of the same components, costs per unit, and efficiencies as the 1000X collectors. Physical and thermal properties of the cell and cell assembly are, however, different (see list 3 and Appendix B). Table 5 displays the collector price and process step value-added costs for 500X collectors. The mean collector price is $0.96/$W_p$, or $0.11/$W_p$ greater than the 1000X collector. Cell and cell assembly value-added costs are shown to be more expensive for the 500X collector than the 1000X collector due the larger cell area required. Except for variations due to the random number sequence, the lens and collector assembly value-added costs and collector efficiencies are the same for 500X and 1000X technologies. Total collector prices are therefore always higher for 500X than for 1000X. A reasonable inference is that the production processes needed to manufacture reliable 1000X concentrators are the preferred alternative, with lower (e.g., 500X) concentration being an alternative if the 1000X alternative is not successful.

Table 6 presents the winning paths from the Monte Carlo simulation using the production network for 500X collectors (refer to Appendix A and Lists 1 and 2 for coding of path numbers).

Table 5. Prices and Value-Added Cost by Production Process Step for 500X Collectors (1982 $/$W_p$)

	Cell Value-Added	Cell Assembly Value-Added	Lens Assembly Value-Added	Collector Assembly Value-Added	Total Collector Price	Collector Efficiency at SOC
Mean	0.182	0.290	0.153	0.332	0.957	0.182
Std. Deviation	0.157	0.076	0.050	0.064	0.196	0.018
Minimum	0.023	0.098	0.064	0.201	0.643	0.138
10th percentile	0.048	0.192	0.101	0.248	0.747	0.155
25th percentile	0.099	0.231	0.120	0.288	0.816	0.170
50th percentile	0.150	0.286	0.149	0.329	0.920	0.185
75th percentile	0.200	0.341	0.177	0.376	1.059	0.196
90th percentile	0.302	0.388	0.205	0.410	1.163	0.201
Maximum	1.290	0.490	0.537	0.538	2.378	0.231

Table 6. Path Selection Histogram for 500X Collectors

Path No.	No. of Selections	Path No.	No. of Selections	Path No.	No. of Selections	Path No.	No. of Selections
25	0	37	0	49	0	61	4
26	47	38	0	50	2	62	23
27	31	39	0	51	5	63	14
28	20	40	0	52	4	64	27
29	0	41	1	53	0	65	0
30	54	42	35	54	0	66	8
31	40	43	13	55	0	67	2
32	32	44	20	56	0	68	1
33	0	45	0	57	0	69	0
34	7	46	25	58	20	70	0
35	4	47	12	59	12	71	0
36	3	48	19	60	15	72	0

Table 7 is taken from Table 6, based on the number of winning paths using the specified cell, lens or housing technological alternative (500 winners per Monte Carlo simulation).

The rankings for 500X technologies are very similar to the 1000X rankings shown in Table 2. There is shown to be a slight shift toward advanced silicon cells, however, presumably due to their lower cell cost in $\$/cm^2$. In addition, the dominant paths for the technological alternatives are similar for 500X and 1000X.

Detailed breakdowns of 500X collector prices closely track the pattern of 1000X collector prices, but modified as in Table 5. Price and efficiency pairs for 500X collectors are displayed as a histogram in Figure 8. These results are similar to those for 1000X collectors, but shifted to higher values for the additional cell and cell-assembly value-added costs due to larger cell size. The largest grouping of 500X collector price and efficiency pairs is in the area around $\$0.75$ to $\$0.95/W_p$ and 0.19 to 0.20 module efficiency at SOC. Module efficiencies differing from those of 1000X modules are due to random variation in the Monte Carlo simulation, 500X cells operating at a cooler temperature (and thus higher efficiency) than 1000X, and selection of cell material on the basis of cost since additional cell material is required.

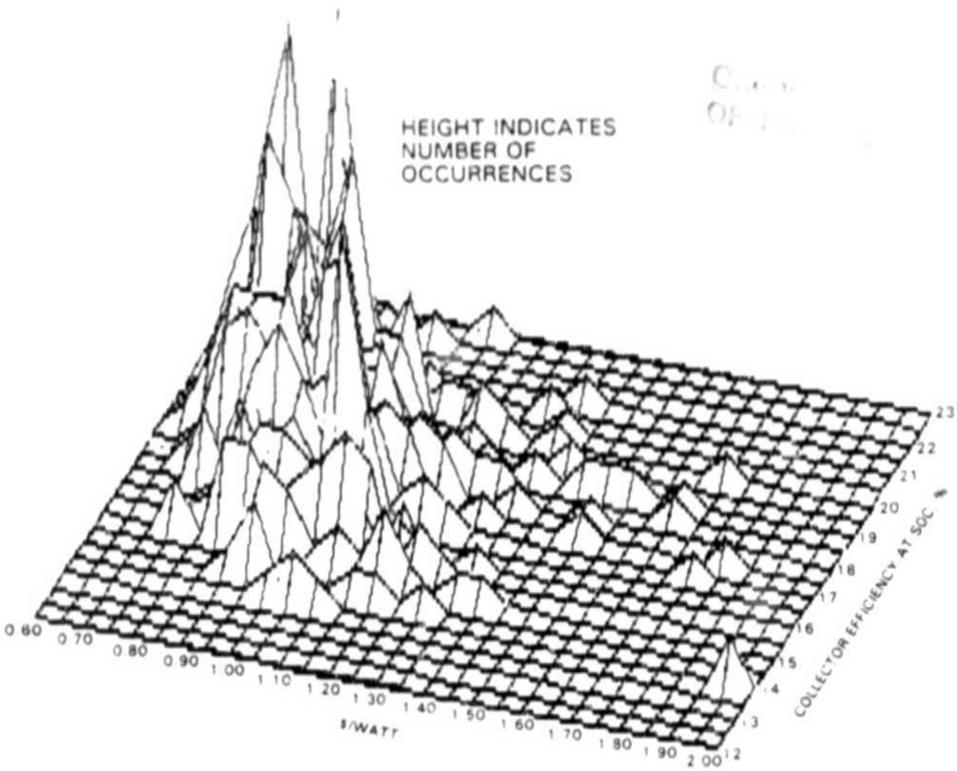
Table 7. Summary of Technologies, 500X Collectors

Technological Alternative	Number of Winners	Path Numbers
Cell		
Advanced Si	214	25-28, 41-44, 57-60
GaAs	250	29-32, 45-48, 61-64
Mechanically Stacked Multijunction	36	33-36, 49-52, 65-68
Monolithic Multijunction	0	37-40, 53-56, 69-72
Lens		
Compression Molded	5	25,29,33,37,41,45,49,53, 57,61,65,69
Injection Molded	221	26,30,34,38,42,46,50,54, 58,62,66,70
Lens Film	133	27,31,35,39,43,47,51,55, 59,63,67,71
Direct-Bond Polymer/Glass	141	28,32,36,40,44,48,52,56, 60,64,68,72
Housing		
Plastic	238	25-40
Aluminum	136	41-56
Steel	126	57-72

D. PRICE RESULTS, 200X COLLECTOR

Production step value-added cost and collector price and efficiency projections for 200X concentrator collectors are shown in Table 7. The mean total module price for 200X collectors is \$1.26/W_p and the mean efficiency is 15.8%. Production step value-added costs contribute to total module price as follows:

Production Step	1982 \$/W_p	Percentage of Total
Cell	0.21	16
Cell Assembly	0.49	39
Lens Assembly	0.18	14
Collector Assembly	0.39	31
Mean Total Collector Price	1.26	100



Collector Price, $/W_p	Collector Efficiency at SOC, %																					
	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23
0.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.65	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	1	0	0	0	0	0
0.70	0	0	0	0	0	0	0	0	0	0	1	1	3	4	5	2	2	0	0	0	0	0
0.75	0	0	0	0	0	0	2	0	0	3	0	5	6	3	8	10	1	4	1	0	0	0
0.80	0	0	0	0	0	0	0	1	1	7	3	6	6	12	4	15	5	1	0	0	2	0
0.85	0	0	0	0	0	0	4	0	4	5	0	4	6	9	8	4	4	0	0	0	1	0
0.90	0	0	0	0	1	0	4	4	1	7	8	4	9	6	7	16	3	1	1	1	1	0
0.95	0	0	0	0	3	4	2	4	4	5	4	8	3	9	11	6	2	0	0	0	0	0
1.00	0	0	0	1	0	3	3	3	2	2	5	9	4	3	4	3	2	0	0	0	1	0
1.05	0	0	0	2	1	1	4	3	12	3	3	3	5	3	4	5	0	1	0	0	0	0
1.10	0	0	0	1	0	2	5	2	5	4	4	0	2	1	1	0	1	0	0	0	0	1
1.15	0	0	0	0	1	1	4	0	1	1	3	3	1	1	0	0	1	0	0	0	0	0
1.20	0	0	0	0	1	3	0	2	0	2	0	2	2	0	1	2	0	0	0	0	0	0
1.25	0	0	0	0	0	1	2	0	0	1	0	0	1	1	0	1	0	0	0	0	0	0
1.30	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0
1.35	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	1	1	0	1	0	0	0
1.40	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
1.50	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
1.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.65	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
1.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
1.75	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

Figure 8. Price and Efficiency Combinations, 500X Collectors

This differs from the cost results for the high-concentration (1000X or 500X) collectors in that the combined cell purchase and cell assembly steps for 200X collectors are both more expensive and constitute a higher percentage of the total module price. In particular, the combined cell purchase and cell assembly production step value-added costs and percentages for 200X and 1000X technologies are $\$0.70/W_p$ and 55%, and $\$0.36/W_p$ and 43%, respectively.

Table 8. Prices and Value-Added Costs by Production Process Step, 1982 $\$/W_p$, 200X Collectors

	Cell Value-Added	Cell Assembly Value-Added	Lens Assembly Value-Added	Collector Assembly Value-Added	Total Collector Price	Collector Efficiency at SOC
Mean	0.207	0.491	0.179	0.388	1.264	0.158
Std. Deviation	0.135	0.133	0.059	0.084	0.200	0.023
Minimum	0.048	0.169	0.075	0.203	0.778	0.124
10th percentile	0.084	0.322	0.121	0.279	1.003	0.132
25th percentile	0.108	0.391	0.139	0.322	1.106	0.137
50th percentile	0.180	0.487	0.166	0.381	1.270	0.153
75th percentile	0.241	0.584	0.212	0.440	1.393	0.180
90th percentile	0.349	0.667	0.248	0.500	1.536	0.193
Maximum	0.649	0.861	0.531	0.627	1.803	0.204

Table 9 displays the winning paths for the 200X collectors.

These results are combined and summarized in Table 10, based on the number of winning paths using the specified cell, lens or housing technological alternative (500 winners per Monte Carlo simulation).

Advanced silicon cells used in 200X modules are shown to be preferred more frequently than the baseline silicon cells. Lens and housing preferences are the same as for the higher-concentration designs. The dominant paths through the network are collector designs using advanced silicon cells, plastic housing with injection-molded, lens film and direct-bond polymer/glass lenses, (paths 6, 7, and 8, respectively), collector designs using baseline silicon cells, plastic housing and injection-molded lens (path 2), and collector designs using advanced silicon cells, aluminum housing, and injection-molded lens (path 14).

Cumulative price probabilities for 200X collectors using baseline silicon and advanced silicon cells are shown separately in Figure 9. Advanced silicon cell collector prices are more uncertain than the baseline silicon alternative as indicated by the flatter slope of the advanced silicon curve.

Table 9. Path Selection Histogram, 200X Collector

Path No.	No. of Selections	Path No.	No. of Selections	Path No.	No. of Selections
1	0	9	0	17	2
2	47	10	21	18	22
3	27	11	10	19	11
4	25	12	20	20	19
5	0	13	1	21	2
6	62	14	40	22	29
7	46	15	20	23	17
8	31	16	24	24	24

However, advanced silicon does demonstrate the potential for cheaper collectors, primarily due to higher efficiency. There is some risk, however, that advanced silicon collector prices will be greater than baseline silicon (in the region to the right of the intersection of the two curves).

Table 10. Summary of Technologies, 200X Collectors

Technological Alternative	Number of Winners	Path Numbers
Cell		
Baseline Si	204	1-4, 9-12, 17-20
Advanced Si	296	5-8, 13-16, 21-24
Lens		
Compression Molded	5	1,5,9,13,17,21
Injection Molded	221	2,6,10,14,18,22
Lens Film	131	3,7,11,15,19,23
Direct-Bond Polymer/Glass	143	4,8,12,16,20,24
Housing		
Plastic	238	1-8
Aluminum	136	9-16
Steel	126	17-24

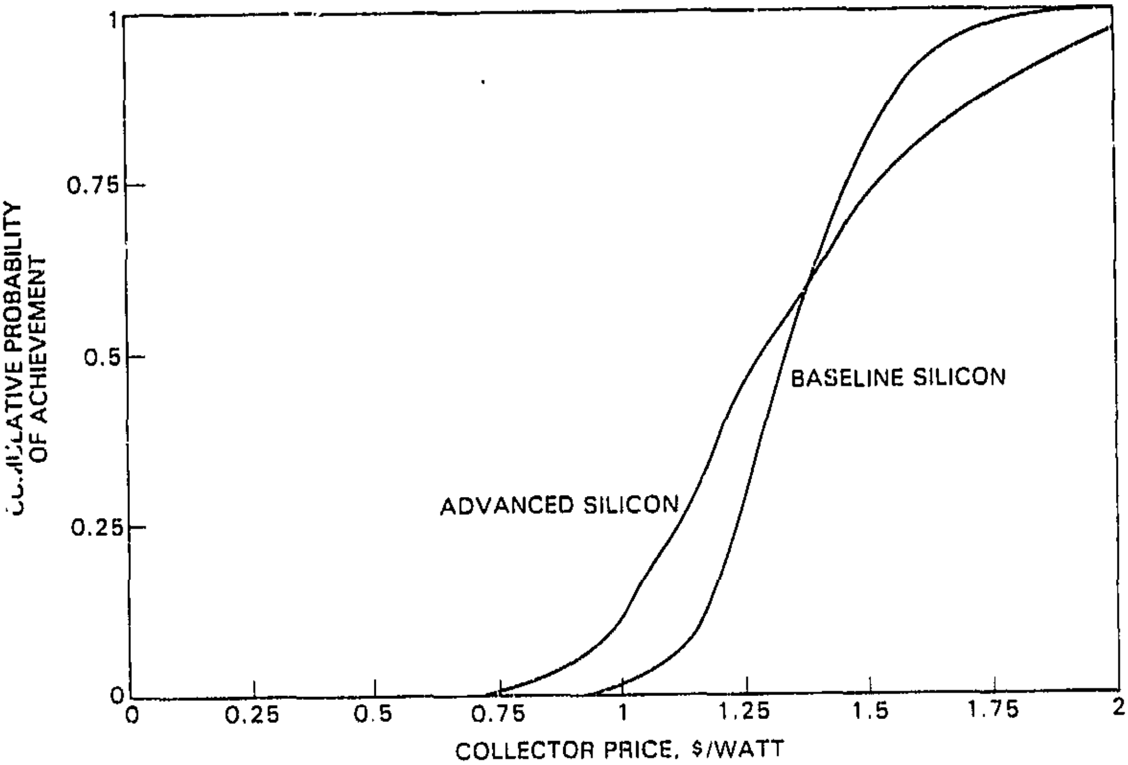


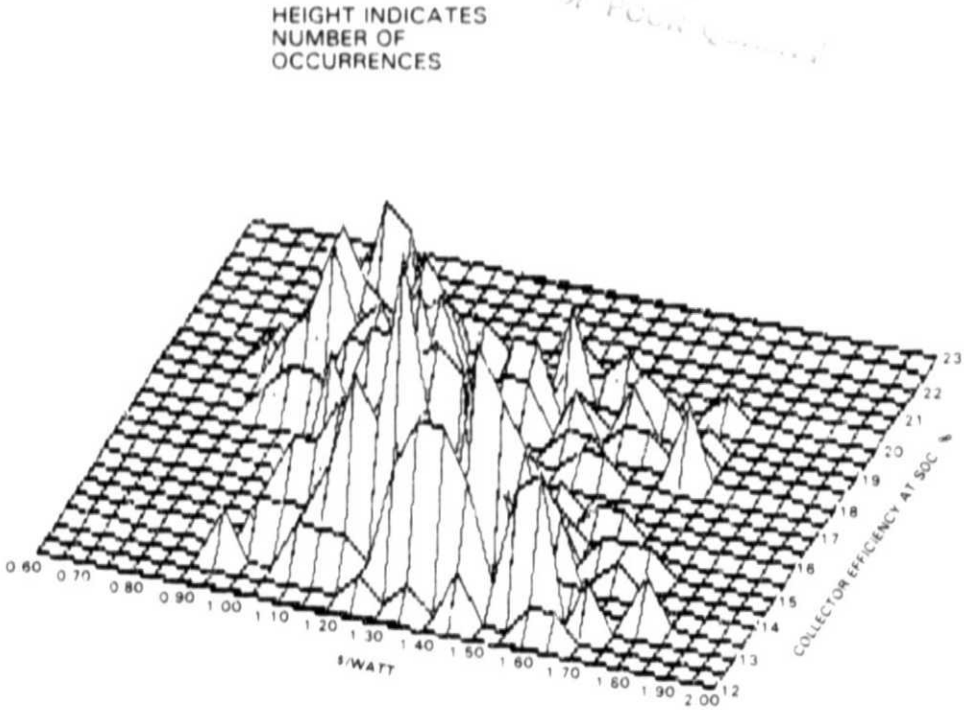
Figure 9. Prices, 200X Collectors

Collector price and efficiency combinations for 200X collectors are presented as a histogram in Figure 10. The largest groupings of 200X collector price and efficiency pairs are at \$1.20 to \$1.50/W_p and 0.135 to 0.140 module efficiency at SOC and also at \$0.95 to \$1.05/W_p and 0.185 to 0.20 module efficiency at SOC.

E. LENS TYPE VALUE-ADDED COST ANALYSIS

Four alternative lens production technologies have been included in this analysis. Currently available is the compression-molding technique. Three potentially more cost-effective techniques are injection molding, lens film and direct-bond polymer-to-glass molding. Cumulative lens value-added costs for each of these alternatives are shown in Figure 11.

The value-added cost results in Figure 11 (assuming 1000X collectors) demonstrate that compression-molded lens costs are higher than any of the other lens alternatives for any given percentile ranking. However, each of the four lens types has the potential to be the lowest-cost alternative from the Monte Carlo simulation discussed in Table 3 and summarized in Table 11.



Collector Price, $/W_p$	Collector Efficiency at SOC, %																					
	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23
0.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.80	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
0.85	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	1	0	0	0	0	0
0.90	0	0	0	0	0	0	0	0	0	0	2	0	3	1	1	3	0	0	0	0	0	0
0.95	0	2	0	0	0	0	0	0	0	0	2	1	6	6	2	2	0	0	0	0	0	0
1.00	0	0	2	2	0	1	1	1	1	0	1	3	3	4	2	6	0	0	0	0	0	0
1.05	0	0	2	4	2	2	2	5	0	1	1	3	4	3	2	5	0	0	0	0	0	0
1.10	0	2	2	4	1	2	4	2	2	3	0	1	1	3	5	0	0	0	0	0	0	0
1.15	0	2	4	6	3	3	7	2	2	0	2	1	3	4	3	2	0	0	0	0	0	0
1.20	0	2	8	5	2	1	7	4	2	3	2	1	0	1	0	2	0	0	0	0	0	0
1.25	1	1	6	7	3	1	9	4	5	1	0	1	1	0	0	1	0	0	0	0	0	0
1.30	0	5	13	8	2	3	5	2	1	2	0	1	2	3	2	1	0	0	0	0	0	0
1.35	1	7	7	9	4	2	6	2	1	1	0	0	2	3	0	0	0	0	0	0	0	0
1.40	0	7	3	8	2	5	1	2	1	1	0	0	0	0	4	2	0	0	0	0	0	0
1.45	2	5	10	2	4	2	4	0	0	0	0	1	2	1	0	1	0	0	0	0	0	0
1.50	0	1	8	3	0	0	2	0	1	0	1	1	0	0	0	2	0	0	0	0	0	0
1.55	0	5	6	5	1	2	1	0	0	0	1	0	1	2	2	0	0	0	0	0	0	0
1.60	1	4	1	3	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0
1.65	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.70	0	2	0	0	1	1	0	0	0	0	0	3	1	1	0	1	0	0	0	0	0	0
1.75	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 10. Price and Efficiency Combinations, 200X Collectors

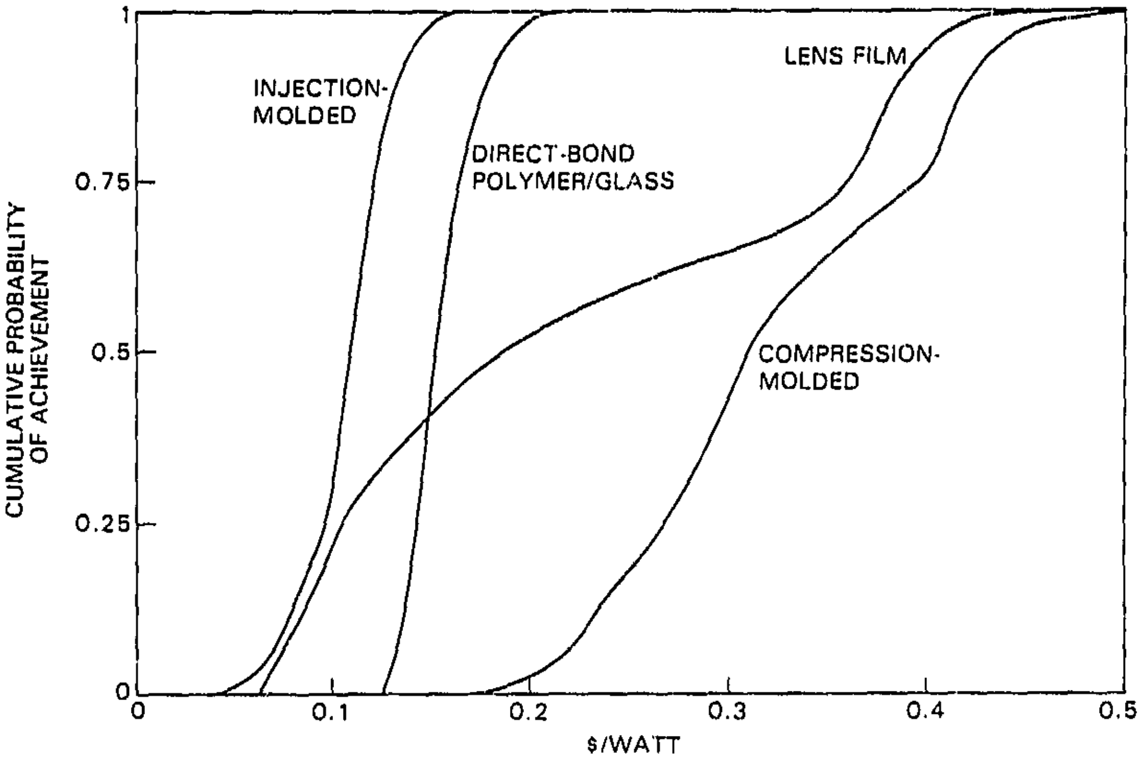


Figure 11. Lens Value-Added Costs for Various Manufacturing Processes

Table 11. Summary of Lens Technologies

Lens Type	No. of Times Selected	Fraction of Times Selected	Probability of Success
Compression-Molded	5	0.01	1.00
Injection-Molded	219	0.44	0.725
Lens Film	135	0.27	0.95
Direct-Bond Polymer/Glass	141	0.28	0.85
Total	500	1.00	

Injection molding appears to be the most cost-effective alternative. However, the probability that this technology will be a technical success is only 72.5% (see Appendix B). Other lens types can successfully compete with injection molding if the technology fails or if it only achieves costs associated with high cumulative probability. Lens-film technology has a high probability of being a technical success, but the variance in value-added costs is very high (the range is approximately $0.07/W_p to $0.50/W_p).

Lens film can therefore be considered a risky technology from the cost viewpoint. The probability of success of the direct-bond polymer/glass approach lies between injection molding and lens film techniques. Cost projections for direct-bond polymer/glass vary on a very small range, but are approximately $\$0.05/W_p$ higher than those for injection molding. Taken together, each lens technology, other than compression molding, demonstrates the potential to be a low-cost process. These data indicate that it is premature to identify a single winner at this time.

F. HOUSING-TYPE VALUE-ADDED COST ANALYSIS

Potential concentrator collector housing materials include plastic, aluminum and steel. Each is considered capable of withstanding expected temperature regimes, but at varying cost and potentially varying reliability. In this analysis, reliability is assumed constant. Heat-sink costs are specific to the material type (aluminum housing does not require any additional heat-sink capability). Housing value-added costs for 1000X collectors, including the associated heat-sink value-added cost, are shown in Figure 12.

Figure 12 displays the narrow cost ranges projected for plastic and steel, but much larger uncertainty for aluminum housing. The discussion of Table 3 identifies plastic housing as the dominant technology (e.g., the lowest cost per watt) approximately half the time, with aluminum and steel splitting the remaining half. A potential advantage for aluminum and/or steel housings that has not been considered in this analysis is that they obviate puncturing the underside of the housing when attaching the cell assembly, removing one avenue for water invasion of the module when in a stowed position. The reliability benefits of this approach are yet to be measured or estimated.

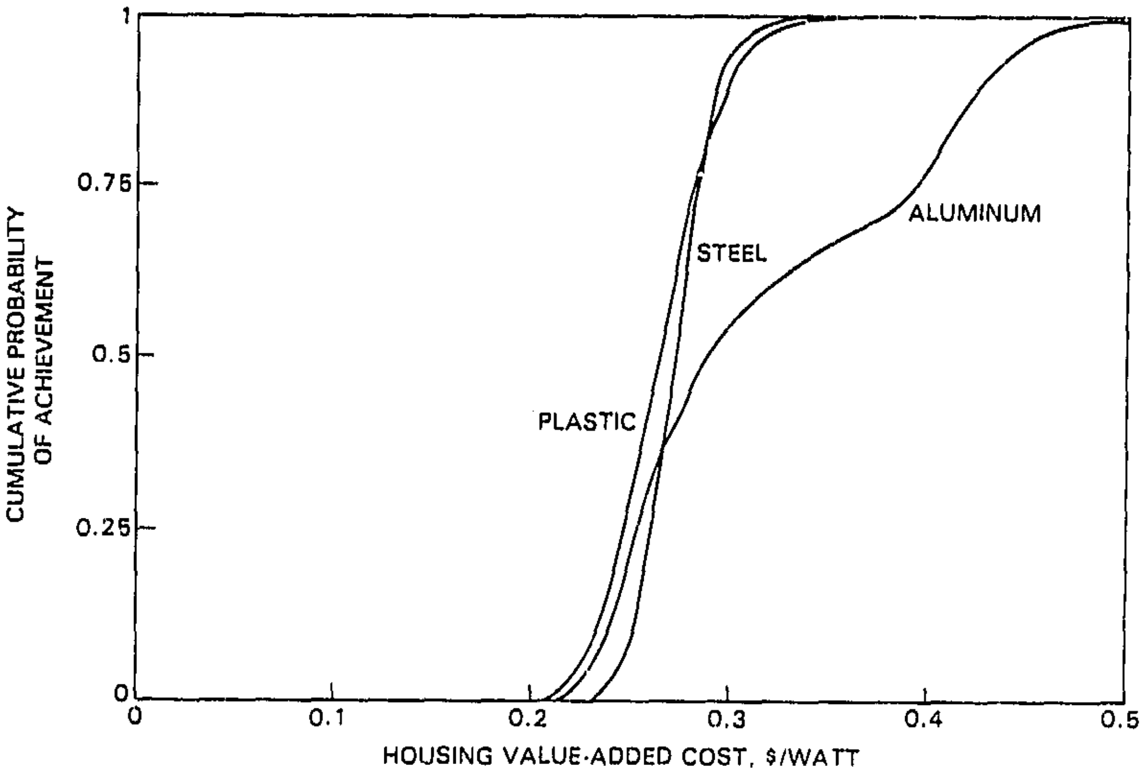


Figure 12. Collector Housing Value-Added Costs for Various Materials

SECTION V

COMPARISON OF CONCENTRATOR AND TWO-AXIS TRACKING FLAT-PLATE PV SYSTEM ENERGY COSTS

Concentrator and tracking flat-plate PV systems in central-station applications can be compared on the basis of their projected costs of energy. Comparisons on the basis of system-level energy cost (in $/kWh) is preferred to module cost comparisons (in $\$/W_p$) since module-level costs exclude information important to the decision-making process (e.g., the effect of module efficiency on balance-of-system area-related costs and the varying levels of direct normal and total insolation received by collectors at different sites). Energy cost estimates, on the other hand, include all of the relevant cost and performance characteristics required for this study. In this report, concentrator technologies are compared with flat-plate modules operating in a two-axis tracking configuration only. The system level benefits (and costs) of tracking are normalized between concentrator and flat-plate designs, and the technologies are set up for comparison of cost and efficiency potential for a number of locations on the basis of their implied cost of energy.

Probabilistic concentrator PV collector price and efficiency projections for commercial collectors in the mid-1990's, presented in Section IV, provide the basis for the concentrator system energy cost estimates. Flat-plate PV module price and efficiency projections, also assuming a mid-1990's commercial product, are supplied in Reference 1 and are summarized in Appendix C of this report. Values for all non-module-related parameters are provided by the Five-Year Research Plan (Reference 3) and reports by Sandia, Albuquerque (Reference 4), the Solar Energy Research Institute (Reference 8) and the Jet Propulsion Laboratory (Reference 9). The remainder of this section presents the structure and results of the comparison study.

A. ENERGY COST EQUATION

Energy costs are determined based on the equation presented in the Five-Year Research Plan (and modified in Reference 9). The revised energy cost (EC) equation in levelized nominal dollars is:

$$\overline{EC} = \frac{FCR}{S/API} \times INDC \times A \times (\$MSQMD + \$MSQBS) + \$KWBS + A \times G \times CRF \times \frac{\$MSQOM}{S/API}$$

where

FCR = Fixed charge rate, fraction

S = Annual insolation received at collector surface, kWh/m^2-yr

API = Site-specific flat-plate or concentrator average peak insolation, kW/m^2

INDC = Indirect cost multiplier

$$A = \frac{1}{API \times \text{system efficiency}}$$

and

System Efficiency = flat-plate systems: balance-of-system efficiency (BOSEFF) x module efficiency at STC x flat-plate module efficiency adjustment for operating temperature;

concentrator systems: balance-of-system efficiency (BOSEFF) x optical efficiency x cell efficiency at STC x concentrator module efficiency adjustment for operating temperature

$MSQMD = Module cost, 1982 $\$/m^2$
$MSQBS = Area-related balance-of-system cost, 1982 $\$/m^2$
$KWBS = Power-related balance-of-system cost, 1982 $/kW
G = Present worth factor
CRF = Capital recovery factor, fraction
$MSQOM = Operation and maintenance cost, 1982 $\$/m^2$-yr

The collector level studies discussed above provide information on module cost ($MSQMD) and efficiency (system efficiency, excluding balance-of-system efficiency). Location-dependent parameters are annual insolation (S) and average peak insolation (API). All other parameters will be held constant between concentrator and flat-plate alternatives. Values for these constants and location-dependent parameters are shown below:

Constants

FCR = 0.153
INDC = 1.5
BOSEFF = 0.865
$MSQBS = 100 (cost of two-axis tracking structures is assumed to be identical for flat-plate and concentrator)

$KWBS = 150
G = 18
CRF = 0.129
$MSQOM = 1.4 (operation and maintenance cost for two-axis tracking flat-plate and concentrator systems is assumed to be identical)

Location-Dependent

S = Concentrator:

Phoenix	2482	(Reference 8)
Miami	1416	(Reference 4)
Boston	1171	(Reference 4)

Flat-Plate (two-axis tracking):

Phoenix	3198	(Reference 8)
Miami	2105	(Reference 4)
Boston	1675	(Reference 4)

API = Concentrator: 0.9 (Reference 7)
Flat-Plate: 1.0 (References 3,7)

Combining these values with the collector cost and efficiency projections into the energy cost equation yields an energy cost in levelized nominal dollars over 30 years. If desired, this energy cost value $\overline{EC}$ can be converted to real 1982 dollars by dividing $\overline{EC}$ by 2.3 (e.g., f $\overline{EC}$ is \$0.15/kWh, it is also \$0.065/kWh in 1982 dollars).

B. CONCENTRATOR SYSTEM ENERGY COSTS

Mid-1990's energy cost projections for 1000X, 500X and 200X concentrator technologies in Southwestern (Phoenix, Arizona), Southeastern (Miami, Florida) and Northeastern (Boston, Massachusetts) locations are presented in Table 12 and displayed in Figures 13-15. Table 12 presents cumulative energy cost probabilities at 0.10, 0.25, 0.50, 0.75 and 0.90 levels, as well as the mean, standard deviation, minimum and maximum of the distribution. Consistent with the concentrator collector price results shown in Figure 1, 1000X concentrator system energy prices are shown to be less than the 500X and 200X alternatives for all locations.

Figures 13-15 display the calculated levelized energy costs for Phoenix, Miami, and Boston, respectively. A vertical line at \$0.15/kWh, the National PV Program energy cost goal, is included in each figure to provide a basis for estimating the cost potential of the technologies at different locations. Energy costs are in levelized nominal terms with a 1982 base year and can be translated into real 1982 dollars by dividing by a factor of 2.3.

The energy cost estimates for flat-plate PV systems in Phoenix, Miami and Boston are now added to the concentrator system energy cost projections (Figures 13-15) in Figures 16-18, respectively. Cumulative flat-plate energy

Table 12. Concentrator Photovoltaic System Levelized Energy Costs for Phoenix, Miami and Boston, \$/kWh

Site	Concentration Level	Mean	Standard Deviation	Minimum	Cumulative Probabilities					Max
					10	25	50	75	90	
Phoenix	1000X	0.161	0.017	0.128	0.136	0.150	0.158	0.169	0.180	0.265
	500X	0.172	0.022	0.134	0.146	0.150	0.165	0.185	0.201	0.330
	200X	0.213	0.026	0.152	0.164	0.184	0.204	0.229	0.245	0.277
Miami	1000X	0.282	0.030	0.224	0.238	0.262	0.277	0.296	0.315	0.464
	500X	0.302	0.039	0.235	0.255	0.262	0.290	0.324	0.351	0.578
	200X	0.374	0.045	0.266	0.288	0.323	0.358	0.402	0.429	0.486
Boston	1000X	0.341	0.036	0.271	0.288	0.317	0.335	0.358	0.381	0.561
	500X	0.365	0.047	0.284	0.309	0.317	0.350	0.392	0.425	0.699
	200X	0.452	0.055	0.321	0.348	0.390	0.433	0.486	0.518	0.588

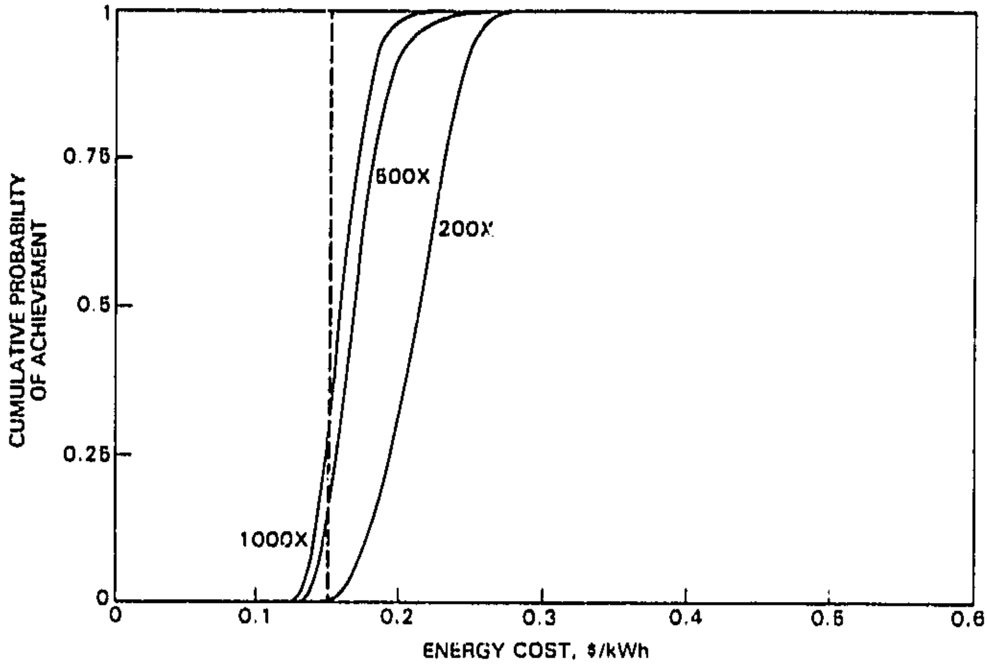


Figure 13. Concentrator System Energy Costs at Various Concentration Ratios (Phoenix)

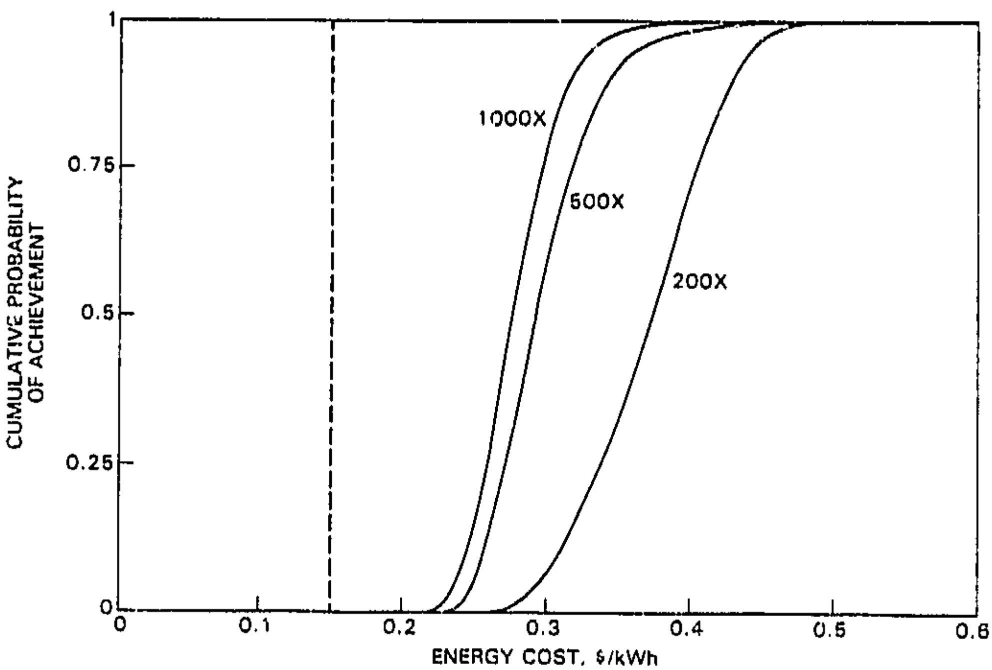


Figure 14. Concentrator System Energy Costs at Various Concentration Ratios (Miami)

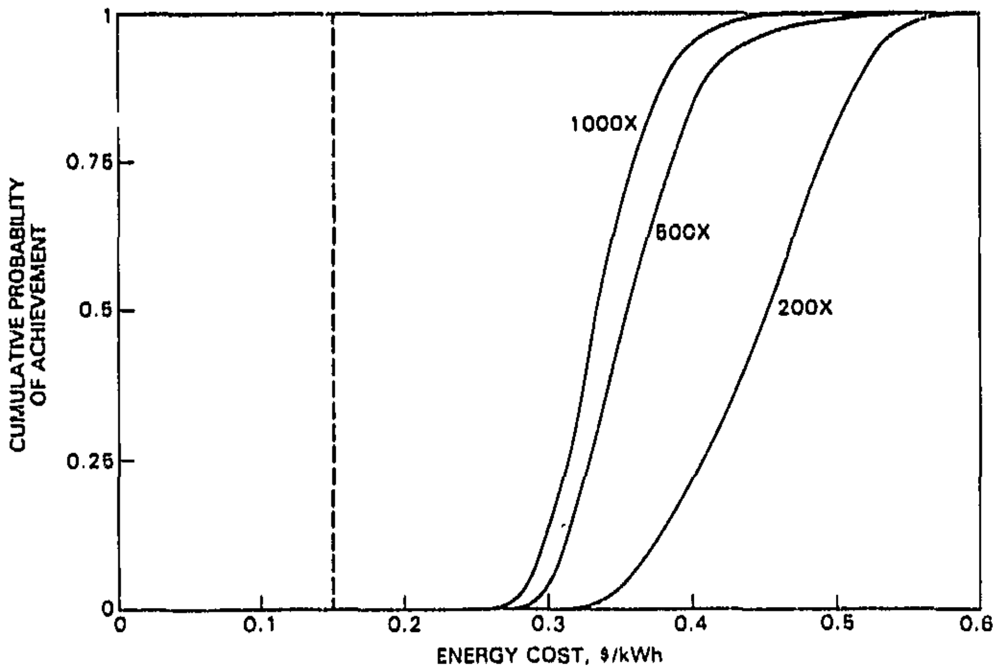
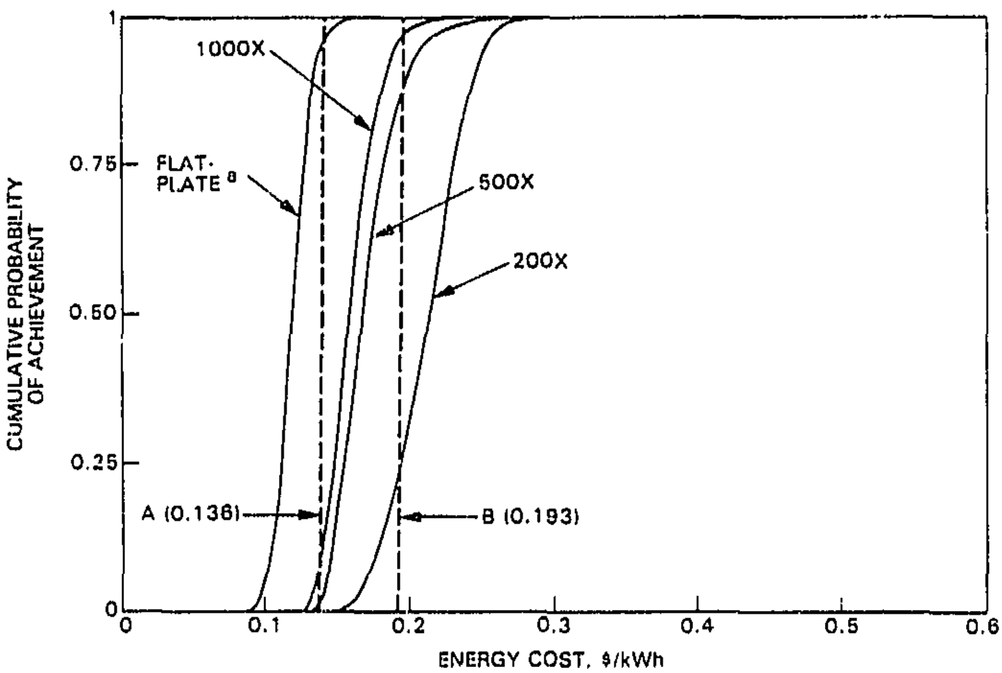
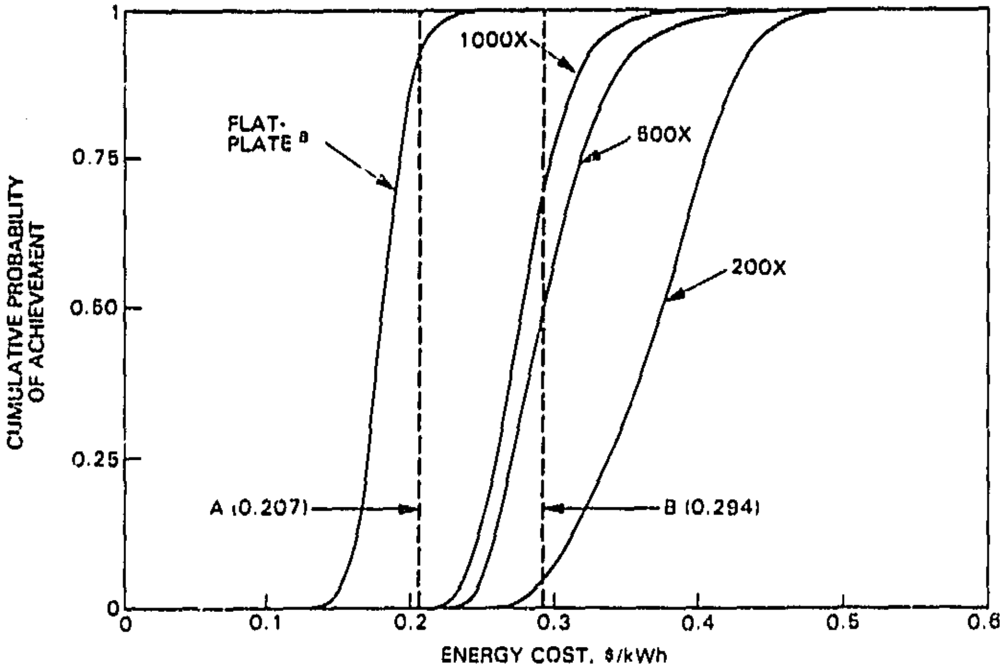


Figure 15. Concentrator System Energy Costs at V..ious Concentration Ratios (Boston)



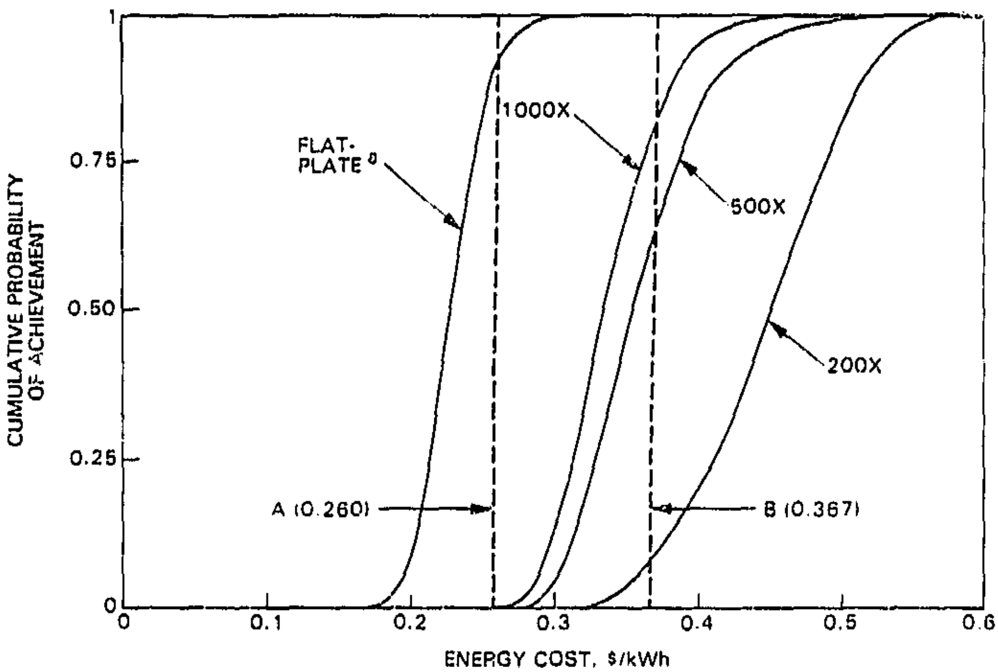
[a]Cumulative probabilities for flat-plate system energy costs are taken from Reference 1. (Note caveats in Advisement on p. iv.)

Figure 16. Concentrator and Flat-Plate System Energy Costs (Phoenix)



[a]Cumulative probabilities for flat-plate system energy costs are taken from Reference 1. (Note caveats in Advisement on p. iv.)

Figure 17. Concentrator and Flat-Plate System Energy Costs (Miami)



[a]Cumulative probabilities for flat-plate system energy costs are taken from Reference 1. (Note caveats in Advisement on p. iv.)

Figure 18. Concentrator and Flat-Plate System Energy Costs (Boston)

cost probability projections are shown to be lower than their concentrator counterparts in all locations. The cost differences are, unsurprisingly, smallest for the Southwestern location. Two additional points (vertical dotted lines) are also identified along the energy cost axis:

(1) Energy cost (A) corresponding to 1988 flat-plate module cost target of $\$90/m^2$ (1982 \$) and 15% STC module efficiency (13.5% at NOC) = \$0.136/kWh (Phoenix), \$0.207/kWh (Miami), and \$0.260/kWh (Boston).

(2) Energy cost (B) corresponding to production scale-up of currently available Cz technology using today's prototype manufacturing equipment, at $\$1.25/W_p$ (1982 \$) and 12% NOC module efficiency (Reference 10) = \$0.193/kWh (Phoenix), \$0.294 (Miami), and \$0.367 (Boston).

The intersection of these vertical lines with the flat-plate curve determines the cumulative probability of achieving these energy costs in the mid-1990's, and the intersection of the vertical lines with the concentrator technology curves identifies the cumulative probabilities that the concentrator technologies can achieve an equivalent cost of energy. Only the 1000X collector is shown to be a potentially viable alternative to flat-plate at energy cost (A). For energy cost (B), both 1000X and 500X concentrator technologies demonstrate strong potential for cost competitiveness, but the 200X alternative has a much lower probability of success.

C. CONCENTRATOR COLLECTOR REQUIRED PRICES AND EFFICIENCIES

Concentrator collector price and efficiency combinations required to achieve a specified cost of energy can be identified based on the technology potential shown in Figures 7, 8 and 10 (histograms for 1000X, 500X and 200X) and the cost, efficiency and insolation assumptions presented in subsection V A. Figures 19-21 display the energy costs associated with Phoenix insolation overlaid on the 1000X, 500X and 200X concentrator collector price-efficiency histograms. Trade-offs between collector price and efficiency required to achieve a given cost of energy are easily determined from the figures. Similarly, Figures 22 and 23 present the 1000X concentrator histogram and energy costs for Miami and Boston, respectively.

The histogram results can also be compared with target energy costs established by flat-plate technology. Figures 24-26 display the required concentrator collector cost and efficiency pairs needed to achieve the 0.10, 0.25, 0.50, 0.75 and 0.90 cumulative energy cost probabilities determined for flat-plate technology for Phoenix, Miami and Boston. Each curve is labeled with an energy cost and cumulative probability (in parentheses) for two-axis tracking flat-plate technology. The curves identify required concentrator collector cost and efficiency pairs needed to achieve equivalent energy costs in the specified location.

Collector Price, $/$W_p$	Collector Efficiency at SOC, % 12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	
0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	1	3	0	0	0	0	0	
0.65	0	0	0	0	0	0	0	0	0	0	3	2	6	3	5	6	4	2	0	1	0	0	
0.70	0	0	0	0	0	0	0	0	0	2	1	6	4	6	18	6	3	3	0	0	2	0	
0.75	0	0	0	0	0	0	1	4	1	4	6	4	16	11	11	8	2	0	0	3	2	0	(0.10), $0.141/kWh
0.80	0	0	0	0	0	1	2	3	1	8	8	9	10	5	13	7	2	2	0	0	0	0	
0.85	0	0	0	0	1	0	1	4	3	8	5	10	5	10	13	8	4	1	6	0	0	0	
0.90	0	0	0	1	0	3	4	3	4	6	4	9	9	3	5	5	2	1	0	0	1	1	(0.25), $0.150/kWh
0.95	0	0	1	0	1	3	1	6	7	3	4	4	8	4	4	0	3	0	3	0	0	0	(0.50), $0.158/kWh
1.00	0	0	0	0	0	4	1	2	3	3	3	2	5	2	1	2	2	0	0	0	0	0	
1.05	0	0	0	0	0	3	0	2	0	2	2	4	0	1	3	1	0	0	0	0	0	0	(0.75), $0.172/kWh
1.10	0	0	0	0	0	3	0	0	0	0	0	3	2	1	0	2	0	1	0	0	0	0	
1.15	0	0	0	1	0	1	0	0	0	1	2	0	0	0	0	1	1	0	0	0	0	0	
1.20	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	(0.90), $0.182/kWh
1.25	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	
1.30	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	
1.35	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 19. Energy Costs for 1000X Concentrator Systems Using Collector Price and Efficiency Combinations, Phoenix; (Cumulative Probability of Achievement), 1982 $/kWh

Collector Price, $/$W_p$	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	
	Collector Efficiency at SOC, %																						
0.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.65	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	1	0	0	0	0	0	
0.70	0	0	0	0	0	0	0	0	0	0	1	1	3	4	5	2	2	0	0	0	0	0	
0.75	0	0	0	0	0	0	2	0	0	3	0	5	6	3	8	10	1	4	1	0	0	0	
0.80	0	0	0	0	0	0	0	1	1	0	3	6	6	12	4	15	5	1	0	0	2	0	(0.10), $0.150/kWh
0.85	0	0	0	0	0	0	4	0	4	5	0	4	6	9	8	4	4	0	0	0	1	0	
0.90	0	0	0	0	1	0	4	4	1	7	8	4	9	6	7	16	3	1	1	1	1	0	(0.25), $0.157/kWh
0.95	0	0	0	0	3	4	2	4	4	5	4	8	3	9	11	6	2	0	0	0	0	0	
1.00	0	0	0	1	0	3	3	3	2	2	5	9	4	3	4	3	2	0	0	0	1	0	
1.05	0	0	0	2	1	1	4	3	12	3	3	3	5	3	4	5	0	1	0	0	0	0	(0.50), $0.169/kWh
1.10	0	0	0	1	0	2	5	2	5	4	4	0	2	1	1	0	1	0	0	0	0	1	
1.15	0	0	0	0	1	1	4	0	1	1	3	3	1	1	0	0	1	0	0	0	0	0	
1.20	0	0	0	0	1	3	0	2	0	2	0	2	2	0	1	2	0	0	0	0	0	0	
1.25	0	0	0	0	0	1	2	0	0	1	0	0	1	1	0	1	0	0	0	0	0	0	(0.75), $0.185/kWh
1.30	0	0	0	0	1	0	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	
1.35	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0	1	1	0	1	0	0	0	
1.40	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	(0.90), $0.197/kWh
1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
1.50	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	
1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
1.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.65	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	
1.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	
1.75	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
1.80	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	

Figure 20. Energy Costs for 500X Concentrator Systems Using Collector Price and Efficiency Combinations, Phoenix; (Cumulative Probability of Achievement), 1982 $/kWh

Collector Efficiency at SOC, %

Collector Price, $/W$_p$	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	
0.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.80	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	
0.85	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	1	0	0	0	0	0	
0.9C	0	0	0	0	0	0	0	0	0	0	2	0	3	1	1	3	0	0	0	0	0	0	
0.95	0	2	0	0	0	0	0	0	0	0	2	1	6	6	2	2	0	0	0	0	0	0	
1.00	0	0	2	2	0	1	1	1	1	0	1	3	3	4	2	6	0	0	0	0	0	0	
1.05	0	0	2	4	2	2	2	5	0	1	1	3	4	3	2	5	0	0	0	0	0	0	(0.10), $0.174/kWh
1.10	0	2	2	4	1	2	4	2	2	3	0	1	1	3	5	0	0	0	0	0	0	0	
1.15	0	2	4	6	3	3	7	2	2	0	2	1	3	4	3	2	0	0	0	0	0	0	
1.20	0	2	8	5	2	1	7	4	2	3	2	1	0	1	0	2	0	0	0	0	0	0	
1.25	1	1	6	7	3	1	9	4	5	1	0	1	1	0	0	1	0	0	0	0	0	0	
1.30	0	5	13	8	2	3	5	2	1	2	0	1	2	3	2	1	0	0	0	0	0	0	(0.25), $0.197/kWh
1.35	1	7	7	9	4	2	6	2	1	1	0	0	2	3	0	0	0	0	0	0	0	0	
1.40	0	7	3	8	2	5	1	2	1	1	0	0	0	0	4	2	0	0	0	0	0	0	
1.45	2	5	10	2	4	2	4	0	0	0	0	1	2	1	0	1	0	0	0	0	0	0	(0.50), $0.214/kWh
1.50	0	1	8	5	0	0	2	0	1	0	1	1	0	0	0	2	0	0	0	0	0	0	
1.55	0	5	6	5	1	2	1	0	0	0	1	0	1	2	2	0	0	0	0	0	0	0	
1.60	1	6	1	3	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	
1.65	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0.75), $0.232/kWh
1.70	0	2	0	0	1	1	0	0	0	0	0	3	1	1	0	1	0	0	0	0	0	0	
1.75	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.80	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0.90), $0.247/kWh

Figure 21. Energy Costs for 200X Concentrator Systems Using Collector Price and Efficiency Combinations, Phoenix; (Cumulative Probability of Achievement), 1982 $/kWh

Collector Price, $\$/W_p$	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	
0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	1	3	0	0	0	0	0	
0.65	0	0	0	0	0	0	0	0	0	0	3	2	6	3	5	6	4	2	0	1	0	0	
0.70	0	0	0	0	0	0	0	0	0	2	1	6	4	6	18	6	3	3	0	0	2	0	
0.75	0	0	0	0	0	0	1	4	1	4	6	4	16	11	11	8	2	0	0	3	2	0	(0.10), $0.248/kWh
0.80	0	0	0	0	0	1	2	3	1	8	8	9	10	5	13	7	2	2	0	0	0	0	
0.85	0	0	0	0	1	0	1	4	3	8	5	10	5	10	13	8	4	1	0	0	0	0	(0.25), $0.262/kWh
0.90	0	0	0	1	0	3	4	3	4	6	4	9	9	3	5	5	2	1	0	0	1	1	
0.95	0	0	1	0	1	3	1	6	7	3	4	4	8	4	4	0	3	0	3	0	0	0	(0.50), $0.277/kWh
1.00	0	0	0	0	0	4	1	2	3	3	3	2	5	2	1	2	2	0	0	0	0	0	
1.05	0	0	0	0	0	3	0	2	0	2	2	4	0	1	3	1	0	0	0	0	0	0	(0.75), $0.301/kWh
1.10	0	0	0	0	0	3	0	0	0	0	0	3	2	1	0	2	0	1	0	0	0	0	
1.15	0	0	0	1	0	1	0	0	0	1	2	0	0	0	0	1	1	0	0	0	0	0	
1.20	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	(0.90), $0.320/kWh
1.25	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	
1.30	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	
1.35	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

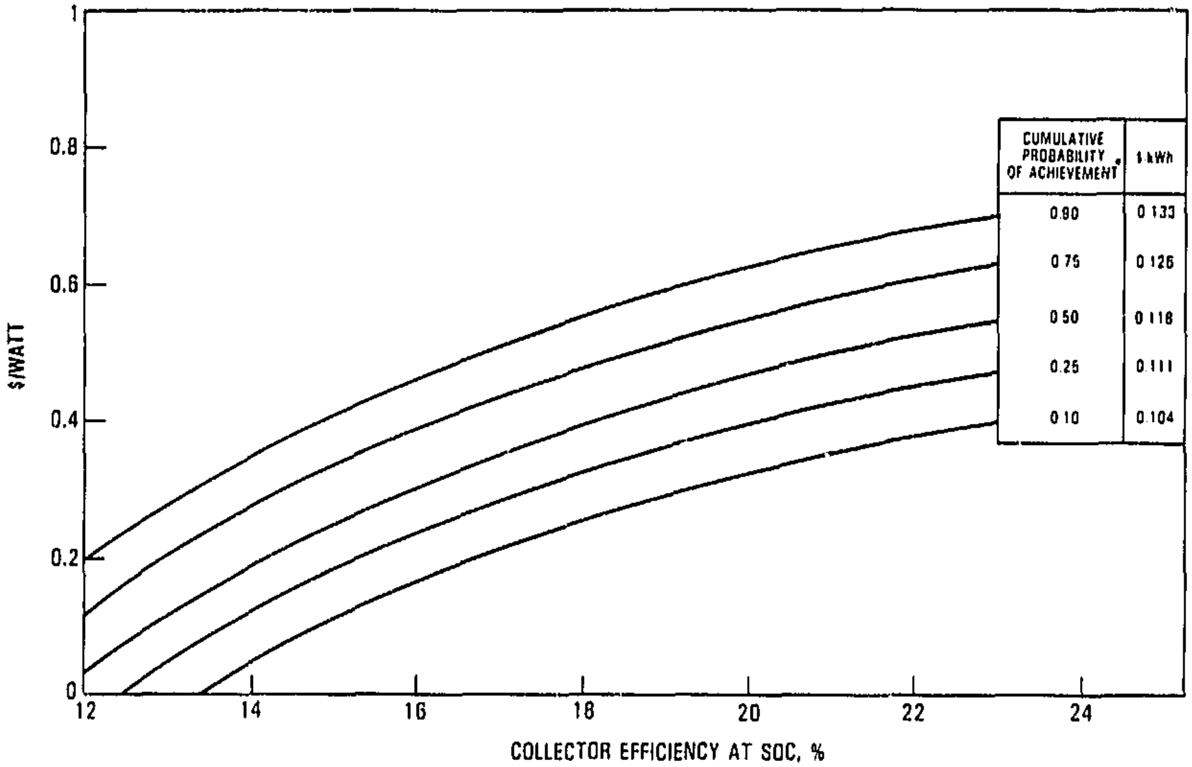
Collector Efficiency at SOC, %

Figure 22. Energy Costs for 1000X Concentrator Systems Using Collector Price and Efficiency Combinations, Miami; (Cumulative Probability of Achievement), 1982 $/kWh

Collector Efficiency at SOC, %

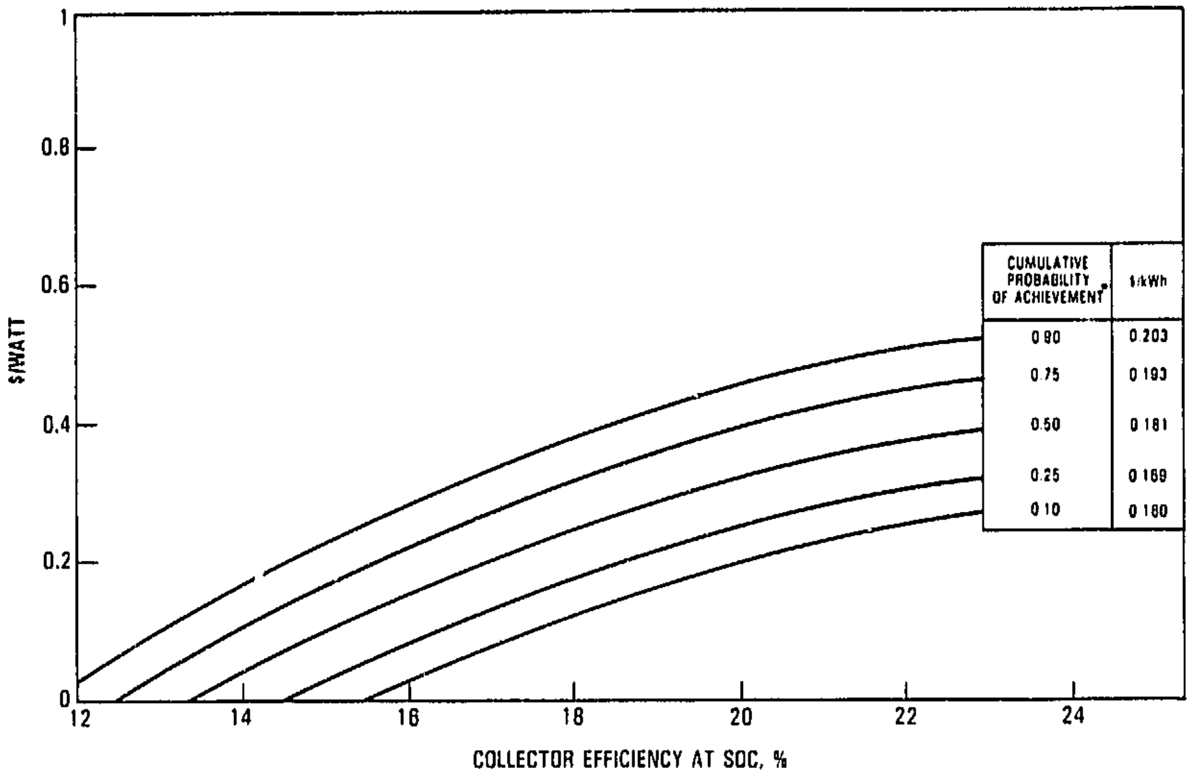
Collector Price, $/W$_p$	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	
0.60	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	1	3	0	0	0	0	0	
0.65	0	0	0	0	0	0	0	0	0	0	3	2	6	3	5	6	4	2	0	1	0	0	
0.70	0	0	0	0	0	0	0	0	0	2	1	6	4	6	18	6	3	3	0	0	2	0	
0.75	0	0	0	0	0	0	1	4	1	4	6	4	16	11	11	8	2	0	0	3	2	0	(0.10), $0.300/kWh
0.80	0	0	0	0	0	1	2	3	1	8	8	9	10	5	13	7	2	2	0	0	0	0	
0.85	0	0	0	0	1	0	1	4	3	8	5	10	5	10	13	8	4	1	0	0	0	0	(0.25), $0.317/kWh
0.90	0	0	0	1	0	3	4	3	4	6	4	9	9	3	5	5	2	1	0	0	1	1	
0.95	0	0	1	0	1	3	1	6	7	3	4	4	8	4	4	0	3	0	3	0	0	0	(0.50), $0.335/kWh
1.00	0	0	0	0	0	4	1	2	3	3	3	2	5	2	1	2	2	0	0	0	0	0	
1.05	0	0	0	0	0	3	0	2	0	2	2	4	0	1	3	1	0	0	0	0	0	0	(0.75), $0.364/kWh
1.10	0	0	0	0	0	3	0	0	0	0	0	3	2	1	0	2	0	1	0	0	0	0	
1.15	0	0	0	1	0	1	0	0	0	1	2	0	0	0	0	1	1	0	0	0	0	0	
1.20	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	(0.90), $0.387/kWh
1.25	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	
1.30	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	
1.35	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 23. Energy Costs for 1000X Concentrator Systems Using Collector Price and Efficiency Combinations, Boston; (Cumulative Probability of Achievement), 1982 $/kWh



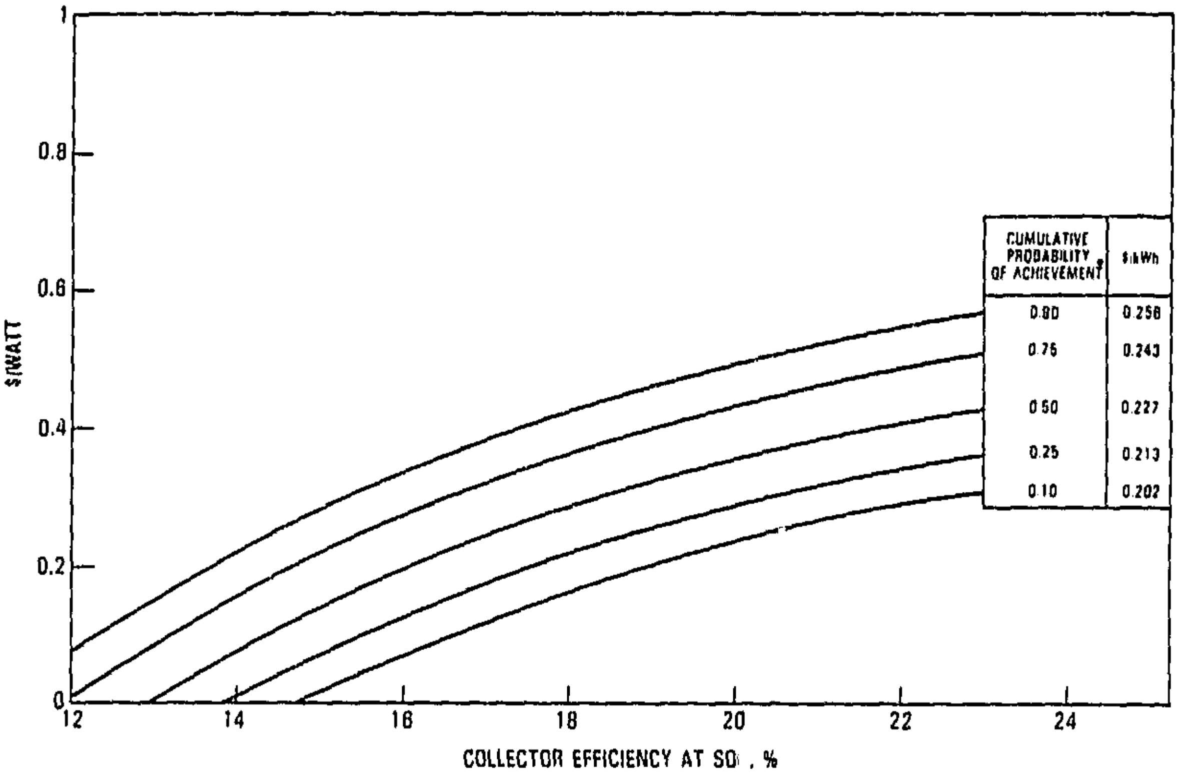
*Cumulative probabilities for flat-plate system energy costs are taken from Reference 1. (Note caveats in Advisement on p. iv.)

Figure 24. Required Concentrator Collector Price and Efficiency Pairs to Meet Flat-Plate Energy Costs at Given Cumulative Probability Points (Phoenix)



*Cumulative probabilities for flat-plate system energy costs are taken from Reference 1. (Note caveats in Advisement on p. iv.)

Figure 25. Required Concentrator Collector Price and Efficiency Pairs to Meet Flat-Plate Energy Costs at Given Cumulative Probability Points (Miami)



*Cumulative probabilities for flat-plate system energy costs are taken from Reference 1. (Note caveats in Advisement on p. iv.)

Figure 26. Required Concentrator Collector Price and Efficiency Pairs to Meet Flat-Plate Energy Costs at Given Cumulative Probability Points (Boston)

D. OTHER POTENTIAL SENSITIVITY ANALYSES

The above analyses provide a comparison of the costs of concentrator and two-axis tracking flat-plate PV systems in utility-grid-connected central-station applications in which only collector and site attributes are treated as variables. All other attributes are assumed to be equal between collector alternatives, including:

(1) Balance-of-system area-related cost, $\$/m^2$

(2) Balance-of-system power-related cost, \$/kW

(3) Balance-of-system efficiency, fraction

(4) Annual operation and maintenance cost, $\$/m^2$-yr

(5) Indirect cost multiplier, fraction

(6) Utility-related financial parameters

It has been suggested that small differences in balance-of-system area-related costs (in $\$/m^2$ of collector area) may exist due to module weight and required differences in pointing accuracy. Structures supporting flat-plate modules may, therefore, be potentially of lower cost because flat-plate modules are lighter than, and do not possess the stringent pointing requirements of, concentrator modules. Land utilization (i.e., the fraction of land area covered by photovoltaic array) is potentially lower for concentrators, which would increase dc wiring requirements. In addition, operation and maintenance costs for concentrator collectors may be higher than for flat-plate collectors if expenditures for alignment adjustment and other incremental maintenance are required. For the purpose of this study, these potential differences were not considered, as they would not alter study conclusions significantly.

Flat-plate collectors are constrained to a two-axis tracking configuration in this study. Analysis of fixed and one-axis tracking alternatives is beyond the scope of this study.

SECTION VI

CONCLUSIONS

The results of this study provide a number of insights into the technical and economic potentials of concentrating photovoltaic collectors and systems in the mid-1990's. In this section, key results are presented and recommendations for future technology development and analysis based on the findings of this study are discussed.

A. CONCENTRATOR COLLECTORS

Concentrator PV collectors are projected to be able to achieve f.o.b. prices in the range of \$0.70 to \$1.50/W_p, assuming large-scale manufacturing production in the mid-1990's. High-concentration alternatives (500X to 1000X) have been shown to have significantly lower achievable costs than lower-concentration (200X) collectors. The lower-concentration modules are estimated to be approximately 50% more expensive (per peak watt) than their high-concentration counterparts. The primary savings for high-concentration collectors are in the cell and cell-assembly value-added costs, due to lower cell material requirements and higher cell efficiencies. Still to be established is the reliability of the high-concentration collector.

Advanced silicon (e.g., point contact) and gallium arsenide cells are projected to cost less per watt than either the mechanically stacked or monolithic multijunction cells. Although the multijunction cells have a higher efficiency potential, today's preliminary estimates of their future costs (in \$/cm^2) imply significantly higher module prices. The analysis of monolithic multijunction cells demonstrates the importance of both efficiency and cost. High-efficiency cell technology development without regard to cost is a losing strategy for a commercial product; cost reduction and cell-efficiency improvement are both required for low-cost concentrator modules.

B. CONCENTRATOR AND FLAT-PLATE SYSTEM COMPARISON

Concentrator systems with concentration ratios of 1000X, 500X and 200X are compared with two-axis tracking flat-plate systems in Southwestern (Phoenix), Southeastern (Miami) and Northeastern (Boston) locations based on their respective costs of energy generated. Due to the low levels of annual direct normal insolation falling in Northeastern and Southeastern locations, concentrators are calculated to have relatively high costs of energy. They are, therefore, not well suited to applications in these geographic regions. Flat-plate collectors fare relatively better in these locations (i.e., they have lower energy costs) due to their ability to take advantage of diffuse as well as direct insolation.

Energy costs for all photovoltaic technologies are lowest in the Southwest due to the high levels of annual insolation, both total and direct normal. Two-axis tracking flat-plate systems are projected to be uniformly lower in cost than all concentrator alternatives in Phoenix across all percentile rankings. Flat-plate system energy costs are on the order of $0.05/kWh cheaper than the lowest-costing concentrator (1000X) alternative (approximately $0.02/kWh, expressed in real 1982 dollars).

C. RECOMMENDATIONS

A result consistently demonstrated by this analysis is the lower-cost potential for high-concentration collectors (1000X and 500X) than for lower-concentration (200X) alternatives. Therefore, it is recommended that concentrator technology research activities focus on developing highly reliable, low-cost, high-concentration collectors. Module reliability testing and analysis is an important complement to high-concentration technology development activities. Development efforts for low concentration (≤200X) designs that can simultaneously provide information benefiting high concentration alternatives may also be worthwhile.

Continued analysis of concentrator PV collector technical capability and manufacturing cost is strongly recommended. Manufacturing cost analysis using either the IPEG (Reference 5) or SAMICS models for estimating prices of collectors using baseline silicon, advanced silicon, gallium arsenide and multijunction cells is the appropriate approach. Elements that were only briefly considered in this report but that should be expanded upon include: capital equipment cost, indirect costs, throughput rates, and yields. Additional process steps such as testing and optical alignment should also be included. In addition, as technology development proceeds, probabilistic input data updates should be made. Multijunction cell costs in particular should be re-evaluated at appropriate intervals. Revisions to input data should proceed on the basis of gathering technical experts at a single forum and attempting to achieve consensus on the probability distribution for each variable.

Extension and application of the methodology developed during this study is encouraged. Expanded thermal and reliability analyses would be useful. Increasing input data completeness (e.g., estimating cell efficiencies as a function of concentration level) also is suggested.

REFERENCES

1. Aster, R.W., A Projection of Flat-Plate Photovoltaic Technology in the Year 1985, JPL Internal Document No. 5101-261, Jet Propulsion Laboratory, Pasadena, California, in press.

2. Miles, Ralph F., Jr., The SIMRAND Methodology: SIMulation of Research ANd Development Projects, JPL Internal Document No. 5101-213, Jet Propulsion Laboratory, Pasadena, California, July 1, 1982.

3. National Photovoltaic Program Five-Year Research Plan, DOE/CE-0072, U.S. Department of Energy, Washington, D.C., May 1983.

4. Jones, Gary J., Energy Production Trade-Offs in Photovoltaic System Design, SAND82-2239, Sandia National Laboratories, Albuquerque, New Mexico, April, 1983.

5. Aster, Robert W., and Chamberlain, Robert G., Interim Price Estimation Guidelines: A Precursor and an Adjunct to SAMIS III, Version One, JPL Document No. 5101-33, Jet Propulsion Laboratory, Pasadena, California, September 10, 1977.

6. Otth, D.H. and Ross, R.G., "Assessing Photovoltaic Module Degradation and Lifetime from Long-Term Environmental Tests," Proceedings of the Institute for Environmenal Sciences, 1983 Technical Meeting, Los Angeles, California, April 19-21, 1983, pp. 121-126.

7. Reiter, Leonard J., et al., Rating Methods for Flat-Plate and Concentrator Photovoltaic Modules and Systems, JPL Internal Document No. 5220-27, Jet Propulsion Laboratory, Pasadena, California, October 15, 1984.

8. Hulstrom, Roland and Bird, Richard, "Comparison of Insolation Available to Two-Axis Tracking Flat-Plate, Two-Axis Tracking Concentrator, and Fixed Tilt Flat-Plate Surfaces at Phoenix, Arizona," SERI Inter-Office Memorandum RRA&I #1704, Solar Energy Research Institute, Golden, Colorado, April 13, 1984.

9. Borden, C., "Recommended Parameter Values for Five-Year Research Plan," JPL Photovoltaic Program Analysis and Integration Center Memorandum, PAIC:CSB:720-84-1697, Jet Propulsion Laboratory, Pasadena, California, February 13, 1984.

10. Henry, Paul K., SAMICS Analysis, Flat-Plate Solar Array Project, Jet Propulsion Laboratory, Pasadena, California, June 22, 1984.

BIBLIOGRAPHY

1. "A Probabilistic Assessment of the Potential for Various Silicon Sheet Materials to Attain a Given Price," Report of the JPL/SERI Study Team on the Assessment of Silicon Sheet Material, Jet Propulsion Laboratory, Pasadena, California, February 8, 1982.

2. Ferber, R.R., et al, Multijunction Cells for Concentrators: Technology Prospects, Issue Study, JPL Document No. 5230-13, JPL Publication 84-71, Jet Propulsion Laboratory, Pasadena, California, November 15, 1984.

3. Arvizu, Dan E., "PV Concentrator Cell Status and Projections," presented at the 19th IECEC Conference, San Francisco, California, August 1984.

4. Jackson, Byron, Advanced PV Module Costing Manual, SERI/TR-214-1965, Solar Energy Research Institute, Golden, Colorado, November 1983.

5. Benner, John, "High Efficiency Concepts," viewgraph presentation at DOE Headquarters, Solar Energy Research Institute, Golden, Colorado, April 9, 1984.

6. Harrison, J.W., Whisnant, R.A., briefing notes for project coordination and planning meeting at EPRI on April 2, 1984, EPRI Contract RP 1975-1, Research Triangle Institute, Research Triangle Park, North Carolina.

7. "PV Status and Prospects Assessment -- Cells and Modules," EPRI Contract RP 1975-1, briefing notes for Research Triangle Institute, Electric Power Research Institute, Palo Alto, California, August 9, 1984.

8. Kaminar, Neil, "Varian 1000X GaAs Module," Varian Associates, Palo Alto, California.

9. Bell, R.L., et al, Development of Mechanically-Stacked Multijunction Solar Cell for Concentrator Applications, Varian Associates, SAND83-7460, Palo Alto, California, February 1984

10. Edenburn, Michael W., and King, David L., "Cost-Effectiveness Comparison of Si, GaAs and Multijunction Concentrator Cells," 11th PV Concentrator Project Integration Meeting, Sandia National Laboratories, Albuquerque, December 13-14, 1983.

11. Maish, Alexander B., "PV Concentrator Array Reliability," 17th IEEE Photovoltaics Specialists Conference, Kissimmee, Florida, May 1-4, 1984.

12. Arvizu, D., "Development of Sandia 200X Experimental Silicon Module," 17th IEEE Photovoltaics Specialists Conference, Kissimmee, Florida, May 1-4, 1984.

13. Beavis, L., "Unique Material Challenges in PV Concentrator Modules," 17th IEEE Photovoltaics Specialists Conference, Kissimmee, Florida, May 1-4, 1984.

14. Edenburn, Michael W. and Boes, Eldon C., "PV Concentrators: Performance and Reliability Data and Future Design Directions," 17th IEEE PV Specialists Conference, Kissimmee, Florida, May 1-4, 198..

15. Maish, A.B. and Chiang, C.J., "Reliability and Performance Degradation of PV Concentrator Modules and Arrays During Outdoor Testing," 17th IEEE PV Specialists Conference, Kissimmee, Florida, May 1-4, 1984.

16. King, D.L. and Chiang, C.J., "Characterization of Performance Loss Mechanisms in a Concentrator PV Module," 17th IEEE PV Specialists Conference, Kissimmee, Florida, May 1-4, 1984.

17. Aster, R., "The E. Boes Price Prediction for Concentrator Costs," JPL Internal Memorandum 311.3-1003, November 15, 1983.

18. Stoiaken, Neil, "A New Generation of PV, Commercialization Efforts Gain Momentum," Alternative Sources of Energy, May-June 1984.

19. Sanders, John A., "The Concentrator Option," Photovoltaics International, June-July, 1984.

20. Taylor, Roger W., PV Systems Assessment: An Integrated Perspective, Electric Power Research Institute, Palo Alto, California, AP-3176-SR, Special Report, July 1983.

21. Proceedings of the 12th PV Concentrator Project Integration Meeting, Albuquerque, New Mexico, August 28-29, 1984.

22. Zimmerman, L.W., and Smith, J.L., "Sensitivities of Porjected 1990 Photovoltaic System Costs to Major System Cost Drivers," JPL Document No. 5220-28, JPL Publication 84-93, Jet Propulsion Laboratory, Pasadena, California, December 15, 1984.

23. Levy, S.L., Black and Veatch Engineers-Architects, High Concentration PV Array Conceptual Design, Research Project, RP1415-7, Draft Report, Electric Power Research Institute, July 1983.

24. Swanson, R.M., Point Contact Silicon Solar Cells, Electric Power Research Institute Research Project 790-2, AP-2859, Interim Report, Stanford University, Stanford, California, May 1983.

25. Design and Development of Low-Cost Photovoltaic Concentrator Collector Modules, Applied Solar Energy Corp., City of Industry, California, SAND83-7022, Sandia National Laboratories, Albuquerque, New Mexico, November 1983.

26. Hodge, R.C., Design and Development of a High Concentration Photovoltaic Concentrator, General Electric Co., SAND81-7007, Sandia National Laboratories, Albuquerque, New Mexico, April 1982.

27. Levy, S.L., and Stoddard, L.E., Integrated Photovoltaic Central Station Conceptual Design, Black and Veatch Engineers-Architects RP2197-1, Electric Power Research Institute, Palo Alto, California, June 1984.

28. Broadbent, Sidney, Second Generation Intersol Module Design, Evolution and Production Status, Intersol Power Corp., Lakewood, Colorado.

29. Sanders, John A., Second Generation Photovoltaic Concentrator Array Development, Intersol Power Corp., Lakewood, Colorado.

30. Shimada, Katsunori, Concentrator Collector Technology Progress and Status: FY1981, JPL Internal Document No. 5230-7, Jet Propulsion Laboratory, Pasadena, California, May 1, 1982.

31. Development of a Photovoltaic Concentrator Cell Assembly for Use in Point Focus Systems, General Electric Co., Space Systems Operations, SAND80-7139, Sandia National Laboratories, Albuquerque, New Mexico, December 1980.

32. Maish, Alexander B., PV Concentrator Array Installed Costs, Sandia National Laboratories, Albuquerque, New Mexico.

33. Hobbs, Robert B., Jr., Design and Development of a Laminated Fresnel Lens for Point Focus PV Systems, General Electric Co., SAND80-7137, Sandia National Laboratories, Albuquerque, New Mexico, January 1981.

34. Photovoltaic Power Systems Research Evaluation, A Report of the EPRI Ad Hoc Photovoltaic Advisory Committee, Strategies Unlimited, EPRI AP-3351, Project 1348-15, Final Report, Electric Power Research Institute December, 1983.

35. Diodes in Photovoltaic Modules and Arrays, General Electric Co., Advanced Energy Programs Dept., JPL Contract 956254, DOE/JPL-956-254-2, JPL Document No. 9950-916, Jet Propulsion Laboratory, Pasadena, California, March 15, 1984.

36. Boes, E.C., and Shafer, B.D., "PV Concentrator Technology," 15th IEEE Photovoltaics Specialists Conference, Kissimmee, Florida, May 1981.

37. Sanderson, R.W., and Backus, C.E., "The Behavior of Silicon Concentrator Solar Cells Between 50 and 500 Suns," 15th IEEE PV Specialists Conference, Kissimmee, Florida, May 1981.

38. Stilwell, C.B. and Shafer, B.D., "Compatibility of Fresnel Lenses and PV Cells in Concentrator Modules," 15th IEEE PV Specialists Conference, Kissimmee, Florida, May 1981.

APPENDIX A

SIMRAND DESCRIPTION

The SIMRAND methodology is designed to aid in the decision processes to select the optimal set of tasks to be funded in a Research and Development project (Reference A-1). It has been used successfully in previous photovoltaics studies (References A-2 and A-3). The SIMRAND methodology is implemented as a Monte Carlo simulation program that can:

(1) Determine the cumulative distribution function (CDF) of the cost of a least cost path in a network of paths with uncertain edge costs.

(2) Perform a risk analysis by combining the utility functions of the decision makers with the computed cumulative distribution function.

In this study, SIMRAND is used to compute the cumulative distribution function of the cost of a solar concentrator module based on probabilistic assessments of the cost of the manufacturing processing steps needed to produce the module and probabilistic assessments of the performance of the components of the module. The cost of a solar module is determined by a set of equations relating the total cost of the module to the module processing step costs and to module performance. The cost and performance variables are given by $X_1, \ldots, X_{15}$ (Section II, List 1). The cost equations are described in Section II (List 3 and Equations 1-5). Associated with each variable $X_1, \ldots, X_{15}$ is one or more cumulative distribution functions obtained from experts in solar concentrator technology. These distributions are defined in Section II, List 2. What remains to be described is the network of paths and the relationship between the input variables, the input distribution functions and the paths in the network.

The network is a set of 120 paths. Each path in the network corresponds exactly to a choice of a distribution function for each input variable $X_1, \ldots, X_{15}$ and reflects a technology choice for each module component. For example, a path that uses distributions D_3 (advanced-silicon cell cost) and D_4 (advanced-silicon cell efficiency) to select values for X_1 (cell cost) and X_2 (cell efficiency) is a path using the advanced-silicon cell technology. The solar concentrator network (paths) used in this study is given in Table A-1. Across each horizontal row, each entry corresponds to a choice of distribution for the column variable. As an example, note that path 30 corresponds to a choice of a gallium arsenide (GaAs) cell technology (D_5, D_6), injection-molded lens technology (D_{20}, D_{21}) and plastic housing (D_{15}, D_{26}) at a concentration level of 500X. (See Lists 1 and 2 for the definitions of the X_i's and D_i's.)

An algorithmic description of SIMRAND follows Table A-1. Each run of SIMRAND consists of 500 Monte Carlo trials. For each trial, module costs and system-level costs are computed for each path in the network. The path with the smallest system-level cost is identified (OPTPATH) and its associated component and module costs are saved in a histogram. At the end of 500 trials, a cumulative distribution of the saved costs is generated. A histogram of the frequency with which each path is selected as optimal is also generated. No risk analysis is performed for this study.

Table A-1. Solar Concentrator Network Paths

Path	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
CONC = 200X															
1	1	2	11	12	14	15	17	18	19	26	28	29	30	33	34
2	1	2	11	12	14	15	17	20	21	26	28	29	30	33	34
3	1	2	11	12	14	15	17	22	23	26	28	29	30	33	34
4	1	2	11	12	14	15	17	24	25	26	28	29	30	33	34
5	3	4	11	12	14	15	17	18	19	26	28	29	30	33	34
6	3	4	11	12	14	15	17	20	21	26	28	29	30	33	34
7	3	4	11	12	14	15	17	22	23	26	28	29	30	33	34
8	3	4	11	12	14	15	17	24	25	26	28	29	30	33	34
9	1	2	11	12	14	16	17	18	19	27	28	29	30	33	34
10	1	2	11	12	14	16	17	20	21	27	28	29	30	33	34
11	1	2	11	12	14	16	17	22	23	27	28	29	30	33	34
12	1	2	11	12	14	16	17	24	25	27	28	29	30	33	34
13	3	4	11	12	14	16	17	18	19	27	28	29	30	33	34
14	3	4	11	12	14	16	17	20	21	27	28	29	30	33	34
15	3	4	11	12	14	16	17	22	23	27	28	29	30	33	34
16	3	4	11	12	14	16	17	24	25	27	28	29	30	33	34
17	1	2	11	12	14	32	17	18	19	31	28	29	30	33	34
18	1	2	11	12	14	32	17	20	21	31	28	29	30	33	34
19	1	2	11	12	14	32	17	22	23	31	28	29	30	33	34
20	1	2	11	12	14	32	17	24	25	31	28	29	30	33	34
21	3	4	11	12	14	32	17	18	19	31	28	29	30	33	34
22	3	4	11	12	14	32	17	20	21	31	28	29	30	33	34
23	3	4	11	12	14	32	17	22	23	31	28	29	30	33	34
24	3	4	11	12	14	32	17	24	25	31	28	29	30	33	34
CONC = 500X															
25	3	4	11	12	13	15	17	18	19	26	28	29	30	33	34
26	3	4	11	12	13	15	17	20	21	26	28	29	30	33	34
27	3	4	11	12	13	15	17	22	23	26	28	29	30	33	34
28	3	4	11	12	13	15	17	24	25	26	28	29	30	33	34
29	5	6	11	12	13	15	17	18	19	26	28	29	30	33	34
30	5	6	11	12	13	15	17	20	21	26	28	29	30	33	34
31	5	6	11	12	13	15	17	22	23	26	28	29	30	33	34
32	5	6	11	12	13	15	17	24	25	26	28	29	30	33	34
33	7	8	11	12	13	15	17	18	19	26	28	29	30	33	34
34	7	8	11	12	13	15	17	20	21	26	28	29	30	33	34
35	7	8	11	12	13	15	17	22	23	26	28	29	30	33	34
36	7	8	11	12	13	15	17	24	25	26	28	29	30	33	34
37	9	10	11	12	13	15	17	18	19	26	28	29	30	33	34
38	9	10	11	12	13	15	17	20	21	26	28	29	30	33	34
39	9	10	11	12	13	15	17	22	23	26	28	29	30	33	34
40	9	10	11	12	13	15	17	24	25	26	28	29	30	33	34
41	3	4	11	12	13	16	17	18	19	27	28	29	30	33	34
42	3	4	11	12	13	16	17	20	21	27	28	29	30	33	34
43	3	4	11	12	13	16	17	22	23	27	28	29	30	33	34
44	3	4	11	12	13	16	17	24	25	27	28	29	30	33	34

Table A-1. Solar Concentrator Network Paths (Cont'd)

Path	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
CONC = 500X															
45	5	6	11	12	13	16	17	18	19	27	28	29	30	33	34
46	5	6	11	12	13	16	17	20	21	27	28	29	30	33	34
47	5	6	11	12	13	16	17	22	23	27	28	29	30	33	34
48	5	6	11	12	13	16	17	24	25	27	28	29	30	33	34
49	7	8	11	12	13	16	17	18	19	27	28	29	30	33	34
50	7	8	11	12	13	16	17	20	21	27	28	29	30	33	34
51	7	8	11	12	13	16	17	22	23	27	28	29	30	33	34
52	7	8	11	12	13	16	17	24	25	27	28	29	30	33	34
53	9	10	11	12	13	16	17	18	19	27	28	29	30	33	34
54	9	10	11	12	13	16	17	20	21	27	28	29	30	33	34
55	9	10	11	12	13	16	17	22	23	27	28	29	30	33	34
56	9	10	11	12	13	16	17	24	24	27	28	29	30	33	34
57	3	4	11	12	13	32	17	18	19	31	28	29	30	33	34
58	3	4	11	12	13	32	17	20	21	31	28	29	30	33	34
59	3	4	11	12	13	32	17	22	23	31	28	29	30	33	34
60	3	4	11	12	13	32	17	24	25	31	28	29	30	33	34
61	5	6	11	12	13	32	17	18	19	31	28	29	30	33	34
62	5	6	11	12	13	32	17	20	21	31	28	29	30	33	34
63	5	6	11	12	13	32	17	22	23	31	28	29	30	33	34
64	5	6	11	12	13	32	17	24	25	31	28	29	30	33	34
65	7	8	11	12	13	32	17	18	19	31	28	29	30	33	34
66	7	8	11	12	13	32	17	20	21	31	28	29	30	33	34
67	7	8	11	12	13	32	17	22	23	31	28	29	30	33	34
68	7	8	11	12	13	32	17	24	25	31	28	29	30	33	34
69	9	10	11	12	13	32	17	18	19	31	28	29	30	33	34
70	9	10	11	12	13	32	17	20	21	31	28	29	30	33	34
71	9	10	11	12	13	32	17	22	23	31	28	29	30	33	34
72	9	10	11	12	13	32	17	24	25	31	28	29	30	33	34
CONC = 1000X															
73	3	4	11	12	13	15	17	18	19	26	28	29	30	33	34
74	3	4	11	12	13	15	17	20	21	26	28	29	30	33	34
75	3	4	11	12	13	15	17	22	23	26	28	29	30	33	34
76	3	4	11	12	13	15	17	24	25	26	28	29	30	33	34
77	5	6	11	12	13	15	17	18	19	26	28	29	30	33	34
78	5	6	11	12	13	15	17	20	21	26	28	29	30	33	34
79	5	6	11	12	13	15	17	22	23	26	28	29	30	33	34
80	5	6	11	12	13	15	17	24	25	26	28	29	30	33	34
81	7	8	11	12	13	15	17	18	19	26	28	29	30	33	34
82	7	8	11	12	13	15	17	20	21	26	28	29	30	33	34
83	7	8	11	12	13	15	17	22	23	26	28	29	30	33	34
84	7	8	11	12	13	15	17	24	25	26	28	29	30	33	34
85	9	10	11	12	13	15	17	18	19	26	28	29	30	33	34
86	9	10	11	12	13	15	17	20	21	26	28	29	30	33	34
87	9	10	11	12	13	15	17	22	23	26	28	29	30	33	34
88	9	10	11	12	13	15	17	24	25	26	28	29	30	33	34

Table A-1. Solar Concentrator Network Paths (Cont'd)

Path	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	X_{14}	X_{15}
CONC = 1000X															
89	3	4	11	12	13	16	17	18	19	27	28	29	30	33	34
90	3	4	11	12	13	16	17	20	21	27	28	29	30	33	34
91	3	4	11	12	13	16	17	22	23	27	28	29	30	33	34
92	3	4	11	12	13	16	17	24	25	27	28	29	30	33	34
93	5	6	11	12	13	16	17	18	19	27	28	29	30	33	34
94	5	6	11	12	13	16	17	20	21	27	28	29	30	33	34
95	5	6	11	12	13	16	17	22	23	27	28	29	30	33	34
96	5	6	11	12	13	16	17	24	25	27	28	29	30	33	34
97	7	8	11	12	13	16	17	18	19	27	28	29	30	33	34
98	7	8	11	12	13	16	17	20	21	27	28	29	30	33	34
99	7	8	11	12	13	16	17	22	23	27	28	29	30	33	34
100	7	8	11	12	13	16	17	24	25	27	28	29	30	33	34
101	9	10	11	12	13	16	17	18	19	27	28	29	30	33	34
102	9	10	11	12	13	16	17	20	21	27	28	29	30	33	34
103	9	10	11	12	13	16	17	22	23	27	28	29	30	33	34
104	9	10	11	12	13	16	17	24	25	27	28	29	30	33	34
105	3	4	11	12	13	32	17	18	19	31	28	29	30	33	34
106	3	4	11	12	13	32	17	20	21	31	28	29	30	33	34
107	3	4	11	12	13	32	17	22	23	31	28	29	30	33	34
108	3	4	11	12	13	32	17	24	25	31	28	29	30	33	34
109	5	6	11	12	13	32	17	18	19	31	28	29	30	33	34
110	5	6	11	12	13	32	17	20	21	31	28	29	30	33	34
111	5	6	11	12	13	32	17	22	23	31	28	29	30	33	34
112	5	6	11	12	13	32	17	24	25	31	28	29	30	33	34
113	7	8	11	12	13	32	17	18	19	31	28	29	30	33	34
114	7	8	11	12	13	32	17	20	21	31	28	29	30	33	34
115	7	8	11	12	13	32	17	22	23	31	28	29	30	33	34
116	7	8	11	12	13	32	17	24	25	31	28	29	30	33	34
117	9	10	11	12	13	32	17	18	19	31	28	29	30	33	34
118	9	10	11	12	13	32	17	20	21	31	28	29	30	33	34
119	9	10	11	12	13	32	17	22	23	31	28	29	30	33	34
120	9	10	11	12	13	32	17	24	25	31	28	29	30	33	34

SIMRAND ALGORITHM[1]

For each trial

SYSMIN: = ∞ (∞ is a value larger than any possible system level cost)

Select a random value from each distribution $D_1, \ldots, D_{34}$;
For each path p

Assign random values to each variable $X_1, \ldots, X_{15}$;[2]
Compute cost of production steps;
Compute total module cost;
Compute system level cost;
If system level cost   SYSMIN then

SYSMIN = system level cost;
OPTMODCOST = total module cost;
OPTPATH = p;

End loop on paths;
save OPTPATH and OPTMODCOST[3]

End loop on trials;
output the cumulative distribution function of the saved OPTMODCOST values;
output the histogram of optimal paths (from the saved OPTPATH values).

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[1]This is a high-level description of the part of the SIMRAND code used in this study.

[2]Immediately after entry to the "For" loop over trials, a random number is selected from each distribution $D_1, \ldots, D_{34}$ and saved as $v_1, \ldots, v_{34}$, respectively. To assign a value to X_i on path p, set k = the distribution corresponding to variable X_i on path p in the solar concentrator network (Table A-1) and let $X_i = v_k$.

[3]The optimal path and its associated total module cost for this trial are added to optimal path and cost histograms.)

REFERENCES

A-1. Miles, Ralph F., Jr., The SIMRAND Methodology, JPL Internal Document No. 5101-213, Jet Propulsion Laboratory, Pasadena, California, March 1, 1982.

A-2. Aster, R.W., A Projection of Flat-Plate Photovoltaic Technology in the Year 1995, JPL Internal Document No. 5101-261, Jet Propulsion Laboratory, Pasadena, California, in press.

A-3. "A Probabilistic Assessment of the Potential for Various Silicon Sheet Materials to Attain a Given Price," Report of the JPL/SERI Study Team on the Assessment of Silicon Sheet Material, Jet Propulsion Laboratory, Pasadena, California, February 8, 1982.

APPENDIX B

SIMRAND INPUT DATA (CONCENTRATOR)

A. INPUT CUMULATIVE DISTRIBUTIONS

In this study, the Simulation of Research and Development Projects (SIMRAND) methodology was used to compute the price of a solar concentrator module based on probabilistic assessments of the cost of the production steps needed to produce the module and of the performance of the module components (e.g., cell and lens efficiency). Cumulative probability distributions for the cost and performance variables were collected from experts in solar concentrator module technology:

Applied Solar Energy Corporation

Frank Ho

Black & Veatch

Sheldon Levy
Larry Stoddard

Intersol Corporation

Sid Broadbent
John Sanders

Jet Propulsion Laboratory

Robert Aster
Dale Burger
Paul Henry
R. G. Ross, Jr.
Katsunori Shimada
Russell Sugimura

Research Triangle Institute

Bill Harrison

Sandia National Laboratory

Dan Arvizu
Len Beavis
Mike Edenburn
James Gee
Alex Maish
Ben Rose
Rebecca Siegel
Charlie Stillwell

Solar Energy Research Institute

John Benner

Stanford University

Dick Swansor

Varian Corporation

Neil Kaminar

The experts were interviewed in person or by telephone by the authors. For each production step of which the expert had knowledge, he or she was asked:

(1) What is the probability that current Research and Development (R&D) efforts for this production step will be successful?

(2) Given that current R&D efforts are successful by 1990-1992, and that there is a 50 to 100 MW per year factory production scale for solar concentrator modules, what do you foresee as the range of costs (or performance values) for this production step in the mid-1990's?

(3) A further set of questions was posed to elicit the expert's subjective probability distribution for the given variable.

In several instances, information in the existing literature on concentrator module technology was used to supplement the information provided by the interviews. There were 34 random variables $D_1, \ldots, D_{34}$ (List 2) for which probability distributions were collected. For each random variable, one to five experts gave their opinions as to the mid-1990's probability distribution of the variable. To assure comparability with other studies and among the experts, the experts' raw input data were modified using standard financial parameters. If the given cost distribution for a manufacturing activity reflected materials and labor only, the costs were multiplied by 1.5 to reflect capital equipment costs, general and administrative (G&A) costs, and profit. If the given cost distribution reflected a component's purchase price rather than a manufacturing cost, the costs were multiplied by 1.2 to reflect G&A costs and profit.

The experts' probability distributions for each variable were combined into a single probability distribution by giving equal weight to each expert's opinion, using the formula:

$$\text{Prob}\ [D_i \le d] = \frac{1}{n} \sum_{k=1}^{n} \text{Prob}\ [D_{i,k} \le d]$$

where n = number of experts giving a probability distribution for random variable D_i

$D_{i,k}$ = probability distribution of D_i given by the k^{th} expert

No attempt was made to smooth the resulting combined distributions. The combined distributions are listed in Table B-1. All cost inputs are in 1984 dollars.

Associated with each distribution is the probability of success of the corresponding technology and a default cost or performance value to be used in case of technology failure. The default value reflects either present values for the technology, present values of a competing technology, or a very high cost or low efficiency value depicting failure. To select random values from distributions $D_1, \ldots, D_{34}$, the SIMRAND simulation model first determines stochastically whether or not there has been a technology failure related to the particular distribution. In the case of a failure, the default value is used; otherwise the distribution is used. In the case of cell (or lens) technology failure, the cell (or lens) either fails on both the cost and the efficiency attribute or succeeds on both the cost and efficiency attribute. For each distribution in Table B-1, the first pair of numbers is the probability of successful R&D computed as the means of the responses from the experts, followed by the default value of the distribution if R&D is not successful. The remainder of the number pairs are the value, percentile pairs for the distribution of the random variable, given that current R&D efforts are successful. For example, distribution D_5 gives the cumulative distribution function of the cost of a gallium arsenide cell in $/cm^2$, given that the current GaAs cell R&D is successful.

Table B-1. SIMRAND Input Distributions

D1 Baseline Silicon Cell Cost ($/cm2)
Probability of Success = 0.9830 Default Value = 0.3600

Value	Cumulative Probability
0.0600	0.0000
0.0900	0.0951
0.1200	0.3152
0.1500	0.5978
0.1800	0.6389
0.2100	0.7222
0.2400	0.8000
0.2700	0.8750
0.3000	0.9167
0.3300	0.9583
0.3600	1.0000

D2 Baseline Silicon Cell Efficiency (fraction)
Probability of Success = 0.9830 Default Value = 0.1950

Value	Cumulative Probability
0.2000	0.0000
0.2020	0.0971
0.2040	0.1943
0.2060	0.2914
0.2080	0.3886
0.2100	0.4859
0.2121	0.5884
0.2141	0.6909
0.2161	0.7934
0.2181	0.8959
0.2201	1.0000

D3 Advanced Silicon Cell Cost ($/cm2)
Probability of Success = 0.7750 Default Value = 5.0000

Value	Cumulative Probability
0.1200	0.0000
0.2170	0.0989
0.3140	0.2883
0.4110	0.4711
0.5080	0.5993
0.6050	0.6667
0.7020	0.6667
0.7990	0.6667
0.8960	0.6667
0.9930	0.6667
1.0900	1.0000

Table B-1. SIMRAND Input Distributions

D1 Baseline Silicon Cell Cost ($/cm2)

Probability of Success = 0.9830 Default Value = 0.3600

Value	Cumulative Probability
0.0600	0.0000
0.0900	0.0951
0.1200	0.3152
0.1500	0.5978
0.1800	0.6389
0.2100	0.7222
0.2400	0.8000
0.2700	0.8750
0.3000	0.9167
0.3300	0.9583
0.3600	1.0000

D2 Baseline Silicon Cell Efficiency (fraction)

Probability of Success = 0.9830 Default Value = 0.1950

Value	Cumulative Probability
0.2000	0.0000
0.2020	0.0971
0.2040	0.1943
0.2060	0.2914
0.2080	0.3886
0.2100	0.4859
0.2121	0.5884
0.2141	0.6909
0.2161	0.7934
0.2181	0.8959
0.2201	1.0000

D3 Advanced Silicon Cell Cost ($/cm2)

Probability of Success = 0.7750 Default Value = 5.0000

Value	Cumulative Probability
0.1200	0.0000
0.2170	0.0989
0.3140	0.2883
0.4110	0.4711
0.5080	0.5993
0.6050	0.6667
0.7020	0.6667
0.7990	0.6667
0.8960	0.6667
0.9930	0.6667
1.0900	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D4 Advanced Silicon Cell Efficiency (fraction)

Probability of Success = 0.7750 Default Value = 0.2100

Value	Cumulative Probability
0.2100	0.0000
0.2190	0.0541
0.2280	0.1282
0.2370	0.4258
0.2460	0.5295
0.2550	0.5967
0.2641	0.6355
0.2731	0.6742
0.2821	0.7785
0.2911	0.8849
0.3001	1.0000

D5 Gallium Arsenide Cell Cost ($/cm2)

Probability of Success = 0.9000 Default Value = 10.0000

Value	Cumulative Probability
0.5600	0.0000
1.1040	0.5840
1.6480	0.6560
2.1920	0.7240
2.7360	0.7780
3.2800	0.8233
3.8240	0.8687
4.3680	0.9140
4.9120	0.9547
5.4560	0.9773
6.0000	1.0000

D6 Gallium Arsenide Cell Efficiency (fraction)

Probability of Success = 0.9000 Default Value = 0.2300

Value	Cumulative Probability
0.2300	0.0000
0.2370	0.0875
0.2440	0.1750
0.2510	0.2675
0.2580	0.3900
0.2650	0.4781
0.2720	0.5475
0.2790	0.6044
0.2860	0.7287
0.2930	0.8644
0.3000	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D7 Mechanically Stacked Cell Cost ($/cm2)
Probability of Success = 0.8125 Default Value = 100.0000

Value	Cumulative Probability
0.9000	0.0000
2.0100	0.1830
3.1200	0.3550
4.2300	0.4994
5.3400	0.6192
6.4500	0.7271
7.5600	0.8250
8.6700	0.9021
9.7800	0.9537
10.8900	0.9769
12.0000	1.0000

D8 Mechanically Stacked Cell Efficiency (fraction)
Probability of Success = 0.8125 Default Value = 0.1000

Value	Cumulative Probability
0.2200	0.0000
0.2350	0.0500
0.2500	0.1000
0.2650	0.3250
0.2800	0.4000
0.2950	0.4875
0.3100	0.7750
0.3250	0.9083
0.3400	0.9333
0.3550	0.9700
0.3700	1.0000

D9 Monolithic Cell Cost ($/cm2)
Probability of Success = 0.6250 Default Value = 100.0000

Value	Cumulative Probability
29.9900	0.0000
29.9920	0.1000
29.9940	0.2000
29.9960	0.3000
29.9980	0.4000
30.0000	0.5000
30.0020	0.6000
30.0040	0.7000
30.0060	0.8000
30.0080	0.9000
30.0100	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D10 Monolithic Cell Efficiency (fraction)

Probability of Success = 0.6250 Default Value = 0.1000

Value	Cumulative Probability
0.2500	0.0000
0.2600	0.0075
0.2700	0.0152
0.2800	0.1061
0.2900	0.1970
0.3000	0.2885
0.3101	0.4937
0.3201	0.6978
0.3301	0.7403
0.3401	0.7832
0.3501	1.0000

D11 Secondary Optical Element Cost ($ each)

Probability of Success = 1.0000 Default Value = 0.6100

Value	Cumulative Probability
0.0600	0.0000
0.1150	0.1833
0.1700	0.3667
0.2250	0.4000
0.2800	0.4000
0.3350	0.4000
0.3900	0.7600
0.4450	0.8000
0.5000	0.8000
0.5550	0.8000
0.6100	1.0000

D12 Substrate ($/cm2)

Probability of Success = 1.0000 Default Value = 0.2930

Value	Cumulative Probability
0.1100	0.0000
0.1283	0.4575
0.1466	0.5000
0.1649	0.5000
0.1832	0.5000
0.2015	0.5000
0.2198	0.5000
0.2381	0.5000
0.2564	0.5000
0.2747	0.5425
0.2930	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D13 Heatspreader ($ each)
Probability of Success = 1.0000 Default Value = 0.1780

Value	Cumulative Probability
0.1400	0.0000
0.1438	0.0950
0.1476	0.1900
0.1514	0.2850
0.1552	0.3800
0.1590	0.5000
0.1628	0.6200
0.1666	0.7150
0.1704	0.8100
0.1742	0.9050
0.1780	1.0000

D14 No Heatspreader
Probability of Success = 1.0000 Default Value = 0.0000

Value	Cumulative Probability
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000

D15 Heatsink for Plastic Housing ($/m2 aperture)
Probability of Success = 1.0000 Default Value = 21.2200

Value	Cumulative Probability
14.7400	0.0000
15.3880	0.6667
16.0360	0.6667
16.6840	0.6667
17.3320	0.6667
17.9800	0.6667
18.6280	0.6667
19.2760	0.6667
19.9240	0.6667
20.5720	0.6667
21.2200	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D16 No Heat Sink

Probability of Success = 1.0000 Default Value = 0.0000

Value	Cumulative Probability
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000
0.0000	0.0000

D17 Cell Packaging Costs ($/cell assembly)

Probability of Success = 1.0000 Default Value = 1.2100

Value	Cumulative Probability
0.3000	0.0000
0.3910	0.3333
0.4820	0.3333
0.5730	0.3333
0.6640	0.3333
0.7550	0.3333
0.8460	0.6000
0.9370	0.6667
1.0280	0.6667
1.1190	0.6667
1.2100	1.0000

D18 Compression Molded Lens Cost ($/m2)

Probability of Success = 1.0000 Default Value = 74.4100

Value	Cumulative Probability
32.2800	0.0000
36.4930	0.0544
40.7060	0.1088
44.9190	0.1632
49.1320	0.2490
53.3450	0.4204
57.5580	0.5918
61.7710	0.6667
65.9840	0.6667
70.1970	0.6667
74.4100	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D19 Compression Molded Lens Efficiency (fraction)
Probability of Success = 1.0000 Default Value = 0.8200

Value	Cumulative Probability
0.8200	0.0000
0.8225	0.1250
0.8250	0.2500
0.8275	0.3750
0.8300	0.5000
0.8325	0.5833
0.8350	0.6667
0.8375	0.7500
0.8400	0.8333
0.8425	0.9167
0.8450	1.0000

D20 Injection Molded Lens Cost ($/m2)
Probability of Success = 0.7250 Default Value = 74.4100

Value	Cumulative Probability
7.7500	0.0000
9.5570	0.0333
11.3640	0.0667
13.1710	0.1000
14.9780	0.1534
16.7850	0.2495
18.5920	0.3789
20.3990	0.7750
22.2060	0.8710
24.0130	0.9667
25.8200	1.0000

D21 Injection Molded Lens Efficiency (fraction)
Probability of Success = 0.7250 Default Value = 0.8200

Value	Cumulative Probability
0.7500	0.0000
0.7610	0.0917
0.7720	0.1833
0.7830	0.2607
0.7940	0.3000
0.8050	0.3393
0.8160	0.3786
0.8270	0.4179
0.8380	0.5905
0.8490	0.8131
0.8600	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D22 Lens Film Cost ($/m2)

Probability of Success = 0.9500 Default Value = 69.8500

Value	Cumulative Probability
12.0000	0.0000
17.7850	0.2678
23.5700	0.3333
29.3550	0.3333
35.1400	0.6667
40.9250	0.6667
46.7100	0.6667
52.4950	0.6667
58.2800	0.6667
64.0650	0.6667
69.8500	1.0000

D23 Lens Film Efficiency (fraction)

Probability of Success = 0.9500 Default Value = 0.7850

Value	Cumulative Probability
0.8200	0.0000
0.8220	0.1000
0.8240	0.2000
0.8260	0.3000
0.8280	0.4000
0.8300	0.5000
0.8320	0.6000
0.8340	0.7000
0.8360	0.8000
0.8380	0.9000
0.8400	1.0000

D24 Direct Poly/Glass Lens Cost ($/m2)

Probability of Success = 0.8500 Default Value = 74.4100

Value	Cumulative Probability
25.1900	0.0000
25.8990	0.5076
26.6080	0.5623
27.3170	0.6171
28.0260	0.6718
28.7350	0.7265
29.4440	0.7812
30.1530	0.8359
30.8620	0.8906
31.5710	0.9453
32.2800	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D25 Direct Poly/Glass Lens Efficiency (fraction)
Probability of Success = 0.8500 Default Value = 0.8200

Value	Cumulative Probability
0.8200	0.0000
0.8220	0.1000
0.8240	0.2000
0.8260	0.3000
0.8280	0.4000
0.8300	0.5000
0.8320	0.6000
0.8340	0.7000
0.8360	0.8000
0.8380	0.9000
0.8400	1.0000

D26 Plastic Housing ($/m2 aperture)
Probability of Success = 1.0000 Default Value = 36.5000

Value	Cumulative Probability
26.8000	0.0000
27.7700	0.0500
28.7400	0.1000
29.7100	0.1500
30.6800	0.2000
31.6500	0.7500
32.6200	0.8000
33.5900	0.8500
34.5600	0.9000
35.5300	0.9500
36.5000	1.0000

D27 Aluminum Housing ($/m2 aperture)
Probability of Success = 1.0000 Default Value = 77.2500

Value	Cumulative Probability
43.0500	0.0000
46.4700	0.3333
49.8900	0.3333
53.3100	0.6667
56.7300	0.6667
60.1500	0.6667
63.5700	0.6667
66.9900	0.6667
70.4100	0.6667
73.8300	0.6667
77.2500	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D28 Interconnects/Bypass Diodes ($/cell assembly)

Probability of Success = 1.0000 Default Value = 0.5800

Value	Cumulative Probability
0.2300	0.0000
0.2650	0.6167
0.3000	0.6667
0.3350	0.6667
0.3700	0.6667
0.4050	0.6667
0.4400	0.6667
0.4750	0.6667
0.5100	0.6667
0.5450	0.6667
0.5800	1.0000

D29 Module Assembly ($/m2 aperture)

Probability of Success = 1.0000 Default Value = 19.3600

Value	Cumulative Probability
3.7400	0.0000
5.3020	0.5000
6.8640	0.5000
8.4260	0.5000
9.9880	0.5000
11.5500	0.5000
13.1120	0.5000
14.6740	0.5000
16.2360	0.5000
17.7980	0.5000
19.3600	1.0000

D30 Balance of Module Efficiency (fraction)

Probability of Success = 1.0000 Default Value = 0.9799

Value	Cumulative Probability
0.9799	0.0000
0.9809	0.5000
0.9819	0.5000
0.9830	0.5000
0.9840	0.5000
0.9850	0.5000
0.9860	0.5000
0.9870	0.5000
0.9881	0.5000
0.9891	0.5000
0.9901	1.0000

D31 Steel Housing ($/m2 aperture)
Probability of Success = 1.0000 Default Value = 39.1600

Value	Cumulative Probability
39.1400	0.0000
39.1420	0.1000
39.1440	0.2000
39.1460	0.3000
39.1480	0.4000
39.1500	0.5000
39.1520	0.6000
39.1540	0.7000
39.1560	0.8000
39.1580	0.9000
39.1600	1.0000

D32 Heatsink for Steel Housing ($/m2 aperture)
Probability of Success = 1.0000 Default Value = 11.0100

Value	Cumulative Probability
10.9900	0.0000
10.9920	0.1000
10.9940	0.2000
10.9960	0.3000
10.9980	0.4000
11.0000	0.5000
11.0020	0.6000
11.0040	0.7000
11.0060	0.8000
11.0080	0.9000
11.0100	1.0000

D33 AR Coating for Lens Back ($/m2)
Probability of Success = 1.0000 Default Value = 5.0000

Value	Cumulative Probability
2.5000	0.0000
2.7500	0.0683
3.0000	0.1366
3.2500	0.2049
3.5000	0.2732
3.7500	0.3415
4.0000	0.4098
4.2500	0.4781
4.5000	0.6269
4.7500	0.8134
5.0000	1.0000

Table B-1. SIMRAND Input Distributions (Cont'd)

D34 AR Coat Lens Efficiency Increase (fraction)

Probability of Success = 1.0000 Default Value = 0.0250

Value	Cumulative Probability
0.0250	0.0000
0.0255	0.0510
0.0260	0.1020
0.0265	0.1530
0.0270	0.2040
0.0275	0.2550
0.0281	0.3060
0.0286	0.3570
0.0291	0.4080
0.0296	0.4590
0.0301	1.0000

B. MODEL CONSTANTS

In addition to the probability distributions shown above, a number of constants (Table B-2) are used to size and cost concentrator module components: Several constants depend on the concentration level being evaluated. These constants relate to the cell and cell assembly as either sizing parameters (cell active area ratio and ratio of substrate area to cell area) or thermal parameters (cell operating temperature above ambient and coefficient of cell efficiency with respect to cell temperature). Manufacturing-related parameters have also been included. In particular, a cell-type-specific correction for potential laboratory efficiency to achievable efficiency in a manufacturing environment and a manufacturing yield for each step in the production process are included.

To compare the costs of different module production steps without regard to a particular "brand name" module, a lens area of 8 in. square = 0.4128 m^2 per cell assembly area has been assumed. In this way, all cell assembly costs can be collected in \$ per cell assembly or \$/m^2 lens aperture area and then converted to \$/W.

A consequence of the lens area assumption and the assumption that all of the concentration is performed by the lens is that the active cell area is 2.064 cm^2, for a concentration of 200X, 0.8256 cm^2 for a concentration of 500X and 0.4128 cm^2 for a concentration of 1000X. The constant ACTIVE is the fraction of the total cell area that is active.

The substrate-to-cell-area-ratio sizes the substrate needed to support a concentrator cell of a given size. This ratio was computed assuming that an extra 1/8 in. is added to one side of the total cell area.

To correct the cell temperature from Standard Test Conditions to Standard Operating Conditions (900 w/m^2 and 20°C ambient air temperature), the following formula is used:

$$\eta_{soc} = \eta_{stc}\ (1 + \text{Temp.coef} \times \text{Temp.diff})$$

where Temp.coef = relative change in cell efficiency per increase of 1°C in cell temperature

Temp.diff = average temperature differential between 25°C cell temperature and the nominal operating cell temperature at a given concentration level.

The Lab-to-Commercial factor is used to correct the cell efficiency estimates from laboratory efficiencies to cell efficiencies achievable in mass production. All cell efficiency inputs in this study are assumed to be for laboratory efficiency at Standard Test Conditions (1000 W/m^2, 25°C cell temperature).

Table B-2. Solar Concentrator Network Model Constants

CONC = 200X, 500X or 1000X (Concentration level)

Substrate-to-cell-area ratio

1.156 at 200X
1.271 at 500X
1.398 at 1000X

ACTIVE

0.5 at 200X
0.6 at 500X
0.65 at 1000X

DNSI = 900 W/m^2 (Direct normal solar insolation)

Temp.coef

-0.0035	using baseline silicon cells
-0.0028	using advanced silicon cells
-0.0020	using gallium arsenide, stacked multijunction, or monolithic multijunction cells

Temp.diff

45°C at 200X
48°C at 500X
52°C at 1000X

Lab-to-Commercial

0.90	using baseline silicon, advanced silicon and gallium arsenide cells.
0.80	using stacked multijunction or monolithic multijunction cells.

ABOS = $100/$m^2$ (array balance of system cost)

DEFL = 1.085 (GNP Implicit Price Deflator to deflate cost inputs in 1984 dollars to 1982 dollars)

C. PRODUCTION PROCESS YIELD INPUTS

The yield rates used for the production processes are shown in Table B-3:

Table B-3. Production Process Yield Inputs

Y_1	Cell yield due to cell assembly step	= 0.98
Y_2	Cell yield due to module assembly step	= 0.98
Y_3	SOE yield due to cell assembly step	= 0.98
Y_4	Heat spreader yield due to cell assembly step	= 0.98
Y_5	Heat sink yield due to cell assembly step	= 0.98
Y_6	Substrate yield due to cell assembly step	= 0.98
Y_7	Cell packaging yield due to cell assembly step	= 0.95
Y_8	Cell packaging yield due to module assembly step	= 0.98
Y_9	Lens yield due to lens assembly step	= 0.95
Y_{10}	Lens yield due to module assembly step	= 0.98
Y_{11}	Housing fabrication yield	= 0.98
Y_{12}	Housing fabrication yield due to module assembly step	= 0.98
Y_{13}	Interconnects and diodes yield due to module assembly step	= 0.98
Y_{14}	Module assembly yield due to module assembly step	= 0.98

APPENDIX C

FLAT-PLATE SIMRAND STUDY

The flat-plate SIMRAND study[1] used the SIMRAND methodology to project the 1995 price and efficiency of flat-plate photovoltaic (PV) modules. Four generic flat-plate photovoltaic module technologies were evaluated, including Czochralski, polycrystalline ribbon, single-crystalline ribbon and thin films. The study developed a detailed set of equations to model the cost and performance of these four classes of PV modules. The equations related total module price and module efficiency to cell processing costs and yields, module processing costs and yields, encapsulant material costs, and cell efficiencies. Probability distributions of the processing step costs, yields, raw materials and cell efficiencies were obtained from manufacturers and other experts in flat-plate PV module technology.

In the flat-plate study, the SIMRAND production network consisted of four paths, one for each PV module technology listed above. Each SIMRAND run consisted of 2500 Monte Carlo trials. Each Monte Carlo trial computed module cost, module efficiency and a system-level cost based on random values selected from the input probability distributions for the processing steps. Separate costs and efficiencies were computed for each path. The system level cost used in the flat-plate study is given by

$$\text{system level cost} = K \times \text{MODULE COST} + \text{ABOS} \times (S \times \text{MODULE EFFICIENCY}) + \text{DISTRIBUTION}/S$$

where

S = insolation (W/m^2)
ABOS = area-related balance-of-system cost
DISTRIBUTION = distribution costs
K = 1.10 reflecting a 10% marketing markup

The path with the minimum system level cost was selected as the optimal path for that trial. The module cost and efficiency of this optimal path were plotted in a two-dimensional histogram.

The flat-plate SIMRAND model was run with various values for the area balance-of-system (BOS) cost. To model the two-axis tracking flat-plate module systems, an ABOS = $95 was assumed. As the two-axis tracking assumption is most comparable with the concentrator SIMRAND study, only the two-axis tracking results are presented in this Appendix.

The two-axis tracking flat-plate module histogram of module cost vs module efficiency is presented in Table C-1. The result is 2500 data points with module efficiencies ranging from 9% to 20% and module costs ranging from

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[1] Aster, R.W., A Projection of Flat-Plate Photovoltaic Technology in the Year 1985, JPL Internal Document No. 5101-261, Jet Propulsion Laboratory, Pasadena, California, in press.

Table C-1. Two-Axis Tracking Flat-Plate Module Cost (1980 Dollars per Watt) and Performance (NOC) Histogram and Probabilities, % (1995 Projection)

	Efficiency											
COST	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.18	0.20	0.22
0.20	1	3	4	10	8	6	6	0	3	0	0	0
0.25	1	1	1	8	5	7	8	4	2	1	0	0
0.30	0	3	8	28	28	34	17	11	11	0	0	0
0.35	1	0	18	56	53	89	66	35	47	3	1	1
0.40	0	0	1	8	28	31	60	54	101	19	24	2
0.45	0	2	1	7	42	48	142	125	121	65	42	3
0.50	1	0	1	6	27	64	153	85	48	77	26	0
0.55	0	0	1	8	10	41	72	40	23	64	17	2
0.60	0	0	0	4	7	13	20	13	16	26	8	0
0.65	0	0	0	1	3	7	15	8	13	13	4	0
0.70	0	0	0	0	1	5	7	1	6	17	0	0
0.80	0	0	0	0	1	1	3	1	0	1	2	0
0.90	0	0	0	0	0	0	1	0	0	1	0	0
1.00	0	0	0	0	0	0	0	0	0	0	0	0
1.10	0	0	0	0	0	0	0	0	0	0	0	0
1.20	0	0	0	0	0	0	0	0	0	0	0	0
1.30	0	0	0	0	0	0	0	0	0	0	0	0
1.40	0	0	0	0	0	0	0	0	0	0	0	0
1.50	0	0	0	0	0	0	0	0	0	0	0	0
1.60	0	0	0	0	0	0	0	0	0	0	0	0

$0.20/watt to $0.90/watt. Each element of Table C-1 shows the number of Monte Carlo trials that resulted in a module cost and efficiency that fell in the element's cost row and efficiency column. For example, 64 out of 2500 Monte Carlo trials resulted in optimal path modules with a cost of $0.50/watt (approximately) and an efficiency of 13% (approximately).

Note that the module price results shown in Table C-1 are in 1980 dollars per peak watt but in the energy cost comparison in Section V, these values are inflated to 1982 dollars per peak watt.

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16. Abstract

The purpose of this study is to assess the relative economic potentials of concentrating and two-axis tracking flat-plate photovoltaic arrays for central-station applications in the mid-1990's. Specific objectives of this study are to provide information on concentrator photovoltaic collector probabilistic price and efficiency levels to illustrate critical areas of R&D for concentrator cells and collectors, and to compare concentrator and flat-plate PV price and efficiency alternatives for several locations, based on their implied costs of energy. To deal with the uncertainties surrounding research and development activities in general, a probabilistic assessment of commercially achievable concentrator photovoltaic collector efficiencies and prices (at the factory loading dock) is performed. The results of this projection of concentrator photovoltaic technology are then compared with a previous flat-plate module price analysis (performed early in 1983). To focus this analysis on specific collector alternatives and their implied energy costs for different locations, similar two-axis tracking designs are assumed for both concentrator and flat-plate options. The results of this study provide the first comprehensive assessment of PV concentrator collector manufacturing costs in combination with those of flat-plate modules, both projected to their commercial potentials in the mid-1990's.

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