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CONCEPTUAL DESIGN AND SYSTEMS ANALYSIS OF PHOTOVOLTAIC SYSTEMS

MASTER

FINAL REPORT

VOLUME I
STUDY SUMMARY

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STUDY SUMMARY
CONCEPTUAL DESIGN AND SYSTEM ANALYSIS
OF PHOTOVOLTAIC POWER SYSTEMS

(Study performed under Contract EY-76-C-04-3686)

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FOREWORD

This report presents the results of a study on the Conceptual Design and System Analysis of Photovoltaic Power Systems. The program was performed under ERDA Contract EY-76-C-04-3686 for the Sandia Laboratories under the guidance of Dr. Billy Marshall.

The report consists of three volumes. Volume I contains a Study Summary of the major study results. Volume II contains the detailed results pertaining to on-site residential photovoltaic systems, central power plant photovoltaic systems, and intermediate size systems applied to commercial and public buildings. Volume III contains supporting appendix material.

The study was conducted by the Advanced Energy Programs of the General Electric Company Space Division. Mr. Aaron Kirpich served as Program Manager and prepared this report with contributions from the following individuals: R. Allred, B. Ayres, R. Biddescombe, E. Buerger, L. Davis, W. Hausz, S. Irwin, W. Kornrumpf, R. Linden, R. McCarthy, G. O'Brien, R. Pohl, N. Shepard, C. Shilas, H. Stoll, J. Triandafyllis, E. Tschupp, and R. Usher. Mr. R. Barchet, Manager, Photovoltaic Programs, and Mr. G. O'Brien provided valuable editorial comment on the content and organization of this report.

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INTRODUCTION

Solar photovoltaic (PV) power, initially developed for the space program, has been identified as a promising alternative to conventional methods of terrestrial power generation. The chief merit of PV generation lies in its direct electrical conversion of pollution-free solar energy. To date, the widespread use of photovoltaics has been hampered by the high cost of the photovoltaic solar cells themselves. Under the sponsorship of the United States Energy Research and Development Administration, the National Photovoltaic Conversion Program has been established to develop low-cost solar cells and PV systems. As part of that program, the study reported herein addresses the feasibility of PV generation by considering the performance, economics, and impact assessment for a range of PV conceptual designs.

SCOPE OF STUDY

This investigation of terrestrial PV systems considered the technical and economic feasibility for systems in three size categories: a small system of about 12 kW peak output for on-site residential use; a large 1500 MW central power plant contributing to the bulk energy of a utility system power grid; and an intermediate size system of about 250 kW for use on public or commercial buildings. In each category, conceptual designs were developed, performance was analyzed for a range of climatic regions, economic analyses were performed, and assessments were made of pertinent institutional issues.

STUDY TEAM

The study was initiated in mid-1975 by ERDA-Headquarters. In late-1975, cognizance for the study program was transferred to the Sandia Laboratories, Albuquerque, NM.

The following organizations participated in this study:

Organization	Contribution
General Electric Company	
Advanced Energy Programs - Space Division	Overall Responsibility
Corporate Research and Development	Power Conditioning - Residential System
Electric Utility Systems Engineering Department	Economic Analysis
Installation and Service Engineering Operation	Central Power Plant Electrical Systems
TEMPO - Center for Advanced Studies	Impact Assessments
*Arizona Public Service	Consultation, Utility/Residence Interface

Organization	Contribution
*Florida Power & Light	Consultation, Utility/ Residence Interface
*Pacific Gas & Electric	Consultation, Utility/ Residence Interface
*Pennsylvania Power and Light	Consultation, Utility/ Residence Interface
*Philadelphia Electric Company	Consultation, Utility/ Residence Interface
*Tredyffrin - Easttown School Districts, Tredyffrin Township, Pa.	Architectural & Engineering Data, Valley Forge Junior High School
C&D Batteries	Lead-acid battery data
Halsey & Ryder, Architects	Roof installation cost data
Sheldahl Corporation	Concentrator Data
Solarex Corporation	Solar Cell Data

*Non-funded support

STUDY ACCOMPLISHMENTS

The major accomplishments of the study are as follows:

1. Residential PV system concepts were developed using a roof shingle solar array design. The concepts were evaluated with and without energy storage for site locations in Cleveland, Phoenix, and Miami.
2. PV central power plant concepts were developed for the following solar array designs: 25 to 1 tracking concentrators; 3.2 to 1 seasonally adjusted concentrators; and fixed flat-plate solar arrays. The concepts were evaluated for a site location in Phoenix.
3. Intermediate-size PV concepts were developed around the characteristics of a medium-sized junior high school. Seven solar array design variations were considered from flat-plate air-cooled designs with and without sawtooth reflector augmentation, to adjustable tilt, low-ratio, fluid-cooled concentrators for building heating and cooling. The concepts were evaluated for site locations in Phoenix, Washington, D. C., and Miami.

4. Using a 30-year discounted cash flow analysis, levelized busbar energy costs were determined for all concepts for a range of solar cell efficiencies and costs.
5. Using utility industry methods of economic analysis, the worth of PV generation was determined for utilities located in Phoenix, Washington, D.C., and Miami. The analysis determined PV worth on the basis of displaced capacity and energy. Parametric data were prepared to show cost combinations that would yield the determined PV worth.
6. Projections of regional electricity prices were compared with levelized busbar energy costs to identify regions of greatest promise for photovoltaics.
7. The question of PV power feedback to utility grids was reviewed with five utility companies, and the dominant technical, economic and institutional issues were identified.
8. The penetration of photovoltaic systems was projected out to the year 2000 for residential, intermediate and central power plant applications.
9. Technology development requirements were reviewed and primary needs identified.

STUDY RESULTS — ON-SITE RESIDENTIAL SYSTEM

CONCEPTUAL DESIGN

Conceptual designs were developed around single family residence applications in three selected regions of the U.S.: Phoenix, Arizona; Cleveland, Ohio; and Miami, Florida. Electrical loads were based on all-electric residences. Fixed daily profiles were used for diversified loads (lighting, appliances, etc.) and domestic hot water needs which resulted in a daily demand of 35 kilowatt-hours. Variable profiles were used for heating and cooling loads, calculated from hourly weather data. A heat pump was used for heating and cooling with resistance heating augmentation when required. The monthly averaged daily electrical heating and cooling varied from 3 kWh (in February) to 52 kWh (in August) for Phoenix with an annual demand of 7921 kWh. In Cleveland the values varied from 85 kWh (in January) to 5 kWh (in May) with an annual demand of 12096 kWh.

Solar array concepts were restricted to rooftop installations with areas limited to roof sizes consistent with houses of contemporary design. Emphasis was placed on planar solar array designs cooled by natural air convection, installed on south-oriented sloping roofs. All concepts were based on using 5.72 cm (2.25 inch) diameter silicon solar cells having an air mass one (AM 1) efficiency of 13.4 percent at a temperature of 28° C and a solar intensity of 100 milliwatts per square centimeter. A nominal design for the rooftop solar array used 32,832 round cells arranged in a redundantly connected matrix of 513 cells in series by 64 cells in parallel. The cell area was 84 square meters mounted on a roof having dimensions of 7.32 x 14.64 meters (24 x 48 feet). Using 19-cell hexagonal shingle assemblies (15.24 cm edge length) as the basic array building blocks, the packing factor within each shingle was determined to be 0.807 with a resulting shingle area of approximately 105 square meters. With allowance for non-photovoltaic shingles along the roof edges, the overall roof packing factor was determined to be 0.786. Figure 1 shows the features of the solar cell shingle and its use on a residence roof.

Systems both with and without battery energy storage were studied. The design for the system with energy storage used a 96-cell, 48 kilowatt-hour lead-acid battery in parallel with the solar array. All photovoltaic power was used for the residence loads or battery charging and was furnished to the loads in the form of three-wire, 120/240 Volt, single-phase ac developed through a DC/AC inverter connected in parallel with the incoming utility line. This arrangement provided instantaneous backup power in the event of any photovoltaic power system interruption and to cover large peak loads. The system without energy storage also used a DC/AC inverter in parallel with the incoming utility line, but in this case solar array power in excess of demand was fed back through the incoming utility line to be used elsewhere in the utility system. For this system the inverter was controlled to extract power from the solar array at its maximum power point. System schematics with and without energy storage are shown in Figure 2. The greater complexity for the system with energy storage arises from the need to prevent battery overcharge. As shown, a binary segmented solar array with transistor shunt elements was selected to provide the required charge control function.

Figure 1. Solar Cell Shingle Roof

Figure 2. System Schematic

PERFORMANCE

Using computer simulations and hourly weather data for the regions being studied, performance analyses determined hourly and annual energy production. Typical results for the residence located in Phoenix and Cleveland are shown in Figure 3 comparing systems with and without energy feedback to the utility grid. Recalling that loads were based on assuming an all-electric residence, the differences in the load curves reflect a peak winter heating demand for Cleveland and a peak summer cooling demand for Phoenix. As shown for the cases without feedback (lower plots), the PV system output closely matches the load during certain seasons (summer for Cleveland; spring and fall for Phoenix) with utility makeup required at other times of the year. Were the PV system made initially larger, excess output at the seasons noted would have been wastefully discarded. With the array size restricted by this consideration, the system displaces 38 percent of the annual demand in Cleveland and 80 percent of the annual demand in Phoenix. The PV system output is based on a solar array roof slope about four to eleven degrees less than the latitude angle. This was found to yield the highest annual energy output. Higher and lower slopes could be used to develop a closer match of output with load. For example, higher slopes in Cleveland would result in a winter peaking output. However, such modifications would result in sacrifices in annual energy collection performance.

These sizing restrictions do not apply to the cases with feedback since any excess output can be usefully absorbed by other utility system demands. Using the same solar array size as for the system without feedback, the upper plots of Figure 3 serve to illustrate the behavior of this approach. The overall PV output is improved, mainly as a result of eliminating battery inefficiency. This increases the displaced energy to 51 percent for Cleveland and 98 percent for Phoenix. This improved displacement compares the total energy developed with the total residence demand, whether supplied to the residence or fed back to the utility. Although the output now exceeds the load at certain times, the excess appears as a net feedback to the utility. In actuality, the exchange of energy with the utility takes place throughout the year as the solar array output increases and diminishes each day. As shown, this exchange results in a net feedback to the utility during certain months and in a net supply from the utility during other months. Using this approach it is apparent that full use is made of the solar array output regardless of its size.

As a result of the above considerations, it was concluded that the feedback approach offered both economic and performance advantages over no-feedback systems. Additional reasons supporting this conclusion are: (1) besides improving performance, the elimination of batteries reduces cost and complexity, and simplifies operation; (2) the solar array is always operated at its maximum power point; (3) where decreased residence loads (e.g., during vacation periods) would limit the output of dedicated solar arrays, the feedback approach permits maximum output operation at all times. Further discussion on the institutional issues of feedback are contained in a later section.

Besides comparing systems with and without feedback, performance sensitivity analyses produced the following results: (1) the best roof tilt angle was found to be somewhat less than the latitude angle and ranged from 4° less in Cleveland (latitude 41°) to 11° less in Phoenix (latitude 33°); (2) a direct southward oriented roof was best in all cases, but $\pm 15^\circ$

Figure 3. Performance With and Without Feedback

from south did not result in significant penalties; (3) for systems with energy storage, maximum power tracking of the solar array was found to result in negligible improvement over direct charge systems; (4) for direct charge systems, a value of 5.35 for the ratio of series solar cells to series battery cells was found to be the best compromise for all climatic regions considered and was close to the optimum value in all cases; (5) frequent updating of the array tilt angle to accommodate the changing declination angle of the sun resulted in negligible performance improvement; (6) forced air cooling of the underside of the solar array resulted in fan power requirements which just about cancelled any performance gain; (7) natural convection cooling of the top and underside of the solar array was found to yield only slight improvement over topside cooling alone and did not justify the additional ducted paneling expense involved; (8) the removal and utilization of heat from the DC/AC inverter by circulating fluid appears to be a worthwhile expense in terms of the energy savings possible.

ECONOMIC ANALYSIS

The results of economic analysis of the residential concepts are presented in 1975 dollars. As described below, studies were performed to determine: (1) capital costs; (2) levelized busbar energy costs; (3) break-even costs.

Capital Costs. Capital costs were derived from a number of vendor and engineering data sources. Nominal costs for the residential PV designs are summarized on Table 1 for an assumed solar array cost of \$52 per square meter. The shingle design selected for the solar array provides three major cost benefits. First, the shingles serve as a roofing surface and can therefore be credited with the savings in conventional roof coverings. Second, they are mounted directly on the roof surface eliminating any need for additional structural support. Third, the method of electrical interconnection avoids the need for extensive interwiring. Based on a nominal solar array rating of 11.25 kW (output of 84 m² of 13.4 percent solar cells at 28°C and 1 kW/m² insolation), Figure 4 presents the capital costs in \$/kW for varying solar array costs. For the system with batteries, additional outlays of \$3700 per system are needed at 10-year intervals to cover battery replacement.

Levelized Busbar Energy Cost. Using the nominal capital costs listed in Table 1, an operating and maintenance cost of \$50 per year for each residence PV system, and the annual output performance results for each region investigated, a discounted cash flow analysis was used to determine levelized busbar energy costs (LBEC). These express the annualized cost (in 1975 constant year dollars) per kilowatt-hour of energy produced. This analysis assumed a 30-year life, and financing and escalation factors appropriate for both utility and consumer ownership cases. For the utility-owned case, the factors included a before-tax discount rate of 15 percent and a corporate tax of 48 percent. For the consumer-owned case, the factors included a before-tax discount (or mortgage) rate of 10 percent and a 20 percent tax bracket. These values were judged to be representative of investment market conditions.

TABLE 1. CAPITAL COST (1975 \$) OF RESIDENTIAL PV SYSTEMS

Item	With Energy Storage			Without Energy Storage		
	Unit Cost	Size	Cost (\$'s)	Unit Cost	Size	Cost (R's)
Solar Array (1)			5460			5460
Solar Cells	\$ 50/m ²	84 m ²	4200	\$ 50/m ²	84 m ²	4200
Substrate	\$ 10/m ²	105 m ²	1050	\$ 10/m ²	105 m ²	1050
Installation (2)	\$ 2/m ²	105 m ²	210	\$ 2/m ²	105 m ²	210
Electrical Equipment			2024			2299
Power Conditioning	\$125/kVA	8 kVA	1000	\$125/kVA	13 kVA	1625
Misc. (wiring, lightning protection, etc.)	—	—	1024	—	—	674
Storage			5465			
Batteries (3)	\$ 77/kWh	48 kWh	3700	—	—	—
Control	—	—	340	—	—	—
Enclosure	—	—	1425	—	—	—
Totals			12949			7759

Notes: (1) With 80% packing factor, effective solar array cost is \$52/m² (=0.8 x 50 + 10 + 2).

(2) Includes credit for conventional roof material and laydown costs.

(3) Recurring cost every 10 years.

Figure 4. Capital Cost for Residential PV Systems

Results for the utility ownership case are shown on Figure 5 comparing systems with and without energy storage, with solar array cost treated as a variable. The effect of higher insolation regions, e. g., Phoenix, is clearly evident in yielding lower LBEC values. The larger LBEC's for the systems with energy storage are the direct result of the initial and replacement battery costs. These poor economic results bolstered the selection of the no-storage feedback system as the preferred approach.

The consumer case produced LBECs about 16 percent less than the utility case. This difference should not be construed as favoring one ownership option over the other. Plausible variations of the economic assumptions used could narrow the difference and possibly yield inverse results. It was rather the intention to show that somewhat different economic analysis methods produce comparable results in establishing energy costs for PV systems.

Using the results for Phoenix, Cleveland and Miami, together with insolation and mean temperature data from the Climatic Atlas of the U.S., regional sensitivity of the levelized busbar energy cost was determined. Comparisons were then made with projected regional costs of conventionally generated electricity. Figure 6 shows this comparison of costs for solar array costs at \$50/m² and identifies potentially promising regions for the application of residential photovoltaic systems. This analysis was based on the no-storage feedback system assuming utility ownership.

Figure 5. Comparison of Levelized Busbar Energy Costs

Figure 6. PV Target Areas

Break-Even Costs. Economic evaluations of the residential PV system were performed using utility industry methods of analysis. Basically these methods considered the residential PV systems to be widely distributed generating units contributing their outputs to the general utility grid. PV break-even costs were equated to the worth of the displaced conventional capacity and energy. The essential results for the residential case are described below with a more complete discussion on the methodology and results of this analysis presented later in the section entitled "Study Results - Photovoltaic Worth to Utilities".

The nomogram of Figure 7 shows the break-even cost results and also includes a parametric extension of the capital costs described previously on Table 1 and Figure 4. The lower right-hand quadrant shows the dependence of break-even cost (\$/W) with capacity factor, defined as the ratio of the average annual output power to the plant rated power. Capacity factors for different locations are shown along the capacity factor scale. The break-even cost dependence is shown for both nominal and higher escalation scenarios, the latter one based on a 25 percent increase in plant costs and a 50 percent increase in fuel costs in addition to normal inflation of 5 percent.

The remaining three quadrants of the nomogram present system costs parametrically, permitting the evaluation of alternate cost combinations. The heavy lines represent the nominal values of cost and efficiency based on the data shown on Table 1. The use of the nomogram is illustrated by the following example.

At a cell cost of \$50/m² the nomogram is entered along the horizontal right-hand axis. Proceeding upward, the nominal combined substrate and installation cost of \$12/m² (see Table 1) is selected resulting in an array cost of \$52/m² indicated along the upper vertical axis. (Note: Since the solar cells occupy 80 percent of the array surface, the solar cell cost is \$40/m² (= .8 x 50) of array area. With the \$12/m² substrate and installation cost, this yields the \$52/m² value.) Continuing leftward to a 13.4% efficient solar cell, downward to an electrical equipment cost of \$200/kW, and rightward, yields a system cost of \$700/kW. This compares with a break-even cost of about \$490/kW considering the Phoenix location (capacity factor equals 0.215) and the higher escalation case.

Several possibilities exist for narrowing the gap between the estimated and break-even costs. Reducing solar cell costs from \$50/m² to \$30/m², and increasing the solar cell efficiency to 15 percent appears to achieve the desired result. Other reductions, either singly or in combination, could also be considered. The nomogram permits a rapid assessment of such strategies. It is apparent from the plot that low insolation regions impose increasingly stringent limits on the costs of the various system elements.

Figure 7. Residential System, Effect of Break-Even Costs

STUDY RESULTS — CENTRAL POWER PLANT

CONCEPTUAL DESIGN

Conceptual designs were developed for photovoltaic central power plants. Such plants, deployed over large land areas, would contribute directly to the bulk energy of utility grid systems. To identify the significant characteristics affecting photovoltaic plant performance and cost, three radically different conceptual designs were prepared and analyzed for a site location in Phoenix, Arizona.

The first concept employs high-ratio (25 to 1) parabolic cylindrical concentrators in the form of pontoons floated on a circular pond of water as shown on Figure 8. A large quantity of the uniformly aligned pontoons joined side by side form a circular array about 150 meters in diameter. The entire pond-floated array is rotated about a central fixed hub slip ring assembly to track the azimuthal position of the sun, thereby concentrating the sun's rays along the focal line of each pontoon parabolic reflector. Solar cells mounted along the focal line convert the concentrated rays into electrical dc power. It is estimated that a thrust of 12 Newtons (2.7 pounds-force) developed by water pump jets located along the periphery of the rotating array would be sufficient to provide the torque for azimuth tracking. Rotation in the same direction continues through the night to reach the proper azimuth position the following morning. The power developed in each pond array is transferred from the central hub slip ring through underground cables to a dc/ac converter station serving a number of ponds. The voltage is raised through several stages of transformation and the power then injected into the utility grid. This concept offers the following advantages: (1) reduction in the number of tracking systems and structural supports; (2) elimination of flexing interconnections; (3) minimal wind loading effects because of the horizontal low profile concentrator configuration.

The second concept, illustrated on Figure 9, consists of low-ratio (3.2 to 1) concentrators in east-west rows whose tilt positions are seasonally adjusted to optimize the collection of solar energy. The concentrators, consisting of semi-parabolic cylindrical reflectors with solar cells mounted on the axial plane, receive solar energy within a limited acceptance angle. Near-optimum performance is achieved by horizontally positioning the collectors during the winter season, and tilting them up about 37 degrees in a northward direction during the summer season.

The third concept, illustrated on Figure 10, uses flat solar cell panels tilted 22 degrees above horizontal in a southward-facing direction. The panels are arranged in east-west rows with a row-to-row pitch distance of about 1.7 times the panel width to minimize morning and evening shadowing.

Figure 8. Solar Azimuth Tracker Power Plant

Figure 9. Low Ratio Concentrator

Figure 10. Fixed Panel Array

The conversion of the photovoltaic dc to 60 Hertz ac is based on the technology developed for high voltage dc transmission systems. For all three concepts, a nominal definition consists of using 30 MW converter stations fed from solar array sectors having comparable peak ratings. Each station delivers its ac output at 69 kilovolts. Ten such stations feed a transformer station which transforms the power to 345 kilovolts for injection into the utility grid.

The use of dedicated energy storage for the plant was precluded as a result of the high cost and complexity uncovered during initial design investigations. Instead, it was assumed that the time-varying nature of the PV plant output could be handled through anticipatory load data and management of the utility's generation sources and remote storage units.

PERFORMANCE

Analytical models were prepared for each concept to establish the predicted behavior under varying illumination and environmental conditions. Performance analyses were conducted using hourly weather data for the Phoenix region for the year 1962. On the basis of unit area performance, the systems were relatively scaled to produce an equivalent annual output. Using nominal cell efficiencies, Table 2 below summarizes the significant sizing parameters for each concept, sized to produce an annual output of 2.83×10^6 MWh.

TABLE 2. SUMMARY OF CENTRAL POWER PLANT CONCEPTS

Concept	1	2	3
Description	Solar Azimuth Tracker	Low-Ratio Concentrator	Fixed Panel Array
Nominal Cell Efficiency	11.8%	13.4%	13.4%
Cell Area	1.0 km ²	7.3 km ²	10.1 km ²
Collector Area	25.0 km ²	32.6 km ²	12.9 km ²
Land Area	50.0 km ²	39.3 km ²	24 km ²
Annual Performance	2.83×10^6 MWh	2.83×10^6 MWh	2.83×10^6 MWh
Plant Rating	1500 MW	1500 MW	1500 MW

The relative monthly performance for the three concepts is shown on Figure 11. The solar azimuth tracker appears to produce a higher percentage of its output during the summer months in comparison with the other concepts which have more uniform characteristics. The significance of this difference lies in the fact that the higher summer output may have greater value in displacing capacity of a summer peaking utility. This potentially greater worth is considered in the discussion entitled "Study Results - Photovoltaic Worth to Utilities."

Output-duration plots for the three concepts are shown on Figure 12. The higher output of the azimuth tracker system over a shorter number of hours is the direct result of the higher

Figure 11. Comparison of Monthly Output

Figure 12. Output-Duration Curve

summer output noted above. As shown by these plots, all three concepts produced peak outputs of about 1500 MW. The plants were accordingly rated at that value.

ECONOMIC ANALYSIS

Economic analysis of the central power plant concepts was similar to that performed for the residential concepts. Capital cost data were assembled from various sources for the nominal designs defined earlier. Levelized busbar energy costs were determined assuming utility ownership of the power plant. Break-even costs were also determined using the methods outlined for the residential case. All cost results are presented in 1975 dollars.

Capital Costs. Table 3 summarizes the capital cost data assembled for point designs of the three concepts evaluated. Parametric presentations are shown later (for Concepts 1 and 3 only) in conjunction with break-even costs derived from the utility methods of economic analysis.

A perusal of the data of Table 3 reveals the cost items of greatest significance. For the solar azimuth tracker (Concept 1), solar collector costs predominate with solar cell costs representing less than 5 percent of total plant costs. The low-ratio concentrator (Concept 2) also indicates that collector costs predominate with solar cell costs increasing to 22 percent of total plant costs. For the fixed panel array (Concept 3), cell costs are of greatest significance, and account for 42 percent of total plant costs.

Fairly significant differences are identified for structural support and solar tracking costs. The solar azimuth tracker concept shows substantially lower support and tracking costs as a result of the floating method of collector support and the use of a single tracking mechanism at the hub of each pond.

Site preparation costs are necessarily rough since they are so dependent on specific site characteristics. The higher cost for the solar azimuth tracker is associated with pond construction in least favorable arid locations. It is likely that locating the plants along coastal regions or on high water table land would diminish such costs substantially. As shown on Table 3, the cost of land itself is small relative to other plant costs.

TABLE 3. CENTRAL POWER PLANT CAPITAL COSTS - (In millions of dollars)

Cost Element	Concept No. 1 Solar Azimuth Tracker	Concept No. 2 Low-Ratio Concentrator	Concept No. 3 Fixed Panel Array
Array System			
Land (@ \$500/hectare)	\$ 2.5	\$ 2.0	\$ 1.2
Site Preparation & Development	116.1	18.5	12.4
Solar Cells (@ \$50/m ²)	50.0	365.0	505.0
Solar Collectors	852.9	789.3	306.6
Structural Support & Tracking	133.4	347.5	231.7
Subtotal	1154.9	1522.3	1056.4
Electrical Plant System			
Converter Stations (50) Bldg. & Equip.	105.6	105.6	105.6
Transformer Stations (5) Bldg. & Equip.	15.0	15.0	15.0
Switching Station (1) Bldg. & Equip.	6.5	6.5	6.5
Plant Control Center Bldg. & Equip.	2.5	2.5	2.5
Underground Cabling & Conduit	11.3	11.3	11.3
Towers & Fixtures, Switching Sta.	1.0	1.0	1.0
Yardwork	0.8	0.8	0.8
Subtotal	<u>142.7</u>	<u>142.7</u>	<u>142.7</u>
Total (Major Components, Labor & Material)	1297.6	1665.0	1199.6

Levelized Busbar Energy Costs. Applying the same methods and assumptions used for the utility ownership residence analysis, levelized busbar energy costs were determined for the three central power plant concepts. Figure 13 compares the LBECs for these concepts against solar cell cost expressed in \$/peak kW, using 12.5 and 25 percent efficient solar cells. The nominal costs for the other system elements listed in Table 3 were used. For comparative purposes the results for the no-battery residence case are included. These plots point out the significance of cell efficiency in affecting the LBEC, with the left-hand plot based on 12.5 percent cells and the right-hand plot on 25 percent cells. It is realized that 25 percent cells are probably not attainable; they are cited here only to illustrate their impact on the several concepts considered. For the high concentration solar azimuth tracker, doubling the cell efficiency almost halves the LBEC. This is attributed to the proportionate reduction in the concentrator collectors, the most costly system elements. The effect of higher cell efficiency on the other concepts is much less pronounced with only moderate reductions in LBECs. It is interesting to note that the shingled residence concept remains practically unaffected. This is due to the fact that the reduction in shingle substrate area contributes small savings. Such savings are more pronounced for the fixed panel concept which used a more costly self-supporting substrate.

Break-Even Costs. As in the residence case, utility industry methods of analysis were used to determine the worth of the PV central power plants in terms of the displaced capacity and energy of conventional equipment. Only two of the three power plant concepts were analyzed: the solar azimuth tracker, and the fixed panel array. In the latter case, the results were

Figure 13. Comparison of Levelized Busbar Energy Costs

derived from the residential analysis since the residence system employed a similar solar array configuration of tilted southward facing fixed panels. Differences in power conditioning efficiency and array operating temperatures were appropriately introduced.

The results for the solar azimuth tracker and fixed panel array are shown on the nomograms of Figures 14 and 15 which use the same presentation format described for the residence results shown on Figure 7. Tracing through these nomograms reveals the difference in cost sensitivity to key variables for the two concepts.

Using a site location in Phoenix (0.215 capacity factor) and the high escalation scenario noted earlier, the break-even cost for the solar azimuth tracker system (Figure 14) is \$540/kW. The heavy lines represent the nominal cost and solar cell efficiency values for the point design costs summarized earlier on Table 3 using a plant rating of 1500 MW. Using a solar cell cost of \$50/m² entered along the right horizontal axis and tracing through counter-clockwise to each nominal cost value and 11.8 percent cell efficiency, results in a system cost of \$870/kW, about 1.6 times larger than the break-even cost. Several strategies may be used to narrow the gap. First, a cell efficiency of 20 percent totally eliminates the difference, although the reliable and consistent achievement of such efficiencies has yet to be demonstrated. Reducing the collector and installation cost item from \$44/m² to about \$30/m² also achieves the desired objective. This too is probably difficult to achieve in terms of present knowledge and experience. However, this item does not involve the complex technological efforts required for cell efficiency improvements, but rather the application of production shortcuts and cost-saving methods. It seems clear that efforts in both of these areas are required. Cost reductions in the electrical equipment area would also yield benefits, of course; however, the estimates for electrical equipment presented in this study were based on current technology and large reductions are not envisioned. The basic cost of solar cells is also important, and in fact, the basic premise underlying this economic analysis is that future solar cell costs will fall in the range of \$50/m² to \$100/m². In this regard, the nomogram (Figure 14) shows that the equipment costs are relatively insensitive to solar cell costs. This is due, of course, to the fact that the solar azimuth tracker uses a 25 to 1 concentration ratio with the cells only accounting for about five percent of the total cost. Thus, doubling cell costs only has the effect of increasing system costs by another five percent.

Except for the greater significance of solar cell costs, a similar story emerges for the case of the Fixed Panel Array shown on Figure 15. For the identical location in Phoenix and the higher escalation scenario, the break-even cost is \$490/kW, about 10 percent lower than the solar azimuth tracker. This is associated with the higher midday and summer peaking output of the solar azimuth system - see later discussion in the section entitled "Study Results - Photovoltaic Worth to Utilities". Starting with the solar cell cost of \$50/m² and tracing through to each nominal cost value and a cell efficiency of 13.4 percent, results in a system cost of \$770/kW, about 1.60 times larger than the break-even cost. Increasing solar cell efficiency and reducing the panel and installation costs results in similar system cost reductions noted for the solar azimuth tracker concept. For this concept, system costs are much more sensitive to solar cell costs. Doubling solar cell costs has the effect of increasing the system cost by 42 percent.

Figure 14. Solar Azimuth Tracker, Effect of Break-Even Costs

Figure 15. Fixed Panel Array, Effect of Break-Even Costs

Normalizing the systems to the use of 15 percent efficient solar cells costing \$500/kW_{pk} results in overall costs that are too high over break-even costs by factors of 1.66 and 2.3 for the solar azimuth and fixed panel concepts respectively, considering a nominal escalation scenario. The higher escalation scenario reduces these factors to 1.30 and 1.75 respectively.

STUDY RESULTS — INTERMEDIATE SCHOOL SYSTEM

CONCEPTUAL DESIGN

Rooftop photovoltaic conceptual designs were developed for large area single story buildings. A junior high school located in Valley Forge, Pa. having a roof area of about 10,000 square meters provided the basis for solar array layouts and load estimates. The designs were evaluated for site locations in Washington, D.C., Phoenix, and Miami.

Two basic solar array approaches, each having a panel or aperture area of approximately 3,000 square meters, were evaluated. The first used adjustable tilt low-ratio concentrators (3.2 to 1) mounted on a steel grid erected over the normal roof surface as illustrated on Figure 16 for a sector of the school building. The second approach considered several variations of flat-panel roof-integrated designs.

A summary of seven design variations investigated is shown on Table 4. Cases 1 and 2 refer to the low-ratio concentrator approach, with and without solar thermal collection (through fluid circulation) for partially meeting the schools heating and cooling loads. Cases 3 to 7 refer to roof-integrated designs from the simple PV-only flat-panel approach (Case 3) to the double paned combined PV/thermal approach with sawtooth reflector augmentation (Case 7).

Considerable analysis preceded the selection of the key parameters defining these designs. Two concepts for low-ratio concentrators were analyzed and compared. The first design consisted of a semiparabolic reflector similar to Concept No. 2 described for the central power plant; the second design consisted of a compound parabolic concentrator (CPC). For both designs, the annual energy reaching the solar cells was determined as a function of the concentration ratio. Using solar cell costs of \$50 and \$100 per square meter and estimates of reflector costs, the concepts were compared in terms of their relative cost to performance ratios. The optimum ratios for both the designs were found to be quite similar. On this basis, it was concluded that more detailed analysis of a single selected point design for determining photovoltaic and thermal performance would be representative of this class of low-ratio concentrators. Such analyses were performed using the semiparabolic design with a concentration ratio of 3.2 to 1.

Preliminary analyses were also performed for determining the optimum panel and reflector slopes of the sawtooth roof integrated designs. Analytical expressions were developed for determining the contributions of beam and diffuse insolation reaching the solar panels both directly and by reflection. The maximum annual energy reaching the solar cells served as the basis for selecting the best combination of solar cell panel and reflector slopes. These analyses were performed separately for site locations in Washington, Phoenix, and Miami.

The designs were developed without considering the use of on-site electrical energy storage. Through a direct tie-in with the schools utility line and with dc/ac conversion to the proper voltage and frequency conditions, the photovoltaic output was arranged to either supply the

Figure 16. Roof-mounted Low-Ratio Concentrator (Seashell)

school's electrical load or to be fed back through the 4.16 kV, 3 phase incoming utility line. A dc/ac conversion efficiency of 95 percent was used. For the different solar array designs considered, the peak PV output ranged from about 200 to 500 kW.

For those designs with combined PV/thermal solar collectors, the thermal energy of the circulating fluid was accumulated in a thermal storage tank, to be withdrawn upon demand for building heating and cooling. An analysis of the building heating and cooling loads was performed for each of the regions considered. This determined the extent to which the collected solar thermal energy could be utilized. Because of the magnitude of the building thermal loads, almost all of the collected solar energy was useful with a minimal excess amount having to be discarded. An absorption chiller was used for meeting the school's air conditioning loads.

PERFORMANCE

Computer simulations and hourly weather data for each of the regions studied were used to evaluate performance. Typical results for the seven designs considered are shown on Figure 17 for a site location in Phoenix. The lower plots indicate relative photovoltaic performance, while the upper plots indicate relative thermal performance for those designs which combined solar thermal collection with photovoltaic generation. As shown on the lower plots, the best photovoltaic performance is provided by the planar designs without

TABLE 4. SUMMARY OF SEASHELL AND INTEGRATED ROOF CONFIGURATIONS

		Description	Panel Area, m ²	Cell Area, m ²	Panel Slope, Degrees			Reflector Area, m ²			Number Cover Windows
					Washington	Phoenix	Miami	Washington	Phoenix	Miami	
1		Seashell, PV - Only	3226	806	0° - Sept 21 to March 21 30° - March 21 to Sept 21			3700	3700	3700	1
2		Seashell, PV/Thermal	3226	806	Same			3700	3700	3700	1
3		Planar Array, PV - Only	2853	2282	30	27	20	-	-	-	0
4		Planar Array, PV/Thermal	3226	2282	30	27	20	-	-	-	1
5		Sawtooth, PV - Only	2853	2282	30	27	20	3075	2580	1753	0
6		Sawtooth, PV/Thermal, 1 Cover	2853	2282	30	27	20	3075	2580	1753	0
7		Sawtooth, PV/Thermal, 2 Cover	3226	2282	30	27	20	3075	2580	1753	2

solar thermal collection. This is explained by their lower operating temperatures and reduced transmission losses since no cover windows are used. The low-ratio concentrator designs also show a relatively lower performance.

The upper plots include the demand for building heating and cooling, which for this Phoenix case is almost all associated with meeting air conditioning cooling needs. As seen, the four designs with thermal collection provisions supply thermal energy in the range of 54 to 63 percent of the total thermal demand.

The evaluation of these designs in the other regions studied, namely Washington, D. C. and Miami, showed a similar ranking of performance.

ECONOMIC ANALYSIS

Economic analysis of the seven design alternatives considered for the intermediate size system proceeded along lines similar to those used for the residential concepts. Capital costs were assembled and then levelized busbar energy costs were developed considering utility ownership assumptions. As previously stated, all costs are presented in 1975 dollars.

Capital Costs. Capital costs for the seven concepts are summarized in Table 5. These costs include both credits and penalties with respect to providing basic roofing functions. When the features of a candidate concept replaced normal roofing coverings it was credited with the associated cost savings. If the concept involved additional roofing expenses, especially where roof penetrations were required to install supporting steel gridwork, appropriate cost penalties were taken into account. For those concepts with the combined collection of solar thermal energy, costs were included for the thermal collectors, piping, tankage, valves, and pumps up to the interface with the building's normal heating and cooling equipment. Chillers for air conditioning were assumed to be part of the building's normal equipment since they could operate with solar thermal energy or from auxiliary heat sources.

Levelized Busbar Energy Costs. The results of levelized busbar energy cost analysis are shown on Figure 18 for the seven concepts considered, against variable solar cell costs. These results were based on a single solar cell efficiency of 13.4% and used the performance results shown earlier on Figure 17. In calculating the LBECs, the systems with the combined collection of solar thermal energy were credited with the savings of an equivalent amount of fuel oil, based on a cost of \$2.96/MM Btu and a burner efficiency of 60 percent. Fuel escalation over the life of the system was taken into account.

The plots of Figure 18 were based on a site location in Phoenix and show that the integrated roof PV-only designs are most cost-effective. LBEC evaluation in the other regions studied, namely Washington, D. C. and Miami, showed a similar ranking of concepts.

TABLE 5. CAPITAL COSTS (IN THOUSANDS OF DOLLARS)

Cost Element	Semi-parabolic		Integrated Roof				
	1	2	3	4	5	6	7
	PV-Only	PV/Thermal	Planar PV-Only (Shingles)	Planar PV/Thermal 1 Cover	Sawtooth PV-Only (Shingles)	Sawtooth PV/Thermal 1 Cover	Sawtooth PV/Thermal 2 Covers
Solar Cells (at \$100/M ²)	80.6	80.6	228.2	228.2	228.2	228.2	228.2
Collectors	88.6	122.0	51.4	161.3	51.4	161.3	193.6
Delta Roof Cost*	112.2	112.2	-27.1	179.5	160.4	120.7	120.7
Cabling	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Thermal Loops	-	133.4	-	133.4	-	133.4	133.4
DC/AC Conversion	25.2	21.3	49.5	31.7	57.0	36.4	30.2
Total (Major Components, Labor and Material)	310.1	473.0	305.3	737.6	500.5	683.3	709.6
Shipping, Design, Project and Management (15% MLM without Cells)	34.1	58.9	11.6	76.4	40.8	68.3	72.2
Total Capital Cost	344.5	531.4	316.9	814.0	540.8	751.6	781.1

*Delta roof cost pertains to added roof construction required to accommodate solar collectors.

Figure 17. Monthly Performance in Phoenix, Arizona, 1962

Figure 18. Comparison of Levelized Busbar Energy Cost for Phoenix Location

STUDY RESULTS — PHOTOVOLTAIC WORTH TO UTILITIES

The worth of PV generation was determined in terms of competing forms of utility system generation. Photovoltaic output was based on the performance results for fixed panel arrays and the solar azimuth tracker described for the central power plant. The worth analyses were based on techniques developed by GE's Electric Utility Systems Engineering Department for the electric utility industry. Calculations were performed for utilities located in Washington, D. C.; Phoenix, Arizona; and Miami, Florida using projections of load and generation growth out to the year 2000. Base case calculations first determined optimum utility system configurations without PV generation using an appropriate set of economic assumptions regarding conventional plant and fuel costs. The calculations were then repeated for an assumed photovoltaic penetration with hourly weather data used to define hour by hour generation. PV worth was determined as the difference in the present worth of the conventional generation for the two cases.

The key results of these studies are summarized on Figure 19, which correlates the worth (breakeven cost) of the solar azimuth tracker and fixed panel array designs with the capacity factor (ratio of the average annual output power to the plant rating). The effects of using nominal and higher escalation scenarios are included along with the plant and fuel costs serving as the basis for the nominal case. The independent evaluation of introducing PV systems into three widely differing utilities produced the proportional relationships shown. Since the capacity factor is proportional to annual energy output, Figure 19 provides a convenient means for estimating breakeven costs in various regions. For example, the annual energy output in Cleveland is about 65 percent of that in Phoenix. Accordingly, for a particular PV design, the breakeven cost in Cleveland is approximately 65 percent of the value in Phoenix. The break-even costs derived from Figure 19 serve as the key inputs to the nomograms of Figures 7, 14 and 15 used to establish required costs for the major PV system elements.

The influence of penetration (defined as the ratio of PV rated capacity to utility system capacity) is shown on Figure 20 for two of the three regions considered. PV break-even costs reduce by 1 to 2 percent for each percent of PV penetration. These results were based on penetrations of no higher than 10 percent. At higher penetrations it is speculated that the break-even costs would drop at increasing rates.

PV systems can displace a significant percentage of conventional generation capacity. As shown on Figure 21 for the fixed panel array, the analysis produced a linear relationship between capacity credit (ratio of displaced capacity to PV plant rated capacity) and capacity factor for the three regions studied. Extrapolating the linear relationship illustrates the result that zero capacity credit may occur at capacity factors in the range of 5 to 10 percent.

The capacity displacement of the solar azimuth tracker was only analyzed in Phoenix as indicated on Figure 21. Its higher capacity credit is attributed to its higher midday and summer peaking capability with the consequent greater displacement of peaking units. The

GENERATION TYPE	PLANT COST \$/KW	FUEL COST \$/MW HR	ANNUAL ESCALATION
NUCLEAR	540	4.20	5%
COAL-STEAM	490	12.50	5%
OIL-STEAM	350	20.80	5%
GAS TURBINE	140	27.00	5%

Figure 19. Break-Even Costs for Central Power Plant Concepts

Figure 20. Effect of PV Penetration on PV Break-Even Cost

Figure 21. Capacity Credit Results

relationship of capacity displacement with capacity factor is conservatively estimated for this system by assuming the same zero crossing point as used for the fixed panel array.

The study investigated how the proportions of displaced generation types affected the PV breakeven costs. The results shown on Figure 22 indicate that optimal results are obtained by mainly displacing nuclear capacity. As nuclear displacement increases, fossil fuel savings diminish rapidly. Note that a relatively broad maximum exists between PV breakeven cost and nuclear capacity displacement. In the vicinity of the maximum point, fossil fuel savings can increase significantly for only a slight penalty in PV breakeven costs. For example, the optimum condition for the system represented in Figure 22 occurs when 30% of the PV capacity displaces nuclear capacity. Nuclear fuel and some oil are saved; however, coal consumption increases slightly. By adopting a strategy that limits nuclear capacity displacement to 10% of the PV capacity fossil fuel Savings will increase by an order of magnitude. This is accomplished with a penalty in PV break-even cost of only 10 percent.

The study also considered the benefits of using energy storage in conjunction with PV generation. The analytical strategy adopted was to store the PV generated energy making it available at the times of greatest value to the utility. The results of this analysis were generally discouraging. For the system analyzed in Washington, the overall worth of the PV generation improved. However, storage costs would have to be less than \$20/kWh to gain the benefit of the worth improvement. A similar analysis in Phoenix considering energy storage only dedicated to a single residence unit (no feedback to the utility grid) indicated a substantial drop in system worth. This was attributed to the utilization of the stored energy during night-time hours when less costly energy from the utility is available.

Figure 22. PV Break-even Cost and Energy Displacement as a Function of Nuclear Capacity Displacement

STUDY RESULTS- IMPACTS AND INSTITUTIONAL ISSUES

The study of institutional issues and impacts regarding the implementation of terrestrial PV systems was focused on the question of PV feedback to utility networks, estimates of PV penetration in the coming decades, environmental impacts, and material availability. The significant findings of these studies are summarized below.

PV FEEDBACK TO UTILITY NETWORKS

Because of battery elimination and better utilization of the PV generated energy, systems with feedback to the local utility network are considered to be more economical than systems without feedback. A number of questions arise concerning the practicality of feedback, particularly with regard to distributed PV systems on residences and other buildings.

Does the feedback of excess array output to the utility grid impose severe technical difficulties? Should ownership of the system reside with the owner or utility? If consumer owned, how would credit for feedback be handled? What are the legal ramifications if the system is utility owned? These and other questions were addressed in an investigation undertaken with the following utility companies:

1. Arizona Public Service
2. Florida Power & Light
3. Pacific Gas & Electric
4. Pennsylvania Power and Light
5. Philadelphia Electric Company

Questionnaires were submitted to each utility company and discussions held in a series of followup meetings. The following represents the consensus of opinion on the major issues considered:

1. Technical Issues - There are no barriers for implementing photovoltaic feedback energy from multiple small systems into the utility networks. Depending on the amount of feedback, as established by the number and concentration of photovoltaic powered residences, varying impacts might be encountered and would involve such considerations as distribution, transformer and circuit breaker sizing. A matter of concern revolves around the question of safety to repair crews who would have to cope with "hot" lines on both sides of a particular fault. A possible solution to this problem would be to make the photovoltaic system output operationally dependent on the presence of utility power. With any loss of utility power, the output of the photovoltaic system would be interrupted automatically. Specific implementation schemes would be worked out on the basis of existing and developing control equipment. Some of the equipment is currently being considered for incorporation into utility networks for other reasons. Some

minor changes in operating procedures and rules may be required, but are not of a serious or limiting nature.

2. Institutional Issues - Questions relating to ownership of the residential photovoltaic systems also are not viewed as significant barriers by the utilities. There are specific problems that must be worked out by appropriate contractual arrangements. The utilities contacted were willing and anxious to lead the way in working out these techniques rather than being confronted with solutions imposed by others (regulatory commissions, etc.). Ownership of the residential rooftop by either consumer or utility can be accommodated by the utility. If owned by the utility, it would assume responsibility for all of the associated problems of maintenance, liability, etc.
3. Economic Issues - The major issue as seen by the utilities is one of economic viability including life and maintenance characteristics, and its translation into equitable rates for consumed and supplied energy. For consumer owned PV systems it was the considered opinion that feedback would be credited only for its energy content and not for any contribution to capacity displacement. Ownership of residential PV systems by the utility would be contingent on both the physical and analytical demonstration of its economic worth. Studies for determining this worth, of the type cited earlier, would have to be carried out within the framework of each utility's operating characteristics before widespread applications would be considered. Utilities are working on analytical and demonstration programs with these objectives in mind.

PENETRATION PROJECTIONS

Study tasks were addressed to determining the plausible penetration of photovoltaic systems into the energy market in the coming decades. Using several independent projection methods, it is estimated that PV systems could provide from 3000 to 30,000 MW of generation by the year 2000. This would correspond to installing PV systems rated at 10 kW each on 300,000 to 3,000,000 residences or installing central power plants occupying from 100 to 1000 square kilometers. Using the penetration rate of comparable technological innovations, it is estimated that by the year 2020, the installed PV capacity would increase by a factor of 10 over that in the year 2000.

The availability of roof area would not limit these rates of penetration. By the year 2000 the number of homes built after 1985 that would be suitable for PV installation is estimated to be about 7 million. By 2020 this increases to about 15 million. Retrofitting PV systems on existing homes at the time of normal roof refurbishment expands the potential market by another 20 to 30 million units.

Similar projections of commercial and public building construction out to the year 2000 indicate the potential for accommodating up to 100 GW of photovoltaic generation.

ENVIRONMENTAL IMPACTS/BARRIERS

The impacts that PV systems will have on local environments are considered to be small. With respect to rooftop installations, no impacts of any significance were identified. Large installations covering sizeable land areas may have some effect on local conditions. It will be necessary, for example, to control vegetation growth and to exclude animals both for their own protection and to prevent damage to equipment. Measures will also be necessary to minimize the presence of birds. Thus, PV installations of this type will require that local ecological condition be modified to some degree.

Where environmental impacts are concerned with how the PV installation affects the environment, barriers are concerned with how the environment affects the PV installations. Such barriers arise mainly from extreme weather conditions. These include the effects of rain, snow, hail, dampness, temperature, wind, sandstorms, lightning, and combinations of these to name a few. Although the conceptual design activities conducted during this study did not deal with these phenomena in detail, it was realized that their accommodation represents one of the major challenges facing the implementation of PV systems. As a result it has become clear that, aside from the development of cheaper and more efficient solar cells, major efforts are needed to provide PV systems with the required environmental durability. This extends from the need for durable coatings and reflective surfaces to providing low-cost wind resistant support structures.

MATERIAL AVAILABILITY

Photovoltaic power plants will employ a range of commonly used materials: silicon, aluminum, steel, copper, glass, concrete, and plastics. Comparing the projected supply of these materials against the projected penetration of PV plants indicated no barriers to PV implementation, although significant growth in the manufacture of silicon solar cells is implied.

MAJOR FINDINGS AND CONCLUSIONS

The major findings and conclusions summarized below have been compiled from the results of the separate investigations, and have been generalized to provide a broader perspective on the capabilities of terrestrial photovoltaic generation.

PERFORMANCE

1. For the PV designs analyzed in this study, the results indicate that annual energy outputs are proportional to annually integrated insolation as plotted on Figure 23. The nominal values of insolation shown for selected locations are based on long-term data taken from the Climatic Atlas of the U.S. Year to year variations could affect these nominal values by as much as ten percent. The results of Figure 23 are based on 80% packing factors (flat-plate designs) and the use of 15 percent efficient solar cells. Outputs would be directly proportional to other cell efficiencies that might be considered.

2. Ambient temperature variations have a small effect on the linear results shown on Figure 23. It is judged that the maximum deviation in annually averaged daytime temperatures, found to be $+13^{\circ}\text{C}$ in a region of the southwestern U.S. relative to a national average of 19°C , would not modify the results of Figure 23 by more than five percent, regardless of the design type considered. On this basis, Figure 23 provides a reasonable means for estimating performance in various regions.

Figure 23. Performance Summary for Representative PV Systems

3. As a result of their smaller optical losses and ability to absorb diffuse sky radiation, flat-panel designs produce PV outputs about 1.5 to 2 times greater than the concentrator designs evaluated on an equal array area basis (Figure 23). Combined PV/thermal collectors yield the highest total collection of energy; however, their higher temperature operation and greater optical losses result in considerably reduced PV performance.

ECONOMICS

1. Energy storage, used with PV systems dedicated to specific loads (residences, buildings, etc.) in competition with utility sources, does not appear to be economically feasible. The reasons for this are: (1) the cost of storage is high; (2) storage is inefficient; (3) the energy from storage is mainly provided at night when cheaper utility energy is available.

2. Although storage appears as a necessary adjunct for residential PV systems by serving as a buffer between the times of peak generation and load demand, an alternative strategy is to eliminate its use by feeding back excess PV output to the backup utility grid. Besides cost reductions and efficiency gains, the PV generation is fully used, while with dedicated systems the PV output must be discarded during periods of low demand. The concept of feedback is considered to be feasible although many technical and institutional issues must be resolved.

3. At solar cell costs of \$500/kW_{pk}, system capital costs (Figure 24) for representative PV-only systems without energy storage range from \$700 to \$1100 per rated kw. At \$500/kW_{pk}, solar cells constitute 70 percent of the system cost for a shingled roof design, down to 6 percent for tracking concentrators. Stated inversely, non-solar cell costs (intercept values on Figure 24) vary from 30 to 94 percent, emphasizing the need to place equal emphasis on cost reduction efforts for non-solar cell array equipment. Rated on an electrical output basis, the cost of combined PV/thermal systems is greater than twice that of PV-only systems; however, valid cost comparisons with PV-only systems must be made on an energy output basis (see later paragraph).

4. Using the performance and capital cost results in conjunction with a 30-year discounted cash flow analysis based on utility ownership, the best regions in the U.S. produced levelized busbar energy costs ranging from 3.5 to 8.5 cents/kWH (Figure 25) for solar cell costs of \$500/kW_{pk}. Over the range of U.S. conditions, levelized busbar energy costs varied by a factor of almost two to one.

5. At a solar cell cost of \$500/kW_{pk}, the economic analysis yielded similar values of levelized busbar energy cost for several candidate concepts evaluated for a Phoenix location (Figure 26). For lower solar cell costs, flat-plate arrays appear more attractive. Of all concepts considered, combined PV/thermal systems appeared least attractive although they were credited at current fuel prices for the thermal energy produced. Similarly, for systems with energy storage, levelized busbar energy costs were more than doubled.

Figure 24. Capital Cost of Representative Designs.

Figure 25. Levelized Busbar Cost for Representative PV Systems

Figure 26. Comparison of Levelized Busbar Costs for Phoenix Location

6. Analysis within the context of utility system economics indicated PV plant break-even costs (Figure 19) in the Phoenix region ranging from \$380/kW for the fixed flat-panel system to \$420/kW for the azimuth tracking concentrator system, considering nominal escalation rates. Estimated plant costs (Figure 24) for these concepts are high by factors of 1.66 for the azimuth tracking concentrator, and 2.3 for the fixed flat-panel system, considering 15 percent solar cells which cost \$500/kW_{pk}. A higher escalation scenario (shown on Figure 19) could reduce these factors to 1.30 and 1.75 respectively.

7. The utility economic analysis indicated that substantial capacity and energy displacements could be attributed to PV generation. A typical result for the Phoenix region showed a capacity factor of 21 percent (compares average PV power with the PV plant rating). Capacity credit (compares displaced capacity with the PV plant rating) ranged from 45 percent for the fixed flat-panel system to 60 percent for the azimuth tracking concentrator.

OTHER ISSUES

1. Intermediate-size and central power plant systems are preferred over residential systems because of less costly management and maintenance, and the potential for higher operating efficiencies. However, the integration of solar arrays into larger structures should recognize a major advantage of residential systems, namely the relatively lower cost of using the sloping residence roof as a solar cell mounting surface. Using solar cell modules as weatherproofing elements provided significant cost benefits.

2. The feedback of photovoltaic power from residences or other distributed installations to the utility network is not considered to be of a serious or limiting nature. Technical problems to be resolved concern the quality of the feedback and interruption of the feedback for safety reasons. These problems can be handled with available technology and within reasonable cost. The legal aspects of power feedback from privately owned installations can be handled although the necessary contractual arrangements are likely to be complicated. In the opinion of five utility companies consulted on the feedback issue, credit for feedback would be made at reduced rates. Utility or third-party ownership of the PV installation offers an alternate arrangement.

3. Projections of new construction for residences and other buildings indicates a large potential for the application of photovoltaic systems. Added potential is provided by the retrofit of PV systems on existing buildings during normal roof refurbishment. Starting in 1985 with a market penetration profile modeled according to comparable technological innovations, it is estimated that PV systems could provide 13,000 MW of generation by the year 2000. At this rate of penetration, no significant raw material availability problems were uncovered.

4. Photovoltaic plants will require large capital investments. However, in contrast with conventional power plants, the PV plant should be capable of producing income much sooner after the start of construction, since the segments making up the overall plant are essentially independent power generators. As soon as one segment is completed, it may be brought on line while remaining segments are still undergoing construction.

5. In connection with on-going solar cell technology and cost reduction efforts, emphasis should be placed on higher cell efficiencies (greater than 15 percent), particularly for use with high concentration systems. Of equal importance, technology efforts should be directed toward low-cost collectors, concentrators, tracking systems, and structural support. Power conditioning technology is judged to exist presently for all system sizes considered, although development programs are required to achieve lower cost and higher conversion efficiencies. The latter efforts are especially needed for small and intermediate-size systems.