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PHOTOVOLTAIC SYSTEMS CONCEPT STUDY

Final Report. Volume 3 of 5

MASTER

April 1977

Work Performed Under Contract No. EY-76-C-04-2748

Spectrolab, Inc.
Sylmar, California

U.S. Department of Energy

Solar Energy

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FINAL REPORT

PHOTOVOLTAIC SYSTEMS CONCEPT STUDY

VOLUME III OF V

- Commercial On-Site Design
- Simplified Design Method for On-Site Applications

PREPARED FOR

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

ALBUQUERQUE OPERATIONS OFFICE

CONTRACT NO. E(11-1)-2748

PREPARED BY

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APRIL 1977

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VOLUME III

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PREFACE

This report documents the work performed in the conceptual design and systems analysis of three sizes of photovoltaic solar electric power systems. Conceptual system designs were developed for a single family residence, a central station power plant, and for two on-site intermediate systems (shopping center and commercial retrofit). The work was carried out by a team consisting of Spectrolab, Inc.; Bechtel Corporation; Ingenasu Associates--a group of faculty members from Arizona State University; Facilities Systems Engineering Corporation; and Midwest Research Institute; with Spectrolab as prime contractor and program manager.

This report has been prepared in nine sections plus appendices, separated into five separate volumes based on subject content. The following outlines the report format and section content:

Volume I Sections 1 and 2

INTRODUCTION AND OVERALL PROGRAM SUMMARY

Volume II Sections 3 and 4

DESCRIPTION OF SOLAR CELL ARRAYS, POWER CONDITIONING,
AND STORAGE COMPONENTS
DETAILED DESIGN OF RESIDENTIAL SYSTEM

Volume III Sections 5 and 6

DETAILED DESIGN OF SHOPPING CENTER SYSTEM, RETROFIT
APPLICATION, AND SIMPLIFIED ON-SITE SYSTEM DESIGN METHOD

Volume IV Sections 7, 8, and 9

DETAILED CENTRAL POWER STATION DESIGN,
ECONOMIC PERFORMANCE CHARACTERISTICS,
AND SOCIAL-INSTITUTIONAL ASSESSMENT

Volume V Appendices

REFERENCE DOCUMENTATION ON ECONOMIC MODELS
TECHNICAL DATA, AND PERFORMANCE ANALYSIS DATA

5.0 COMMERCIAL ON-SITE SYSTEM DESIGN

Shopping centers and commercial buildings of the future may well provide the most logical choice of application for photovoltaic solar power systems both for new construction and retrofit. Their electric energy requirements are quite susceptible to design conservation measures and their total power requirements are small enough to permit a significant fraction to be furnished on site. Their space conditioning energy requirements are sufficiently great to justify economically the development and utilization of solar thermal energy refrigerating and heating systems.

For purposes of evaluating on-site photovoltaic power generation, two applications were chosen. One was the new construction of an intermediate sized shopping center of 23,200 square meters (250,000 square feet) floor space, located in the San Fernando Valley, a Los Angeles suburb. The other was a retrofit application applied to a small low-rise office building of 3,000 square meters (32,000 square feet) floor space, located near the Los Angeles International airport.

Significant uncertainties presently exist in future costs of fossil-fueled and nuclear-generated utility power, but the safest assumption is that the trend will continue upward. Similar uncertainties exist with respect to costs associated with utilization of solar energy, but the most reasonable assumption is that the trend will continue downward. The effort reported in this system design report is based upon the credibility of both assumptions.

It is widely recognized that photovoltaic systems need not be competitive in terms of first costs with existing and planned power stations in order to fulfill an important role in the future search for alleviation of an energy crisis which promises not to go away but only worsen. They offer environmental advantages over alternate sources of energy, and if they are available at reasonable cost, they may prove attractive to a large number of purchasers.

The objectives of the efforts which are reported in this section are essentially only two in number in a major sense. The first is to explore measures for energy conservation by architectural and engineering design which can help make solar energy a feasible and viable partial solution to the growing energy crisis. The second is to examine the photovoltaic system-building interface for fundamental economic and operating characteristics of the marriage which will lead to a preferred configuration of the combination.

As explained in detail in Section 5.3 of this report, significant opportunities exist in the mechanical design and architectural approach to future shopping centers to reduce electrical demand and consumption, while preserving the quality of service and profitability of the enterprise. The most effective possibility in this direction is the use of solar thermal energy to meet space conditioning requirements for winter heating and summer cooling. This is done by the use of improved multistage lithium bromide absorption chillers for summer cooling, and heating coils for winter use and for heated water consumption. In addition, the use of direct current for lighting and most internal (motor driven) loads offers opportunities for significant improvement in operating efficiencies and reductions in energy requirements. Architectural treatment to employ maximum utilization of natural lighting, careful attention to thermal losses, ventilation and recirculation requirements, heating and cooling loads, and miscellaneous AC convenience loads can contribute additional reductions in power and energy needs.

The synergistic effect of the many avenues for energy conservation in shopping center design and optimization of photovoltaic system configuration and characteristics is such that more than one-third the annual energy requirement of the facility can be met with thermal and photovoltaic collection systems having a total area requirement which does not exceed the roof area of the facility. If the cost of installed flat fixed arrays can be reduced to \$100 per square meter in the next ten years, their initial cost would be paid back in less than ten years of energy cost savings. The incremental cost of the entire

energy saving package could be paid back in two and a half years by the reduction in operating costs (at zero interest).

The philosophy for retrofit of a light commercial building with a photovoltaic solar power system also emphasizes synergistic energy conserving changes in lighting, power drives, and architecture. Reduction of unessential lighting and use of more efficient lighting fixtures brings about a large decrease in electrical demand, partly because of the smaller cooling load. DC motors, increased natural lighting and shading from the arrays bring about further reductions. The roof mounted solar arrays then provide over 70% of the remaining electrical consumption. The retrofit package has a pay back time of eighteen years at .8% interest based on utility energy costs escalating at 5% per year.

5.1 INTRODUCTION--SYNERGISTIC EFFECTS

Because the adoption of on-site solar photovoltaic power generation depends on both reduced array costs and increased energy costs in the future, it is important to find out how increased energy costs would impact the cost-effectiveness of solar power systems. The logical consequence of an increase in the cost of energy is that conservation measures will be considered in connection with any attempt to apply photovoltaic arrays to new construction or existing buildings. The purpose of this section is to explore in general the interactions between various energy conserving alterations in electrical, mechanical and architectural systems and the use of solar photovoltaic arrays. Detailed analyses of the effects mentioned here are given in Sections 5.3 and 5.4 in connection with the design of a model shopping center and the retrofit of an existing light commercial building.

A significant decrease in energy used can be obtained from redesigning the lighting system to reduce inessential lighting, utilize natural lighting, more

efficient kinds of lights (fluorescent and sodium lights, where the yellow color of the latter is acceptable), and high frequency current. The last can be done by distributing D.C. current to the lighting fixtures which each contain high frequency inverters. Any decrease in the energy used for lighting would also decrease the need for air-conditioning. The modifications of the lighting system have two favorable impacts on photovoltaics. First, decreases in the load reduce the amount of space needed for the solar array, and so makes it possible for a larger part of the load to be met by photovoltaics installed in the most favorable part of the site. Second, the lighting load now requires DC power, so the output of the solar arrays can be used without inversion. Use of adjustable speed DC motors for the power drives would also bring about reduced electrical consumption with the same synergistic effects.

The adoption of solar thermal arrays for the heating and cooling loads removes a highly variable part of the load from the electrical system, which would benefit both electrical utilities and on-site solar electrical systems. There might, however, be competition between the two systems for the most suitable on-site space.

Fixed flat arrays augmented by reflectors offer a configuration which can be easily installed on a roof with only a small increase in structural loads, and which can either be attractively integrated with the roof construction or, if desired, hidden from view. The arrays can provide shading of the roof in summer, or, through the installation of skylights, help reduce the need for interior lighting.

Thus, energy conservation measures tend to increase the attractiveness of solar power systems for on-site applications, while the introduction of solar arrays can produce additional energy conservation. This synergism increases the potential for the use of on-site solar photovoltaic systems when array costs reach \$50 to \$100 per square meter.

5.2 COMPARISON OF COMMERCIAL APPLICATIONS

This section contains an evaluation of the suitability of various classes of light commercial buildings for incorporation of on-site conversion of solar energy. Hourly and seasonal variations in demand as well as average demand density are considered. The considerations discussed in this section led to selection of a shopping center for the design study presented in Section 5.3 of this report and to the choice of a low-rise office building for the retrofit study of Section 5.4.

Energy Demand Profiles

Predictions of daily load profiles were made for four basic building types, as shown in Figure 5.2-A. These basic profiles were generalized from data provided by Southern California Edison and the Los Angeles Department of Water and Power. Discussions of these basic profiles follow. Estimates were made of the annual load profiles which are experienced in various parts of the country. These estimates, shown in Figure 5.2-B are based on weather data, current architectural practice and engineering judgement, due to the lack of hard published data. A discussion of the reasoning and conclusions follows. The annual averages observed for various building types are also listed in Figure 5.2-C (page 5-12).

Four basic profile types were observed for intermediate size buildings. These types correspond directly to the normal operating hours of the building types. Unfortunately, it is impossible to make specific rules about electrical consumption profiles and these charts (Fig. 5.2-A) should be used for approximate calculations only. On each chart the vertical axis represents the percentage of the average daily power rate that is being used and the horizontal axis represents the time of day.

The solid line on each chart represents a typical daily power consumption profile for each basic type of building. As an aid in the visualization of

DAILY DEMAND PROFILES BY CLASS

Figure 5.2-A

CLIMATOLOGICAL EFFECTS ON DEMAND PROFILE

FIGURE 5.2-B

the range of deviation of the data, dotted lines representing the range within which most buildings will fall is also included on the charts.

The upper-left chart (5.2-A) represents a profile typical of continuous operations, like hospitals and industrial manufacturing plants. The consumption is a steady rate with a small peak in the afternoon. Hospitals are generally well insulated acoustically and well sealed against infiltration of outside air and can therefore maintain a constant indoor temperature fairly easily. Industrial plants generally have no air conditioning loads and usually maintain steady ventilation rates day and night.

The upper-right chart (5.2-A) represents a profile typical of office buildings and schools which maintain standard office hours. The consumption rate remains low during the night until an hour or two before opening. Around 7:00 a.m. the curve rises sharply to a plateau around 9:30 a.m. The curve rises slowly and steadily until closing time when it slopes back down to the night-time values. Schools generally peak earlier (3:00 to 4:00 in the afternoon) but decrease more slowly than offices. The minimum curve represents off days in which the building is empty. Buildings which consistently turn off the automatic thermostats on off days have a lower power consumption rate (~ 20% of daily average) and little or no afternoon peaks.

The lower-left chart (5.2-A) is typical of services. The peak consumption is around 2:00 p.m. in the afternoon with high consumption rates from 10:00 in the morning to 8:00 at night. The slope of the curve is less in the evening because some stores remain open late and most leave lighted displays on until after midnight. College libraries and labs are generally moderated (higher minimum, lower peaks) due to some continuous usage.

The lower-right chart (5.2-A) is typical of residential complexes. The minimum power consumption occurs around 3:00 to 4:00 in the morning, followed by a steep rise around 7:00. This peaks around 8:00, and subsides for a few hours

until it builds up to another peak around 6:00 in the evening. The power consumption drops drastically around 11:00 in the evening to the night-time levels. The minimum curve here also represents off days, during which the curve slowly rises to the initial peak around 2:00 in the afternoon, then remains high. Hotels and motels do not fit into this building type without moderation. Their power consumption profiles follow the same pattern, but the minimum levels are higher and the peaks are slightly lower, due to many building functions that are continuous.

Annual power consumption profiles generally have two peaks, summer and winter. Which peak is higher is dependent upon the climate involved. Four basic climates exist within the United States in terms of building electrical profiles; mild (no peaks), severe (two peaks), hot (summer peaks), and cold (winter peaks). The relative strength of each peak is dependent upon numerous factors, including climate, weather, annual insolation profile, proximity to water, building type, winds, etc. Although electrical load usually does not peak as high in winter as in summer (due to non-electric heating), thermal collectors would be useful in reducing the winter fuel needs. The curves shown in Figure 5.2-B are intended to demonstrate how consumption should vary in various climates.

A number of factors are involved in ranking applications as to suitability for the use of solar energy. First it is advantageous if the timing of energy demands coincides hourly and seasonally with the availability of sunlight, because in this case solar power can be used directly without the additional costs and efficiency losses associated with energy storage, particularly of electrical energy. Office and service buildings in particular have daily demand profiles which are highest during daylight hours. Summer peaking and seasonally level loads are more easily supplied with solar energy than are winter peaking loads although the array type and orientation (tilt angle) can affect the seasonal distribution of energy output to some extent. Second, the energy density is a factor in what fraction of utility power can be displaced by solar energy. However, there is a tendency to overemphasize this

consideration. Actually, within a fairly large range, solar cost-effectiveness is not sensitive to the fraction of the load supplied by solar energy. Also, the aggregate effect of supplying 10-20% of many large electrical loads by solar photovoltaics would be greater than the effect of supplying 70-80% of a few smaller loads.

A third consideration is that changes in the load can make it more amenable to supply by solar energy. The use of solar thermal energy for the heating and cooling loads should be considered. The advantage of using solar thermal energy for the heating load is that thermal energy can be collected more efficiently and stored more cheaply and efficiently than solar electrical energy, to supply a load which is poorly matched to insolation. Backup can be provided by any combustible fuel. Finally, it is logical to expect that measures for conserving electricity (such as reduced lighting levels, higher efficiency equipment and lights) would be adopted prior to or simultaneously with the introduction of photovoltaic arrays. The impact of conservation measures on the timing of the load and on the energy density also affects suitability.

Table 5.2-C presents the results of a survey of 32 intermediate-size on-site applications. Data for this survey was obtained from records furnished by Los Angeles area utilities and from architectural and building engineering handbooks. For each application, the daily electrical energy use profile was classified into the four categories discussed above. The typical intensity of electrical usage within the building was classified into low, medium and high ranges. These correspond approximately to 0 to 15, 16 to 40, and 40 to 70 average watts per square meter of total floor area during the operational hours.

An overall rating of good, fair or poor was given to each application, depending on the two factors listed and also upon typical architectural features of the building affecting the ease of integration of the solar arrays with the building structure. For example, building aesthetics are of more importance

in the design of a city hall or courthouse than in the design of government office buildings, and therefore, it must be anticipated that more constraints on the placement of solar arrays will be imposed. As another example, it can be anticipated from the results of the energy conservation study of the shopping center that buildings with open floor plans offer more opportunities for the application of energy conservation techniques.

It can be concluded from this survey that the best choices for on-site photovoltaic systems applications are low-rise buildings with relatively open floor plans, which are occupied mainly during the day. A considerable number of applications satisfy these requirements, including both government and commercial buildings. Within this group, preference should be given to buildings with relatively low energy consumption per unit floor area.

Table 5.2-C

COMPARISON OF COMMERCIAL ON-SITE APPLICATIONS

<u>Division</u>	<u>Type</u>	<u>Daily Profile</u>	<u>Average Density (W/m²)</u>	<u>Suitability</u>
Commercial	Automotive Sales and Service	Service	Med/High	Fair
	Restaurant	Variable	High	Poor
	Retail Store	Service	Med	Good
	Hotel/Motel	Continuous	Med	Fair
	Bank	Office	Med	Good
	Warehouse	Office	Low	Good
Educational	College Classroom	Office	Low	Good
	College Student Center	Service	Low	Fair
	College Dormitory	Residential	Low/Med	Fair
	Gymnasium	Service	Low	Good
	Library	Service	Low	Good
	Elementary School	Office	Low	Good
	High School	Office*	Med	Fair
Recreational	Auditorium/Theater	Variable	Med	Poor
	Bowling Alley	Service	Med	Fair
	Club	Service	Low	Fair
	Community Center	Service	Med	Fair
Industrial	Factory	Continuous	High	Poor
	Research	Office	Med	Fair

Table 5.2-C - Continued

<u>Division</u>	<u>Type</u>	<u>Daily Profile</u>	<u>Average Density (W/m²)</u>	<u>Suitability</u>
Medical	Hospital	Continuous	Med.	Poor
	Medical Offices	Office	Med	Fair
	Nursing Home	Residential	Low	Good
Religious	Church	Variable	Low	Poor**
Residential	Single Family Dwelling	Residential	Low	Fair
	Elderly Housing	Residential	Low	Good
	Condominiums, Townhouses, Low-rise Apartments	Residential	Low/Med	Fair
Government	City Hall/Court House	Office	Med	Poor**
	Admin. Offices	Office	Med	Good
	Police/Fire Station	Continuous	Med	Poor
Office Buildings	Low Rise (1-3 stories)	Office	Med	Good
	Medium Rise (4-7 stories)	Office	Med	Fair
	High Rise (8+ stories)	Office	Med	Poor

*Significant evening use.

**Downgraded due to architectural factors.

5.3 SHOPPING CENTER DESIGN

Application of photovoltaic systems to shopping center requirements of the future appears to require two distinct directions of effort. The first is aimed at photovoltaic system configuration selection under constraints of space and structural integration. The second, dictated by a scenario of rising energy costs, is aimed at reducing demand and consumption requirements through design for maximum conservation measures. The second analysis allows evaluation of interactions between anticipated changes in building design and the economic feasibility of solar energy.

Selection of a preferred configuration is dependent upon a large number of variables, both economic and technical. If a parametric approach were taken for configuration selection, it is clear that some combinations of variables would favor flat fixed arrays, others flat tracking arrays, and still others concentrating arrays; while storage systems could be attractive in some circumstances and unattractive in others. Similarly, a preference for direct current systems under one combination of variables might be reversed in favor of alternating current for a different combination.

The following sections describing analytic effort and results include those of functional analysis (to establish energy requirements and design criteria), engineering analysis (to establish configurations and system specifications for major subsystems), and cost analysis (to evaluate the economic feasibility of the design). The engineering analysis includes thermal and photovoltaic arrays, space conditioning, and the major electrical and mechanical subsystems.

5.3.1 Analysis of Application

This section outlines the approach, methods, and conclusions of an effort to establish design criteria for a photovoltaic system for a shopping center.

Predictions of peak load (watts per square meter) vs. time of day for a 1985 shopping center, and the resulting daily energy requirement (watt hours per square meter per day) were made, and are illustrated in Figure 5.3.1A. These predictions are for locations in the San Fernando Valley, a suburb of Los Angeles, and are based upon typical current experience of three large department stores and a large shopping center. These daily and annual power demands and energy consumption are from Los Angeles Department of Water and Power data, and are summarized in Figures 5.3.1-B, 5.3.1-C, and 5.3.1-D. The shopping center had a large incandescent lighting load.

The ten-year extrapolation of energy conservation in design results in a 62% decrease in watt hours per day per square meter and in peak watts per square meter. Based upon two significant assumptions, both of which appear technically feasible and which are detailed in Sections 5.3.3, 5.3.4, and 5.3.5 of this report, such a reduction in electrical energy requirements will have a beneficial effect upon the attractiveness of photovoltaic systems.

The first assumption results in eliminating space conditioning loads from the electrical system, by the use of solar-heated absorption refrigeration equipment of advanced design (see Section 5.3.3). This assumption removes an estimated peak demand of 38 watts per square meter, decreases consumption by an estimated 400 watt hours per day per square meter (by elimination of electric-driven vapor compression machinery), and accounts for 40% of the total predicted decrease in shopping center electric energy requirement by 1985. The remaining reductions in power and energy (from 74 to 72 watts per square meter and from 1200 to 600 watt hours per day per square meter, respectively) are expected to result from design improvements in the areas of lighting, ventilation, and internal loads; evenly divided between minimization of requirements and maximization of efficiency, largely accomplished by the use of a direct current electrical system for the shopping center.

From the foregoing data and assumptions, it is concluded that within ten years it will be feasible to design and build a shopping center in the San Fernando

SHOPPING CENTER POWER GOAL

FIGURE 5.3.1-A

17,195 METER² DEPARTMENT STORE, SAN FERNANDO VALLEY

DEPARTMENT STORE POWER & ENERGY REQMNTS.:

○ 15,000 M², SAN FERNANDO VALLEY

□ 25,000 M², WEST LOS ANGELES

DEPARTMENT STORE CHARACTERISTICS

Valley which will have characteristics of electric power demand and consumption illustrated in Figure 5.3.1-A. There should be a peak load of about 42 watts per square meter occurring after noon on a typical day, and a daily consumption of about 600 watt hours per square meter. In order for such improvements to be possible within ten years, developments are required in the fields of multiple-stage absorption refrigeration, area lighting, ventilation equipment, and internal load efficiencies.

Even with such challenging reductions in power and energy requirements postulated for future shopping center design, the area requirements for solar energy conversion systems are so great that space constraints will have a powerful influence on the choice of configuration of photovoltaic arrays, as described in Section 5.3.2.

For planning estimates of the cost and worth of photovoltaic systems applied to shopping centers ten years hence, the following design criteria have been adopted:

1. Site cost is between \$100,000 and \$150,000 per acre, \$2.29 to \$3.44 per square foot, or \$24.70 to \$37.10 per square meter.
2. Silicon photovoltaic array costs, delivered on site, are \$55 per square meter (\$500 per kilowatt at 11% conversion efficiency)
3. Fixed array photovoltaic system installed costs are between \$75 and \$100 per square meter, including costs of cells, substrate, structure, wiring, and installation.
4. Nominal shopping center floor area is 23,200 square meters (250,000 ft²).
5. Minimum site area is 32,000 square meters (345,000 ft² or 7.9 acres) for the nominal shopping center.
6. Peak demand (lighting, ventilation, and internal loads) is 42 watts per square meter. For the 23,200 square meter nominal shopping center, peak demand is 975 kW.

- 7.. Daily consumption for the same loads is 600 watt hours per day per square meter, for an average demand of 25 watts per square meter, or 14,000 kWh per day for the nominal shopping center.
8. Peak demand for lighting will be 22 watts per square meter or 515 kW for the 23,200 square meter shopping center. High efficiency lighting will be direct-current powered through DC to AC high frequency inverters.
9. Air handling equipment (circulation and make-up air fans) will be DC powered and designed to require no more than four watts per square meter or 93 kW for the nominal shopping center. For six air changes per hour, the 175,000 CFM air handling requirement should require a total fan motor power of about 75 kW at a pressure rise of 2.5" W.G. to allow for filters, ducts and coil pressure drops. Fresh air make-up will be about 15,000 CFM of the 175,000 CFM recirculation required.
10. Maximum (design day) indoor winter heating design value is 68°F. Minimum (design day) indoor summer temperature with absorption refrigeration air cooling will be 78°F.
11. Approximately 10% of the internal loads' peak demand and about 5% of the consumption of internal loads will be utility-furnished alternating current (convenience outlets for vacuum cleaners, appliances, etc.).
12. For photovoltaic arrays sized to provide up to 300 watt hours per square meter of shopping center floor area per day during the best month (50% of shopping center needs) no electric storage capacity need be provided for the nominal shopping center.
13. Except for convenience 115 VAC outlets furnishing a portion of the shopping center internal loads, all utility power will be rectified to satisfy demand at any time. If a battery is provided it can be charged off-peak with rectified utility power.
14. Domestic hot water consumption is estimated at 20,000 gallons per day, average, at 160°F. This may preclude some relatively low revenue tenants such as laundromats.

5.3.2 Photovoltaic System Analysis

Many alternate configurations were considered during the course of the study in each of the broad categories of: flat, fixed, inclined arrays; flat

tracking arrays; and concentrating arrays. U.S. Weather Bureau insolation data for Los Angeles, Phoenix, and Cleveland were analyzed for both direct and diffuse components to produce the typical monthly average variations for the typical year as shown in Figure 5.3.2-A. From this data it may be observed that on an annual basis at any location, flat fixed arrays are exposed to only two-thirds as many watt hours per square meter as are (unshadowed) flat tracking arrays, due to varying angle of incidence, while concentrating arrays receive about seven-eighths of the integrated flux of flat tracking arrays, due to loss of the diffuse component of solar radiation. Coincidentally, relative to any configuration located at Phoenix, the same configuration in Los Angeles will receive about seven-eighths as much insolation on an annual average basis. From examination of insolation data it appears advantageous to select flat tracking arrays at a Phoenix location to maximize annual insolation on each solar panel. For a variety of reasons a less obvious choice of flat fixed arrays in a San Fernando Valley location was made.

Obviously Phoenix is among the best locations for solar energy applications, and no doubt will be in the forefront for applications of solar energy to commercial buildings for power and space conditioning. It was believed desirable, however, to choose a less-endowed location for design of a photovoltaic system for a shopping center to demonstrate its potential for a variety of locations, since feasibility in Los Angeles would certainly prove feasibility in Phoenix; but the converse would not necessarily be true.

A preference for flat fixed arrays over tracking and concentrating arrays is predicated upon achievement of a target cost of \$55 per square meter for silicon cell arrays, and the space constraints attending the characteristically high land values of desirable shopping center sites in high population density locations. Since flat fixed arrays use available space more efficiently than tracking arrays (maximum array area for zero shadowing at noon is 60% of available horizontal surface area at 34°N latitude, if arrays are inclined 34° from horizontal and the centers of all arrays lie in the horizontal plane), and

DESIGN INSOLATION VALUES -- WATT HOURS
PER SQUARE METER PER DAY
(BASED ON CELL AREA)

FIGURE 5.3.2-A

since flat arrays have advantages of simplicity over tracking arrays, their use is postulated for the basis of the shopping center study.

The relative merit of tracking and fixed arrays is strongly determined by photovoltaic array cost, tracking mechanism costs, and space availability and land value. Single polar axis tracking arrays will suffer some shadowing by adjacent arrays during morning and evening hours, in an amount which may be approximated as follows:

1. No north-south shadowing (north-south spacing is $2.96 h$, where h is the vertical height of the tops of the arrays above the horizontal plane of the bottoms of the tracking arrays). The same north-south spacing is observed for fixed arrays, and both fixed and tracking arrays are assumed to be inclined at an angle from the horizontal equal to the local latitude, 34° .
2. East-west shadowing depends upon east-west spacing for the polar-axis tracking arrays, and also upon sun azimuth angle during early morning and late afternoon hours, a function of season and solar elevation, that is, time of day.
3. East-west spacing for the cases of 90° and 270° azimuth angles measured from true north can be approximated for shadowing losses by that fraction of the day required to change from fully shadowed to fully unshadowed, as equivalent to two daily periods during each of which shadowing causes a 50% time-average loss. As a function of spacing expressed by center-to-center separation (in terms of array radius r about the polar axis of rotation) the solar elevation angle change for this condition is the angle whose sine is $2r/d$, where d is the separation of centers. Minimum value of d is $2r$, at which value the edges of adjacent arrays would be touching each other at local noon, and tracking arrays would degenerate into the performance and cell area requirement of fixed arrays.

For simplicity the shadowing loss is evaluated for the first day of spring and the first day of autumn, by expressing the shadowing angle so calculated as a fraction of 180° . The results of more detailed calculations appear in Section 6.1.3. Therefore the losses so approximated overstate the summer losses and understate the winter losses, but for an average the shadowing losses vary with east-west separation distance as follows:

<u>Separation of Centers:</u>	<u>2r</u>	<u>3r</u>	<u>4r</u>	<u>5r</u>	<u>6r</u>
Shadowing Loss:	.333	.232	.167	.131	.108
July Output*	750	860	933	974	1010
Annual Avg. Output*	590	680	738	770	787
Array Area/Land Area	0.60	0.40	0.30	.024	0.20
Array Area/Roof Area	0.80	0.70	0.65	0.62	0.60
Land Area/Roof Area	1.33	1.75	2.17	2.58	3.00
Plus Thermal Collectors	1.56	1.98	2.40	2.81	3.23

*Watt hours per day per square meter at 10% efficiency.

Figure 5.3.2-B has been drawn to illustrate the fundamental trade-offs attending the contemplated use of flat tracking arrays. Individually, without shadowing losses, a tracking array could convert about 50% more solar energy to electric energy than the same area fixed inclined array on an annual basis, based on beam insolation. However, in order to approach the capability of providing energy independence for a shopping center whose total site area is only twice the floor or roof area, the array spacing is constrained to small values where shadowing losses become so significant that only small improvement over fixed arrays is possible. For instance, shopping center requiring 600 watt hours per square meter (through advanced energy conservation measures outlined in Section 5.3.1) would require 300 watt hours per day per square meter of site area if the center occupied one-half of the site. During July, August, and September a fixed array system inclined at 34° to the horizontal would

TRACKING ARRAYS' SPACING EFFECTS

FIGURE 5.3.2-B

yield about 650 watt hours per day per square meter of array at 10% efficiency, or 390 watt hours per day per square meter of horizontal space dedicated to arrays, and require space about 54% greater than the shopping center roof area including spacing requirements. (This would allow space for thermal collectors for space conditioning.)

Consider tracking arrays also sized to meet total energy requirement during July (best month) and also to occupy 154% of shopping center roof area. Unshadowed arrays could deliver about 1120 watt hours per day per meter² during July, but when spaced to provide 390 Whrs/day/m² of available space (with no shadowing losses accounted for) the array area must be equal to 35% of space available. However, when tracking arrays are spaced in the north-south direction sufficiently to prevent winter shadowing at noon, they must be spaced in the east-west direction on centers which are only about 3.5 times the array radius to equal 35% of the available horizontal space. Such crowding of tracking arrays permits only 900 watt hours per day per square meter of array area during July due to shadowing effects during early morning and late evening hours, or a 20% reduction relative to the capability of the unshadowed array.

Attempts to provide energy independence during the best month, July, with shadowed tracking arrays under a space constraint of 1.54 x roof area would lead to still further crowding of the arrays and still greater shadowing losses. If east-west spacing were reduced to 2.5r between centers, array area would be 48% of horizontal space available, but shadowing losses would be almost 30%, resulting in only 780 watt hours per day per square meter of flat tracking array surface at 10% efficiency. However, daily shopping center electric energy needs during July would nearly be met by such a configuration, since it would provide 375 watt hours per day per square meter of horizontal area available. In this situation polar-axis tracking arrays would need 80% of the photovoltaic array area required by fixed inclined arrays capable of meeting 100% of the shopping center electric energy requirements during

July, August, and September, or 85% of the array area of a fixed array system with the same capability (96.5% of requirements in the best month).

It is illuminating to consider the two alternatives in the light of annual average capabilities relative to shopping center requirements, as illustrated in Figure 5.3.1-A. A fixed array system with 10% efficiency designed to provide 100% of shopping center electrical needs during July, August, and September will provide 91% of the annual energy requirement. It will require a total array area of 92% of the shopping center roof area. A tracking array system designed to provide 96.5% of the shopping center energy required during July will provide 76% of the annual energy requirement, and will require a total array area of 74.5% of roof area.

In design of the shopping center, considerations create space constraints on the photovoltaic array. First, there is a cost advantage for on-site arrays, because land acquisition costs are high in the densely populated areas where a shopping center would be built. Second, an additional cost saving can be obtained by placing arrays on the shopping center roof, by which means the cost of constructing a special array support structure is avoided.

The preceding discussion shows that for tracking arrays, an attempt to exploit these cost advantages of on-site and roof space by putting tracking arrays closer together reduces their insolation advantage in comparison to fixed arrays. On the other hand, increasing the distance between tracking arrays, on a limited space, reduces the capability of the system.

It does not appear desirable to size the photovoltaic system to a capability during the best month which exceeds shopping center needs. Because of this, during winter months there will always be a requirement for some conventional utility power. Seasonal storage and sale of excess energy seem equally impractical, so maximum photovoltaic system size and capability should be

matched to the daily demand average during the best summer month. Daily storage for night use is required if the system is sized to provide it, but a smaller system meeting only the larger daytime needs and requiring no storage could be a viable alternative.

Flat Fixed Array Improvement Options

It has been demonstrated that rows of roof-mounted flat fixed arrays of silicon photovoltaic cells inclined from the horizontal at the local latitude and oriented in east-west rows facing south will offer advantages in simplicity, space utilization, reliability, and economics in comparison with tracking configurations, if array costs can be reduced to the order of \$55 per square meter. Fixed flat arrays are enhanced by the addition of reflecting surfaces between arrays, which contribute up to 26% additional energy and may also serve to reduce roof heat gains, thereby reducing cooling requirements.

The following reflector-array parameters are used in optimizing the geometrical configuration:

A = Array length in the meridian plane (north-south direction)

R = Reflector length in the meridian plane

β = Array inclination angle from horizontal

i = Reflector inclination angle

D = Array north-south spacing

The relationships of these parameters are given in Section 6.1.2. The solar energy incident on arrays with reflectors over the year was determined using hour-by-hour simulation. Clear day 1 kW/m^2 direct normal insolation was assumed for the limited purpose of determining the optimum geometrical configuration.

For a latitude of 34° and a mirror reflectance of .75 the annual incident energy per unit area of array was determined for various reflector and array tilt angles. This data is given in Figure 5.3.2.-C. Figure 5.3.2-D shows the annual incident radiation seen by the array per unit of horizontal area. This energy is denoted as "theoretical" since its computation used ideal clear day insolation.

As with tracking arrays, maximizing energy per unit horizontal area and per unit array area lead to opposite results. The maximum calculated energy per unit horizontal area is $2260 \text{ kWh/m}^2\text{-yr}$ for an almost flat array, inclined at 4° , and almost vertical reflector inclined at 86° . The array area is nearly equal to the horizontal area, and the reflector area is very small, only 7% of the horizontal area. On the other hand a fairly steep array (64°) and flat reflector (16°) give the largest calculated value, $3340 \text{ kWh/m}^2\text{-yr}$, for incident energy per unit array area. In this case the array area is 28% and the reflector area is 91% of the horizontal area. Energy input to the array per unit horizontal area is only $940 \text{ kWh/m}^2\text{-yr}$. From the figures it can be seen that the large reflector angles which lead to high energy per unit horizontal area give low incident energy per unit array area, and that large array tilt angles which increase the latter quantity decrease the former.

The data in Figure 5.3.2-C may be compared to annual theoretical insolation of $2647 \text{ kWh/m}^2\text{-array-yr}$ for a surface tilted at the latitude angle (with no shadowing). The value of $3340 \text{ kWh/m}^2\text{-array-yr}$ for a reflectorized array represents a 26% augmentation of insolation.

The tilt angles used for the shopping center design were those that maximized the theoretical incident energy per dollar of combined array and reflector cost, excluding installation costs. Using ERDA goal costs for solar arrays, a price ratio of 10:1 for array and reflector costs can be assumed ($\$55/\text{m}^2\text{-array}$ and $\$5.5/\text{m}^2\text{-reflector}$). The computed values of this criterion are given in Figure 5.3.2-E. The maximum occurs near $\beta = 35^{\circ}$ and $i = 45^{\circ}$, and these angles were adopted for the photovoltaic array of the model shopping

Figure 5.3.2-C

Theoretical* Insolation of Array with Reflector

kWh/m² Array-yr.

Latitude = 34°

Specular Reflectance = .75

Array Tilt Angle - i	Reflector Tilt Angle - β								
	6	16	26	36	46	56	66	76	86
4	2350	2370	2370	2370	2370	2340	2310	2290	2260
14	2530	2630	2630	2650	2600	2490	2390	2310	2220
24	2680	2850	2860	2890	2760	2570	2410	2270	2110
34	2800	3030	3060	3050	2840	2570	2360	2150	1940
44	2900	3180	3230	3150	2850	2510	2240	1980	1710
54	2960	3290	3300	3150	2770	2380	2050	1740	1440
64	2970	3340	3290	3060	2610	2170	1800	1460	
74	2960	3320	3180	2870	2370	1890	1490		
84	2910	3190	2980	2600	2070	1560			

*Array-reflector tilt studies were performed using clear day 1 kW/m² direct normal insolation.

Figure 5.3.2-D

Theoretical* Insolation of Array with Reflectors

kWh/m²-horizontal-yr

Latitude = 34°

Specular Reflectance = .75

Array Tilt Angle - i	Reflector Tilt Angle - β								
	6	16	26	36	46	56	66	76	86
4	1410	1910	2080	2170	2220	2240	2250	2250	2260
14	770	1450	1800	2040	2160	2200	2220	2240	2250
24	560	1220	1640	1960	2110	2170	2200	2230	2240
34	460	1090	1550	1910	2070	2130	2190	2220	2240
44	400	1010	1500	1880	2050	2120	2170	2220	2230
54	360	970	1470	1850	2020	2100	2160	2210	2230
64	330	940	1440	1820	2000	2070	2140	2200	
74	310	910	1420	1800	1970	2050	2120		
84	300	890	1390	1770	1940	2020			

*Array-reflector tilt studies were performed using clear day 1 kW/m² direct normal insolation.

Figure 5.3.2E

Theoretical* Insolation per Dollar Array and Reflector Cost

kWh/yr-dollar

Latitude = 34°

Reflectance = .75

Array Tile Angle - i	Reflector Tilt Angle - β								
	6	16	26	36	46	56	66	76	86
4	15.3	17.2	17.3	17.5	17.4	17.3	16.0	16.9	16.7
14	15.2	17.3	18.6	19.0	18.7	18.0	17.3	16.8	16.1
24	14.3	18.4	19.5	20.1	19.4	18.3	16.9	16.2	15.1
34	13.6	18.7	20.2	20.7	19.6	17.9	16.6	15.1	13.7
44	13.1	18.9	20.6	20.9	19.3	17.3	15.4	13.8	11.9
54	12.5	19.1	20.7	20.6	18.5	16.1	14.0	12.0	9.9
64	11.9	18.8	20.3	19.6	17.3	14.5	12.2	9.9	
74	11.3	18.2	19.4	18.4	15.5	12.6	10.0		
84	10.9	17.4	18.0	16.6	13.5	10.4			

*Array-reflector tilt studies were performed using clear day 1 kW/m^2 direct normal insolation.

center. The dimensions of the arrays and reflectors are as follows: 7500 square meters of array and 9246 square meters of reflector occupying 69.7% or 12887 square meters of the 18500 square meters of roof space. The theoretical insolation received by the arrays is $3166 \text{ kWh/m}^2\text{-array-yr}$ or $1844 \text{ kWh/m}^2\text{-roof-yr}$. The augmentation of output per unit array area compared to an unshadowed latitude tilted array is 19.6%.

In earlier analyses an array of double this size with output equal to the whole load in the best month had been proposed for the model shopping center. Larger than the roof, this array would have extended to a structure built over the parking area. However, the costs of storage and of installing the array support structure made the large array less attractive economically.

When the effects of reflecting surfaces and array inclination change were applied to the average daily watt hours per square meter of cell array as a function of season from Figure 5.3.2-A (flat fixed arrays inclined 34° in Los Angeles) the resulting array output (peak watts and watt hours per day per square meter) become as illustrated in Figure 5.3.2-F. When these data are used for sizing of electrical system components for the $250,000 \text{ ft}^2$ (23,000 square meter) shopping center, the following required characteristics result:

- 1) Photovoltaic array area is 7,500 meters².
- 2) Reflector area is 9,250 meters².
- 3) Maximum peak power is 1.1 MWE.
- 4) Horizontal area (space requirement for arrays and reflectors is 13,000 meters², or 70 per cent of the shopping center roof area of 18,500 meters².
- 5) Annual energy requirement of the shopping center is estimated at 4.7 million kWh consumed, of which 4.6 million kWh are DC and 0.1 million kWh are AC.
- 6) All of the AC energy and part of the DC energy will be utility furnished.

Figure 5.3.2-F. Reflector Effects

- 7) The photovoltaic system will furnish 2.1 million kWh of the 4.6 million kWh of DC required annually, with a loss of about .2 million kWh of array output due to power availability in excess of the load.
- 8) In addition to 0.1 million kWh of AC used directly, there will be required an additional 2.64 million kWh of AC to be rectified to DC.
- 9) No storage capacity is provided.
- 10) The rectifier-regulator must be capable of delivering the nominal 240 volt DC maximum load of 4000 amperes to internal loads.

Based upon the assumed electric energy requirements of the 23,200 square meter shopping center which derive from Figure 5.3.1-A, an estimate of 10% for that portion of the requirements which is met by AC power, and regarding daily energy requirement (~14,000 kWh) to be independent of season the photovoltaic array would supply 130 to 200 MWH per month (30 to 48 per cent) of the monthly electrical load of 420 MWH. Monthly utility energy used would range from 200 to 230 MWH. The total used of photovoltaic and utility energy by the shopping center is two percent higher than the load because of losses from rectifying utility power for the DC loads.

5.3.3 Space Conditioning Options

In order to reduce electrical energy requirements of the photovoltaic powered shopping center, it is proposed to accomplish space heating and cooling by means of solar thermal energy. The thermal storage and control systems are covered in more detail in Section 5.3.5. It is the purpose of this Section to establish design criteria for the space conditioning components and thermal collector arrays.

Absorption Refrigeration Equipment

Because of the initial cost of thermal arrays, it is desirable to minimize the collector area requirement in meeting the summer cooling requirements.

In addition, the space available for thermal collectors must compete with that for photovoltaic arrays, providing additional incentive for reducing thermal collector area. In order to match the collector area requirement for summer cooling with that for winter heating, it is necessary to design for absorption refrigeration coefficient of performance higher than any commercially available hardware is capable of delivering presently. One company offers two-stage lithium bromide absorption chillers in the approximate range of sizes from 400 to 1000 tons, with C.O.P. of about 1.0 at full load to about 1.35 at 50% load.

Due to reduced internal loads planned for the photovoltaic power shopping center (high efficiency lighting, variable speed DC motors, etc.) and architectural improvements in fenestration and roof heat gain reductions, it is possible to meet an objective space cooling requirement of 60 square meters per ton, resulting in a design space cooling load of about 400 tons. At a coefficient of performance of 1.0, the absorption chiller would require the input of 4.8 million BTU per hour to sustain full 400-ton load operation. This exceeds winter space and water heating design requirement by a factor 2.5. Therefore a balanced thermal collector design would be possible if the absorption chiller were capable of coefficient of performance of 2.5. Significant economic incentive exists for the development of a four-stage absorption chiller with such a high coefficient of performance, as suggested by Figure 5.3.3A. Currently there is no economic incentive for improved C.O.P. because of increased first cost of chiller hardware; but when coupled with solar thermal collectors quite the opposite is true.

Examination of the technical problems attending the development of an advanced four-stage absorption chiller has been undertaken, with the conclusion that a fairly low-cost, low-risk program toward the objective of a coefficient of performance of 2.5 could be defined, and that it could have very great influence on the acceleration of solar thermal collection for space cooling in commercial buildings. Some of the more significant findings are reported in the following paragraphs.

TOTAL ACQUISITION COSTS OF THERMAL COLLECTORS AND ABSORPTION CHILLERS--
(EXCLUDES LINES, PUMPS, STORAGE, AND HEAT SINK HARDWARE COSTS)

Figure 5.3.3B illustrates the fundamental requirements for increased coefficient of performance: high source temperature and low sink temperature. Most of the effort currently underway in this country is in the direction of making low source temperatures work in absorption cycles, but it should be apparent that the resulting low coefficient of performance leads to a requirement for excessive (and relatively expensive) collection area. Space cooling hardware contemplated for the shopping center is based upon an assumed successful development of a four-stage 500-ton lithium-bromide absorption chiller with a coefficient of performance of at least 2.0 at full load and 2.5 at part load. This requires a source (thermal storage) temperature of 350°F or greater, as shown in Figure 5.3.3C.

Thermal collector design criteria are established by the absorption chiller requirements for flow rate and temperature. Sizing the collector system for an average collection rate of 2.0 million BTU per hour on the most favorable day at a maximum temperature of 400°F results in a requirement for 2,000 square meters of collector area and 1,250 square meters of reflector area; with 1,000 square meters of collector being flat fixed arrays augmented by reflectors, and the remaining 1,000 square meters of collector being fixed concentrating collectors typified by Figure 5.3.3D. The flat collectors, augmented by reflectors, will operate at maximum collection temperature of 275°F and collection efficiency of about 60%; careful design and fabrication will be required to minimize conductive and convective heat losses. The fixed concentrating collectors will operate at maximum collection temperature of 400°F and collection efficiency of about 40%, and will be coupled in series with the flat collectors, so that the thermal transport fluid (low vapor pressure) will be circulated first through the flat collectors, then the concentrating collectors, en route to the thermal storage and control system, detailed in Section 5.3.5.

In reality, the "fixed" concentrating collectors of the parabolic trough type shown in Figure 5.3.3D may have adjustable inclination angles of $34^{\circ} \pm 20^{\circ}$,

ABSORPTION CHILLERS ($T_L = 40^\circ\text{F}$)
 IDEAL REVERSE CARNOT COEFFICIENT OF PERFORMANCE

$$\text{C.O.P.} = \frac{T_L}{T_H} \left(\frac{T_H - T_S}{T_S - T_L} \right) \dots \text{(ABSOLUTE SCALE OF TEMPERATURE)}$$

FIGURE 5.3.3B

ABSORPTION REFRIGERATION; $COP = \left(\frac{T_L}{T_H} \right) \left(\frac{T_H - T_s}{T_s - T_L} \right) = (\text{CARNOT})$

FIGURE 5.3.3C

FIXED CONCENTRATING
SOLAR THERMAL
COLLECTOR

$T_{MAX} \sim 400^{\circ}F$

$\rho = 0.90$ REFLECTANCE OF PARABOLIC TROUGHS
 $\tau = 0.96$ TRANSMITTANCE OF COVER TUBE
 $\alpha = 0.86$ ABSORPTANCE OF ABSORBER TUBE
 $\epsilon = 0.07$ EMITTANCE OF ABSORBER TUBE

$\eta_{MAX} = .9 \times .96 \times .86 = 0.74$ (OPTICAL EFFICIENCY,
ZERO THERMAL LOSS)

$\eta_{AVG} \approx 0.40$ (OVERALL EFFICIENCY,
46 % THERMAL LOSS)

FIGURE 5.3.3D

but required adjustment on an average of about 7° once each month to correct for solar declination changes. The frequency of such adjustment depends upon the concentration ratio, but with the low concentration required for 400°F (approximately 3 to 5) optical losses become negligible below 6° to 8° off axis.

Figure 5.3.3D suggests only one of many possible fixed concentrating thermal collectors which can be designed on the parabolic trough principle. Not shown in the example selected are the glass tubes (possibly double-walled evacuated) surrounding the fluid-bearing thin-walled copper or glass tubing along focal lines, and the required glass cover. Other requirements, in common with all similar fixed concentrators, are those of black selective surfaces on the absorber tubes (high absorptivity and low emissivity) and insulating materials to minimize convective and conductive heat losses at the high fluid temperatures desired.

Maximum performance of the selected thermal collector array configuration is illustrated in Figure 5.3.3E, as it depends upon season. Since the flat fixed arrays and their reflectors will have the same geometry (inclination angles) as the flat fixed photovoltaic collectors, the collected thermal energy will show a maximum in the vicinity of the equinox, when reflectors are most effective. Average daily collection of thermal energy will of course be less than that shown due to occasional cloud cover. At such times the concentrating collectors, and lower temperatures of the thermal transport fluid will require that auxiliary gas or oil heating will have to be employed if demanded by the shopping center thermal load requirements.

On an annual average basis, with 10% loss due to cloudiness, the thermal collector system will deliver 23 million BTU daily (230 therms). This is equivalent to five barrels of oil per day; a modest bonus when compared to the saving in electrical energy attributable to absorption refrigeration space cooling.

Figure 5.3.3-E. Cloudless Day Solar Thermal Energy Collected, Therms (1 Therm = 100,000 BTU)

The absorption refrigeration space cooling chiller cycle is illustrated in Figure 5.3.3F and 5.3.3G. In typical operation at 500 tons cooling load and coefficient of performance of 2.5, the thermal transport fluid would be circulating at a rate of 40 gallons per minute, with an inlet temperature of 350°F and an outlet temperature of 120°F. Refrigerant (water) would be vaporized from the weak absorbent solution at a rate of 11.5 gallons per minute, largely condensed in the condenser by the cooling effect of 240 GPM cooling water entering the condenser at 80°F and leaving at 100°F. Refrigerant (water) out of the condenser is liquid at about 1 PSIA and 85°F. from which condition it is pre-cooled to about 65°F by the effect of the low pressure (~ 5mm Hg) low temperature (~ 60°F) vapor exiting the evaporator. From its pre-cooled condition the refrigerant is evaporated at low pressure (maintained by the absorber) by the heat extracted from the chilled water loop, while reducing the temperature of 400 GPM from 70°F to 40°F. Vaporized refrigerant leaves the evaporator en route to the pre-cooler at about 60°F to pre-cool the following refrigerant. Vapor at 80°F leaving the pre-cooler is drawn into the absorbent spray of the absorber, giving up its latent heat to the cooling water exchanger in the absorber, and diluting the strong absorbent. The absorber has the largest cooling requirement of all the absorption chiller components, and at 500 tons operation must reject to atmosphere nearly 6 million BTU per hour, requiring cooling water flow of 600 GPM with a 20° range of cooling water temperature. Diluted absorber solution is pumped from the absorber sump to the generators through heat exchangers (one per generator) as shown in Figure 5.3.3G. The function of each heat exchanger is to increase the temperature of the weak solution entering each generator and to reduce the temperature of the strong solution leaving each generator. High heat exchange effectiveness is important for this application to minimize those heat losses and irreversibilities which adversely affect the cycle thermal efficiency. Large heat transfer area counter-flow exchangers are indicated in spite of cost, for they are crucial to the thermal collector area trade-off with coefficient of performance.

FOUR STAGE ABSORPTION CHILLER

For generators (A), (B), (C), and (D) operating at 15 psia, 7 psia, 3 psia, and 1 psia respectively (Figure 5.3.3G), the weak solution inlet temperatures are estimated at 190°F, 157°F, 122°F, and 90°F respectively, following heat exchange with the respective strong solution outlet temperatures of 200°F, 167°F, 132°F, and 98°F. In all cases, the strong solution out of the heat exchangers is at about the same temperature, around 90°F, since the weak solution inlet temperature to the heat exchangers is the same for all, about 80° to 85°F, depending upon the effectiveness of the evaporative coolers, which depends upon atmospheric wet bulb temperature and the thermal load on the coolers.

It will be noted from Figure 5.3.3G that the large temperature drop in the thermal transport fluid (350°F to 120°F) is possible only because of the series arrangement of the four generators, each working at a lower pressure and temperature than its upstream counter part. It is important from the standpoint of thermal collector efficiency to have low inlet temperature to the arrays, so additional evidence of the superiority of multi-stage absorption chillers for use with solar thermal collectors should be noted from this fact.

While thermal transport fluid is efficiently utilized by successive staging of generators, there is a more significant utilization of generated refrigerant (water vapor) from each generator. The heat required to generate each pound of steam from the first generator is not wasted to atmosphere in the condenser, as is true in single-stage machines, but is used again to generate water vapor in the second stage at lower pressure and temperature, at the same time that the second generator partially condenses the output of the first, and so on. Thus the succeeding generators perform part of the duty of the condenser, while increasing the total production of refrigerant for the fixed quantity of thermal energy which must ultimately be rejected. It may be observed that the coefficient of performance of absorption machinery can exceed unity only by the number of pounds of vapor which can be produced from each pound produced in the first generator, since all the source heat input is removed and rejected from the condenser, and all heat input to the evaporator

(refrigeration effect) is removed and rejected from the absorber. Therefore a C.O.P. of 2.5 is possible if each pound produced in the high temperature generator will lead to the production of one and one-half additional pounds from succeeding stages of generation, to a first approximation, at least. If it were possible to condense in generators (B), (C), and (D) all of the refrigerant produced by each preceding generator, the coefficient of performance would equal the number of stages. If thermal losses were zero and heat exchangers 100% effective, complete condensation would occur in the generators except for the vapor produced by the last generator, which would carry all of the heat transferred from the thermal transport fluid loop, to be rejected to atmosphere via the condenser and the evaporative cooler. Since such an idealized situation can never be realized in practice, the production of refrigerant is less than four times greater than that of a single stage for the same heat input rate. However, a fertile area of design trade-off exists between hardware cost and coefficient of performance through considerations of insulation and heat exchanger effectiveness (size), so a coefficient of performance of 2.5 is regarded as achievable but not necessarily maximum.

Steady state control of the absorption chiller is accomplished by the coordinated responses of pressure regulators downstream of the refrigerant heat exchanger in each generator (illustrated in Figure 5.3.3G) with the flow control valves in the weak absorbent (inlet) lines, the pressure control valves in the strong absorbent (outlet) lines, and the pump speed controls. The pressure regulators function to permit mixing of refrigerant vapor out of a generator with the partially condensed vapor from its upstream counterpart. The flow control valves govern the flow of weak absorbent into the generators in response to level sensors, and the pressure control valves respond to pressure sensors in the corresponding generators. In turn, the strong absorbent pump speeds are controlled by the pressure control valve positions, while the weak absorbent pump speed responds to the flow control valve positions.

5.3.4 Electrical System

General

The electrical system conceived for the shopping center is based on electrical utility ownership of the photovoltaic array system, the electrical collection system, the regulator battery system (if included), D.C. rectifier and primary service. The developer will receive the metered power at one location and distribute power to the tenants. Tenants will be billed by the developer for electric power in a manner similar to billing for the air conditioning system. A single line diagram of an electrical system is shown in Figure 5.3.4A. The system depicted in the figure differs from that proposed for the shopping center in that it includes battery storage and is a 15,000 square meter photovoltaic array. A 5000 ampere rectifier capacity would suffice if no off-peak battery charging were planned.

The electrical system will include the following major divisions:

- Photovoltaic array
- Storage Batteries
- Rectifier
- Power System
- Lighting System

The photovoltaic array size and configuration is described in detail in Section 5.3.2. Its design and performance are also described in Section 3.1 of Volume II. Configuration of the array when selecting voltage and current levels is very versatile permitting power to be collected at almost any desired voltage and current level. A voltage level of 240 volts has been selected. This voltage level will permit utilization of 600 volt level equipment with corresponding levels of electrical skills. This 600 volt level is compatible with the electrical loads in a 250,000 square foot shopping center.

Figure 5.3.4A
ELECTRICAL SYSTEM DIAGRAM

A voltage level of 550 volts was considered initially and may ultimately prove to be a very acceptable voltage level. However, present electrical code requirements limit the D.C. voltage level for lighting to 300 volts. With this 300 volt limit and approximately half the electrical load being consumed in lighting the higher voltage level could not be justified. In the future if the electrical code should be changed to accept 550 volts D.C. for lighting this higher voltage would reduce by one-half the D.C. cable and bus sizes.

The rectifier will be required to provide power to the D.C. mechanical equipment and lighting system when solar generation is insufficient. A regulator to control the charging of the batteries, if any, and to maintain voltages and currents from the photovoltaic array within system limits can be provided separately or integrated into the rectifier. Power conditioning is further described in Section 3.2, Volume II of this report. The rectifier is sized to handle the entire load when no power is available from the batteries or solar cells. Should rate structures develop that would offer an advantage to the use of off-peak power, this would improve the economics of including batteries which could be charged at night from the rectifier power and discharged during the day to reduce the overall peak utility demand. There is about a 25% power loss in recovered battery power which would have to be offset by any off-peak rate schedule, in addition to battery amortization.

Power System

Present practice for electrical power systems for power and lighting, as used in a shopping center would require the use of 60 hertz power. First considerations in this study were given to this system with all the photovoltaic D.C. power being inverted to 60 hertz for use on motor and lighting loads. As this study developed it became apparent that use of the D.C. power directly from the photovoltaic source presented some distinct advantages.

These advantages can be summarized as follows:

1. Rectifiers are less expensive and more efficient than inverters.
2. Direct current inversion to high frequency square wave power is easy to accomplish and provides for high efficiency lighting. This is described in detail in the next part of this section.
3. Direct current is ideal for speed control of motors. The use of variable speed motor drives for the ventilating fans reduces air handling power requirements.

The motors to be used for variable speed drives will be shunt wound motors with speed control obtained by varying the field current. With only a 2 to 1 speed range required this method of speed control appears to be the most efficient. Motors and motor starters for this application are available from several sources and require no special design effort.

The drivers for the air handling equipment have been sized at four 40 HP motors which if used continuously at 40 HP would exceed the electrical energy allowed for this load. With a variable volume air system and efficient speed control of motors the full connected load will be required for less than 10% of their operating hours.

Speed control of loads other than the air handling units and fluid pumps is not planned; however, these smaller loads will be supplied directly from the D.C. rather than the conventional A.C. power. The cost of A.C. motors and starters in these smaller sizes, 2 HP to 10 HP, is less than the cost of D.C. motors and starters; however, when the cost of inverting D.C. to A.C. is considered, the cost advantage of A.C. equipment is reduced. In motor sizes larger than 10 HP the D.C. costs are actually less than A.C. costs based on inverter cost of \$200 per kilowatt.

Permanent magnet type D.C. motors will be specified for the fractional horsepower motors. These motors are competitively priced with A.C. motors of this horsepower and will operate directly from the photovoltaic D.C. power source.

Utilization of D.C. power directly eliminates an inverter which consumes 15% of the power it inverts to 60 hertz power and which costs from \$100 to \$400 per kilowatt in the size required for a 250,000 square foot shopping center load.

Two power systems will be utilized. The major mechanical and lighting load will be supplied directly from the D.C. system. The utility outlets for tenant equipment (mostly duplex type outlets) will be supplied from the utility 60 hertz system. This separation of load will provide for utilization of the major loads directly from the D.C. system as previously discussed. Providing tenants with the 60 hertz power permits them to utilize standard electrical products at the store and display level. These loads are generally quite small when compared to air conditioning and lighting loads. Voltage levels will be as follows:

Mechanical equipment	- 240 volts D.C.
Tenant power utility outlets	- 115 volts 60 Hz
Lighting	- 240 volts D.C.

Lighting System

Present practice in shopping center lighting design includes the use of fluorescent, incandescent and high intensity discharge lighting systems supplied from a 60 hertz source at either 277/480 volts or 120/208 volts. Lighting levels vary over a wide range depending on the lighting environment desired. Some typical levels are:

Circulating areas	30 footcandles
Merchandising areas	100-200 footcandles
Showcase	200-500 footcandles
Stock rooms	30 footcandles
Parking lots	1-2 footcandles

Lighting from two different sources is utilized very effectively in many areas. Fluorescent lighting may be used for circulating areas with incandescent spot lights used for additional emphasis at merchandising and display areas. Present light efficiencies range from 19 lumens per watt for incandescent to 78 lumens per watt for fluorescent and 100 lumens per watt for high intensity discharge lamps. Present practice in lighting levels and fixture usage result in power requirement for lighting of from 3 to 5 watts per square foot.

To meet the power allowance of 2 watts per square foot (21.6 watts per square meter) projected for this shopping center several approaches will be required:

1. Extensive use of sky lights.
2. Reduced levels of lighting.
3. Minimum use of incandescent lamps.
4. High frequency power for fluorescent and high intensity discharge lamps.

Sky lights will be located throughout the center in areas shaded by the solar panels. This arrangement will significantly reduce the lighting required during daylight hours. Proper design and location of sky lights will be required to prevent added air conditioning load.

Reduced lighting levels will reduce the energy consumption. This approach however, has a very definite drawback in the marketing field. In general, this approach must be somewhat limited in application as it would be of little value to design a shopping center with light levels too low to attract customers. Lighting the specific task or display rather than wash lighting an entire area can be utilized.

Use of high intensity discharge lamps in lighting commercial buildings is increasing. When compared with 78 lumens per watt for fluorescent lighting, the 100 lumens per watt for metal halide lighting offers a significant advantage

in an energy conservative design. Presently on the market are high pressure sodium lamps with lumen outputs of 125 lumens per watt and low pressure sodium lamps rated at 183 lumens per watt. The accompanying table shows the efficiency of various types of lamps.

One disadvantage that low pressure sodium has is the yellow color. Nearly the entire light output falls in the yellow frequency range. Not as significant although still noticeable, is the golden yellow appearance of the high pressure sodium lamps. Present practice limits the low pressure sodium to outdoor application.

This color disadvantage is present to some extent in all lighting except incandescent but many marketing areas are very successfully lighted with fluorescent lighting. Proper selection of furniture, floor and wall covering can reduce the color disadvantage of the high pressure sodium lamp.

High frequency lighting for fluorescent and high energy discharge lamps received considerable coverage in technical journals about 20 years ago with some effort made to create interest in this area. Today there is very little lighting by this method; however, this method of lighting offers two very distinct advantages when applied in a large D.C. power system.

1. Low cost of inverting D.C. power to high frequency square wave power when compared with inverting to 60 hertz commercial quality power.
2. Increased light efficiency of fluorescent and high energy discharge lamps at high frequencies.

Early testing of the conventional fluorescent lamp at frequencies from 60 hertz to 20,000 hertz revealed light increases of about 12% (see Figure 5.3.4.C1). Testing of high pressure sodium lamps at these higher frequencies revealed light increases of about 9% (see Figure 5.3.4.C2). There was a further increase in lamp efficiency over that shown in the two figures when

Figure 5.3.4-B

Lamp Comparison Table

<u>Lamp</u>	<u>Watts</u>	<u>Hours of Lamp Life</u>	<u>Initial Lumens</u>	<u>Lumens Per Watt</u>
Incandescent	150	750	2,880	19
	300	1,000	5,820	19
Fluorescent	40	20,000	3,150	78
Mercury Vapor	100	24,000	4,200	42
	175	24,000	8,600	49
	250	24,000	12,100	48
	400	24,000	22,500	56
Metal Halide	175	7,500	15,000	86
	400	15,000	40,000	100
High Pressure Sodium	100	12,000	9,500	95
	150	16,000	16,000	107
	250	15,000	30,000	120
	400	20,000	50,000	125
Low Pressure	35	18,000	4,650	133
	55	18,000	7,700	140
	90	18,000	12,500	139
	135	18,000	21,500	159
	180	18,000	33,000	183

LIGHT OUTPUT VS. FREQUENCY-FLUORESCENT LAMP

(FIGURE 5.3.4.C1)

LIGHT OUTPUT VS. FREQUENCY-HIGH PRESSURE SODIUM LAMPS

(FIGURE 5.3.4.C2)

the lamps were tested on a square wave form of current. In addition, high frequency ballasts are less expensive and more efficient than 60 Hz ballasts. With present solid state components the square wave is much easier to produce than the sine wave.

Presently available is a high frequency ballast for use with conventional fluorescent lighting fixtures. The ballast is designed to operate on 60 hertz power, rectify this power to D.C. and invert the power to a 20,000 hertz square wave. The published literature on this high frequency ballast indicates energy reduction of 40% with no change in light levels. This 40% energy reduction is the result of a 12 to 25% increase in light output and a ballast which is 95% efficient. Present high power factor fluorescent ballasts are about 80% efficient.

Also considered for high frequency inverters were larger units centrally located at lighting panels with the high frequency power being distributed from the panels to the fixtures. This method has the advantage of permitting a higher voltage D.C. system with lower current density. A 550 volt system could be implemented since the D.C. power would not be distributed directly to the lighting fixtures. Nevertheless, 20 KHz units in fixtures are preferred for the following reasons:

1. If distribution loss in HF wiring is negligible, as for the case of the in-fixture mounting, 20 KHz is the best (most efficient) choice.
2. In-fixture mounting avoids the costs and power losses associated with a separate HF distribution system.
3. In-fixture inverters and HF ballasts would be standardized high-volume items produced by fixture manufacturers, and this is expected to offset the possible economy of larger units.
4. A survey of manufacturers indicated that small HF inverters can be obtained at reasonable prices for this application, while larger units are not designed for this application and are more costly.

The lighting system recommended for a photovoltaic powered shopping center will use high frequency, high intensity discharge lighting predominately. Power will be distributed at 240 volts D.C. to the inverters located in very close proximity to the fixtures. The lamps will operate on 20,000 hertz square wave current controlled by the locally mounted inverters. Dimming controls will be located at areas throughout the building to take full advantage of the light available through the sky lights. Present electrical code rules limit voltage to lighting fixtures to 300 volts D.C. (250 volts D.C. in California). Higher D.C. voltages at the inverters would be desirable if code limitations could be changed.

In areas where the high intensity discharge lamps are not suitable, such as in a low ceiling area, high frequency fluorescent lighting will be used.

Light levels will be reduced, but the extent of the reduction will be determined somewhat by competition.

Electric Storage System

Many design alternatives exist for sizing the electric storage system, which at present must be considered to be a lead-acid system, although currently funded developments of competing systems could impact this decision within the next ten years. The design philosophy leading to selection of photovoltaic array area also fixes the minimum size requirement of the storage system. (Electrical storage is further discussed in Section 3.2, Volume II.)

If it were desired to design the photovoltaic array area so that it would be capable of meeting peak shopping center demand for power under favorable conditions of insolation, only 975 kw capability would be needed, and total array area would be only about 6770 square meters. A storage system would perform no useful purpose, since the demand of the shopping center would always equal or exceed the output of the photovoltaic system. Such a system is not without merit, as it avoids storage costs and losses, and because the array can fit entirely on the roof.

A somewhat larger system would result from a desire to match the 9:00 a.m. to 6:00 p.m. energy requirement under most favorable insolation days - about 8100 KWH, requiring about 7500 square meters of array area and 9,230 square meters of reflecting surfaces. For demand-availability matching a small (1,250 KWH) storage system could be included to store excess midday energy for evening and morning use. However, the proposed system for the model shopping center, which uses this array size, does not include storage because of the extra expense of storage, including installation.

The largest system considered would match the 24-hour shopping center requirement for energy with a photovoltaic stored energy system whose average best month output is capable of providing energy independence to use center (if the average were realized each day, and convenience A.C. duplex outlets usage is neglected). This system size, which would require the construction of an array support structure over the parking lot, would have 15,000 square meters of array area and 18,750 square meters of reflecting surfaces. The maximum power of almost two megawatts is twice the maximum demand of the shopping center. Storage of excess energy for night use requires a minimum capacity of 6,000 KWH (25,000 AH at 240 volts). At an estimated cost of \$50 per KWH, the storage system would represent a first cost of about \$350,000 (including construction of a 20 ft. x 30 ft. subterranean storage room).

5.3.5 Mechanical Systems Design

General

The mechanical systems which are required in order to maintain acceptable environmental conditions within the model shopping center are indicated in Figures 5.3.5-A and 5.3.5-B in the form of flow diagrams. Figure 5.3.5-A describes the thermal energy systems, while Figure 5.3.5-B covers the air conditioning systems. Descriptions of the thermal collectors and the absorption refrigeration equipment have been included in previous paragraphs.

FLOW DIAGRAM - THERMAL ENERGY SYSTEMS

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FIGURE 5.3.5-A

FLOW DIAGRAM - A/C SYSTEMS

KEY TO SYMBOLS

T	THERMOSTAT
DO	DAMPER OPERATOR
EC	ENTHALPY CONTROLLER
SP	STATIC PRESS. CONTROLLER
MSC	MOTOR SPEED CONTROLLER
FA	FRESH AIR
RA	RETURN AIR
EA	EXHAUST AIR
VAV	VARIABLE AIR VOLUME

FIGURE 5.3.5-B

Thermal Energy Systems

See Figure 5.3.5-A. This flow diagram includes all of the components which are necessary to generate and utilize the energy that will provide chilled water for space cooling, hot water for space heating and potable hot water for domestic needs.

Thermal Collectors

For reasons noted previously, the maximum design temperature of the heat transport fluid leaving the roof-mounted thermal collectors will be 400°F. The rate of flow will be such that the heat transported from the collectors will be adequate to handle the design air conditioning load without the need for drawing energy from a storage system. In order to maintain the transport fluid system pressure at a reasonably low value, a fluid will be selected which has a very low vapor pressure while at the same time having good specific heat characteristics such as a Dowtherm or Therminol 55. Thus the operating pressure in the transport fluid system may be only slightly above atmospheric pressure whereas, with water as the heat transport medium, a pressure of approximately 150 psia would be required.

Thermal Energy Hot Water Storage Tank

A large heat storage capacity is required as the source of energy for heating/cooling during periods when the solar collectors are unable to function to full design capacity, such as cloudy days or night time. A 12,000 gallon storage tank will be used, with water being chosen as the storage medium. Due to the high temperature that will be maintained in the tank, it will be necessary to set the design pressure at approximately 150 psia to avoid vaporizing the water. The contents of the tank will act as the "store" only and will not be circulated to other heat exchange devices. The heating coil in the storage

tank functions both to bring the store to its maximum design temperature, when heat is input via the thermal collectors, and to extract heat from the storage when needed due to inadequate input from the thermal collectors. Other mediums than water may be considered if they would prove to be more cost-effective.

Gas Fired Auxiliary Heater

If enough energy could be accumulated in the storage tank to provide a source of energy to run the building heating/cooling systems, no matter how long the input from the thermal collectors was inadequate, an auxiliary heater would not be required. However, to provide a cost-effective selection of equipment as well as to provide at least limited heating capability when the thermal collector sub-system is inoperative a gas-fired auxiliary heater will be installed. It will function to assure a temperature of 350°F in the transport fluid supply.

Building Hot Water Heater and Storage Tank

The transport fluid system will provide the source of heat to maintain a hot water heating system at approximately 200°F for space heating and for heating domestic hot water. The heating coil in the tank will utilize transport fluid at 350°F to heat the recirculated water entering the tank at 160° to 180°F. The heating coil will be selected for maximum temperature drop of the transport fluid.

Domestic Hot Water Heater and Storage Tank

Hot water from the tank described in the previous paragraph will be circulated through the heating coil in this tank to provide domestic hot water at 120° to 140°F.

Chilled Water Sub-System

The transport fluid system will provide the source of heat for the four-stage absorption refrigeration water chiller previously described. Design inlet temperature of the transport fluid will be 350°F. The heat rejected in the refrigeration cycle, from both the absorber and the condenser, will be transferred to a closed-circuit cooling water system and in turn dumped to atmosphere by means of an evaporative cooler. The use of an evaporative cooler and a closed-circuit cooling water system will minimize scaling and corrosion within the refrigeration machinery. It will, however, require selection of a slightly higher condensing design temperature than if a cooling tower were used, resulting in a somewhat lower coefficient of performance at design conditions. Since design conditions occur such a small percent of the time, this is not a significant factor.

The chilled water generated in the absorption refrigeration equipment will be circulated to the cooling coils in the air conditioning equipment. A chilled water storage tank will be provided to minimize the use of the gas-fired auxiliary heater as a source of heat for the refrigeration equipment. When solar energy is unavailable (cloudy days, night time) the large reservoir of chilled water will permit extended operating time of the cooling coils before it would be necessary to replenish the supply of chilled water by the use of the auxiliary heater to run the absorption refrigeration system.

Transport Fluid Circulating Pumps

Transport fluid will be circulated by means of variable speed D.C. motor-driven pumps. Dual pumps will provide redundancy as well as the capability to split the piping system so that one pump may circulate transport fluid through the thermal collectors and into the storage tank while the other circulates transport fluid to the system via the auxiliary heater. This mode of operation could be used for warm-up of the store or for cool-down of the store preparatory to shut-down of this part of the system for maintenance or repairs.

Thermal Energy Systems Operation

Whenever the temperature of the transport fluid leaving the thermal collectors is greater than the temperature entering the collectors valve V-1 will permit modulated flow through the collectors thus utilizing whatever solar energy may be available. When the leaving temperature drops below the entering temperature, valve V-1 will divert all of the transport fluid flow through the by-pass line to avoid transferring energy back to atmosphere via the collectors. However, valve V-1 will contain a drilled port to permit a very small flow through the collectors even though the port is closed; this is to establish enough flow for the differential temperature controller to function.

Whenever the temperature in the thermal energy hot water storage tank drops below 340°F the gas-fired auxiliary heater will be used to heat the transport fluid so that it is maintained at 350°F in the supply line to the absorption machine. This will be accomplished by diverting the flow through the heater by means of valve V-2.

The flow of transport fluid will be variable, as a function of demand for heat energy by the absorption machine and the building hot water heater. Also, the flow path will be variable since at times the thermal collectors will be by-passed and at times the auxiliary heater will be in use. This situation provides an opportunity to minimize pumping power costs by varying pump speed to maintain a fixed supply pressure. As the flow is throttled by control valves V-3 and V-4, the tendency to increase supply pressure is offset by a static pressure controller which signals a reduction in pump speed thus conserving pump motor power. In a similar manner, pump speed will be controlled for the chilled water and hot water circulating pumps. All pump motors will be wired for use on direct current.

Air Conditioning Systems

See Figure 5.3.5-B. This flow diagram includes all of the components which are necessary to provide heating, ventilating, and air conditioning of the various spaces within the model shopping center. It represents an energy-conscious design approach and utilizes those features which minimize power requirements and energy loss. It also takes advantage of free cooling by means of enthalpy control of the fresh air/return air mixture.

Alternate Methods of Air Conditioning

Various methods could be used to achieve the environmental conditions that would be considered acceptable in the model shopping center. Alternate designs include: all-air systems, air-water systems, all-water systems, and multiple unit or unitary systems. The decision to use a central four-stage absorption refrigeration water chiller eliminates the last alternative, multiple unit or unitary systems, since these systems have individual refrigeration capabilities within each unit.

All-water systems utilize fan-coil units or unit ventilators. These systems do not provide humidity control and lack positive ventilation unless wall openings are used. They do not use ducting for air distribution and consequently are limited in the amount of area which can be served by one unit. They are not generally used to air condition large open floor areas such as department stores. Also, they do not lend themselves to energy-saving techniques. Therefore, all-water systems are not considered desirable for the model shopping center.

Air-water systems utilize central air conditioning equipment, ducting and room terminals (induction units) plus a chilled water and hot water piping system to the room terminals. They are especially well suited for office buildings, hotels, hospitals, apartment houses and similar structures where

numerous rooms, zones or smaller spaces must be separately controlled. They do not readily lend themselves to energy saving techniques. These systems do not appear desirable for application to the model shopping center.

All-air systems utilize either a single-path (single duct) system or a dual-path (double direct or multi-zone) system. They offer many advantages including centralized location of major equipment, simplified use of free cooling, good flexibility in zoning and air distribution, ability to handle large exhaust requirements and little building interference except for overhead air ducting. Dual-path systems are usually appropriate for a large number of zones or where the zones are likely to be subject to future change. However, there is one significant disadvantage of a dual-path system which requires mixing of hot and cold air from double ducts or plenums, and that is the leakage which occurs through the mixing dampers. Although leakage can be minimized by the use of properly designed dampers the long term result is a reduction in efficiency in both the cooling and heating subsystems since leakage must be overcome by using additional conditioned air to offset it. Therefore, a single-duct system is indicated for the model shopping center. Further, variable air volume will be used as a means of temperature control thus effecting substantial saving in fan power requirements since fan speed may be reduced as system capacity requirements are decreased.

Selected Air Handling Systems

Each air handling system will be a single-duct, variable air volume system. Any number of zones can be handled by a single duct since each zone will have a variable air volume terminal box, in a branch duct, to control the amount of air discharged to the zone. Thus only the amount of air actually required is moved through the system. Whenever the air conditioning load is at less than design conditions air flow is reduced. This concept offers a true energy conservation system since full advantage may be taken of shifting loads

(diversity) due to occupancy, solar, and lighting loads. Thus the maximum system volume flow is calculated on the basis of the simultaneous peak load (block load) rather than the sum of the maximum zone peaks. The system, therefore, has fixed fan energy savings at all times and during periods when the block load is less than design even further energy savings can be provided by controlling fan volume.

Zoning

For the model shopping center the outside design conditions are such that heating will not be required for the interior zones. Therefore, as indicated in the flow diagram (Figure 5.3.5-B) the temperature of interior zones will be controlled only by throttling the flow of cold air from the air handling unit by means of VAV terminal boxes. It is expected that there always will be a cooling load in the interior zones; however, at the same time there could be a requirement for heating in the perimeter zones. To reduce the amount of reheat required for the perimeter zones the cold air supply temperature can be reset upward as a function of outdoor temperature. While this would result in a greater volume flow to the interior zones there will be a net energy saving due to a proportionately greater saving in reheat requirements for the perimeter zones.

Air Handling Units

The flow diagram shows a typical air handling unit containing fresh air/return air mixing dampers, air filters, chilled water cooling coil and a centrifugal fan driven by a variable speed motor. For the model shopping center a total of four such units would be used. Chilled water for the cooling coil will be obtained from the distribution system as indicated in Figure 5.3.5-A. Temperature control of the cooled air will be accomplished by throttling the chilled water control valve V-5. Fan capacity will be optimized by means of a

static pressure controller located in the discharge ducting which will actuate a motor speed controller to control the speed of the D.C. motor driving the fan.

Hot Water Reheat Coils

As the cooling load is reduced in the perimeter zones, the variable air volume mixing boxes will be throttled to minimum flow by the room thermostat, in the same manner as the interior zones are controlled. Any further call for less cooling (actually, then, a call for heating) will modulate control valve V-6 to admit hot water to the reheat coils, thus providing heating capability for the perimeter zones. Hot water for the reheat coils will be obtained from the distribution system as indicated in Figure 5.3.5-A.

Enthalpy Control

As an additional energy conservation measure outdoor air will be used, when possible, to reduce the load on the refrigeration equipment. To accomplish this it will be necessary to determine the total energy (enthalpy) in the outdoor air and return air and then select the source having the lowest total heat. Controls are commercially available which sense humidity and temperature conditions in the outdoor air, return air, and mixed air and then position the dampers to make optimum use of outdoor air. A return air fan will collect return air from the various rooms and deliver it to the mixing dampers where it can be modulated to exhaust to atmosphere or to return to the unit. The fresh air damper meanwhile will be positioned to admit the same amount of outdoor air as is exhausted via the exhaust damper.

Equipment Arrangement

A mechanical equipment room will be provided in the basement to house the following equipment: Gas fired auxiliary heater, absorption refrigeration

water chiller, building hot water heater and storage tank, domestic hot water heater and storage tank, circulating pumps for chilled and hot water systems, and associated piping systems including expansion tanks.

The thermal energy hot water storage tank and the chilled water storage tank will be located outside the structure, underground and adjacent to the basement mechanical equipment room. They will be insulated to prevent the exchange of thermal energy with the surrounding soil.

The remaining equipment will be mounted on the roof of the structure. This includes the evaporative water coolers, cooling water circulating pumps and the air handling units. An alternate location of the air handling units would be in equipment rooms throughout the structure, in the vicinity of the areas they would serve.

Ductwork will be installed in the above-ceiling space throughout the structure and ceiling diffusers will be used for air distribution. Variable air volume terminal boxes and reheat coils will be located in the ductwork, in the vicinity of the zones they serve.

5.3.6 Architectural System Design

The application of a photovoltaic energy source as applied to shopping centers brings about the following architectural considerations which bear further investigation:

- How the photovoltaic cells will be applied to both new and existing facilities.
- Design and orientation of buildings and their siting with respect to solar angles.
- Areas of application of photovoltaic cell arrays and their aesthetic integration into the architectural design of the development.

- Economic and structural considerations resulting from the application of photovoltaic power systems.
- The influence of building, fire, and planning codes and their effects on the basic design concept as applicable to existing and future shopping center developments.

It must also be recognized that a photovoltaic system appears as an external system architecturally, as compared with conventionally powered buildings where the electrical system is not as visually prominent, therefore special considerations must be made to integrate the system into the building architecture.

Commercial Categories of Shopping Center

Among other considerations which strongly influence shopping center developments are the following factors: trade area population served, site location and configuration, the real estate value of the land, and governing planning, building and fire codes enforced by the local municipalities.

These remaining influencing factors strongly affect the final nature and magnitude of the resulting development.

Shopping centers, as is true of most other real estate developments, have certain outstanding features which set them aside and typify their final developmental form. These forms result in the following three classifications based on size, under which most shopping center developments tend to fall.

Neighborhood Shopping Center

The neighborhood shopping center is the smallest of the three types under consideration, and is designed to provide convenience shopping center facilities for a trade area population of approximately 5,000 to 40,000 people.

The principal tenant or major attraction of the neighborhood shopping center is usually a supermarket.

Neighborhood shopping centers generally contain between 30,000 square feet for smaller developments and may increase up to 100,000 square feet in size for larger centers.

5.3.6.1 Intermediate Shopping Centers

The intermediate shopping center is usually developed to serve a trade area population varying from 40,000 to 150,000 people. The total floor area contained is generally from 100,000 to 250,000 square feet, with major tenants consisting of a junior department store or a strong specialty store. Usually these tenants require square footages of approximately 25,000 to 75,000 square feet.

The additional attractions of intermediate sized shopping centers are variety stores and supermarkets.

Regional Shopping Centers

Regional shopping centers are developed to serve a trade area population of between 150,000 and 400,000 people and may contain floor area square footages varying from 300,000 to over 1,000,000 square feet. Regional shopping centers constitute the largest of the three developmental types.

Major attractions are the department stores which are the dominant tenants with square footage requirements occupying about one third to one half of the total shopping center area.

Complete comparison shopping facilities are provided with a drawing attraction of customers living perhaps as much as 10 to 15 miles from the site.

5.3.6.2 Future Trends in Shopping Center Design

The number of shopping centers has been growing rapidly from a total of 15,000 at the end of 1972, to a projected growth of 21,000 by the year 1980. This growth pattern has manifested itself in the inclusion of expanded facilities offered to the shopping public which are medical and other professional offices, child care centers, teen centers, libraries, meeting halls and other public related facilities which could bring the shopping center into public focus.

There is a marked tendency for transportation to go underground with the distance from car door to shop door diminished.

Other features already emerging include large enclosed climate controlled malls, more elaborate landscaping features, and other pedestrian oriented amenities which would entice public visitation. The future shopping center has been likened to the historical small town where people can shop and mix, and will in essence, become a cultural center as well as a place for vendors to exhibit and sell their wares. A recent survey of public desires include the following amenities to be included in future shopping centers:

46% of the shoppers would like library facilities, 22% favored teen centers, and some 9% wanted the inclusion of religious facilities.

One interesting trend that appears to be developing is the location of sites in the densely populated downtown areas. There appears to be a decrease in the tendency of the 50's and 60's to rush to the suburbs partly because of the decline in building construction starts and partly due to mortgage rates and the energy problems now facing the nation.

The central core downtown location adapts itself well as an incorporation of the urban renewal programs now underway, and utilizes an area that has been

previously overlooked. These areas are usually more restricted in size, and necessitate the inclusions of subterranean parking areas which are required on land that is generally considered to be expensive real estate. Figures 5.3.6-A, B, & C, represent a schematic concept of this type of high density development which would incorporate a photovoltaic power system into the basic architectural design.

The lack of surface parking space has severely diminished the available area that could be utilized for photovoltaic cell application. Cell array surfaces were utilized on the south wall of the high rise structure.

Even though cell array areas appear extensive, it was found that they could only supply approximately twenty percent of the power load demand for a development of this nature. This would indicate a major reliance on conventional power systems, and does not appear to justify the cost from an efficiency and economical point of view.

Other future design considerations appear to be the tendency toward smaller and more controlled signage, the inclusion of art and other visual communication media, and the tendency for the center to face away from main automobile traffic areas onto an environmentally controlled mall containing generous landscaping and other pedestrian-related amenities.

5.3.6.3 Shopping Center Evolution and Development

Historically, shopping centers developed as a row of stores along a highway. Parking and sidewalks were located along the front of the stores, with supplies and shoppers entering the same way if a rear alley was not available. Refer to Plan I Figure 5.3.6-D. The concept was a decentralized approach which evolved along with the streets and highways of the developing town or city, and can be likened to the small frontier towns in which horses preceeded automobiles as a means of transportation.

SITE & FIRST FLOOR PLAN

Figure 5.3.6-A

ROOF PLAN

Figure 5.3.6-B

SECTION THROUGH BUILDING

Figure 5.3.6-C

SHOPPING CENTER DEVELOPMENT CONFIGURATION

PLAN I

A ROW OF STORES ALONG
THE HIGHWAY

PLAN II

STORES MOVED BACK FROM
THE HIGHWAY WITH OFF STREET
PARKING

PLAN III

MALL CENTER WITH PARKING
AND MAJOR BOULEVARDS AT
THE PERIPHERY OF THE CENTER

While this concept is the most primary of the examples shown, it still manifests itself widely in a majority of older centers located in towns and cities throughout the nation. This early concept is gradually being replaced however, by more centralized and contained developments.

Plan II, Figure 5.3.6-D represents a variation of the original scheme with the only new innovation being that the stores are set back from the street with on-site parking provided. This scheme was encouraged as a result of planning and zoning laws requiring off-street parking provisions. Generally, this concept had a major store which provided the main drawing attraction to the center and identified it as an individual entity. This scheme is generally representative of most neighborhood type shopping centers and usually demonstrates little sophistication in modern merchandising techniques.

The increase in population and the competition to attract a larger segment of the buying public resulted in the advent of the mall type shopping center which appears as Plan III. The major tenant is the department store as the centralized magnet, along with ancillary stores which would benefit from their proximity to the department store.

A further development of the mall type shopping center would be the addition of above grade or subterranean parking facilities to provide greater public convenience from car door to store door. The concept was broadened to increase the number and scope of commercial facilities offered to attract the buying public.

5.3.6.4 Model Application of Photovoltaic Cells to Shopping Centers

The hypothetical selected site is located in the San Fernando Valley area of the City of Los Angeles, California. Required ratio of parking area to building floor area is comparable to most municipalities located throughout the country.

The subject site is rectangular containing approximately 632,000 square feet (58,600 square meters) or approximately 14.6 acres of land surrounded by major streets or boulevards on all sides. Parking lot areas provided are based on the City of Los Angeles requirements of one car per 500 square feet of floor area and resulting in a minimum of 500 total required spaces to be provided. The site configuration may be seen in Figure 5.3.6-E.

The longest dimensions of the site run in an east-west direction permitting the buildings to be oriented in the same direction which is advantageous to permit a southern exposure for the arrays on the roof.

Buildings are located in the northern portion of the site, with mechanical equipment located on the north area of the roof. This will serve to avoid shadowing of the array areas on the roof surface. Other site features include a service road at the rear of the site with appropriate maintenance areas included.

Tenants include a major department store, a food market or drug store, and a series of smaller variety shops facing onto a mall area. Total square footage available categorizes the center as an intermediate sized development.

The roof plan showing cell array arrangements may be seen in Figure 5.3.6-F. Roof areas also serve to accommodate the thermal collectors required for hot water heating. Insulated storage tanks would be located below grade for both the hot and chilled water supply. Battery storage space, if required, would also be provided below grade for electrical supply during evening and cloudy day periods when cell output diminishes.

In the preferred system design, the photovoltaic array area is determined by the condition that the array output under clear day insolation in the most favorable month shall not exceed the electrical load; therefore battery storage is not required. This condition results in a horizontal area

SITE PLAN
SCALE: 1" = 100'

Figure 5.3.6-E

ROOF PLAN

SCALE: 1" = 100'

Figure 5.3.6-F. Roof Layout of Shopping Center Used as Intermediate Sized PEPS System Studied

requirement of 12,887 square meters for array mounting, and therefore permits mounting all of the photovoltaic arrays, as well as the solar thermal collectors, on the building roof.

A "double-scale" design was also considered, in which the photovoltaic array area was doubled in order to provide the maximum practical amount of the electrical requirements of the shopping center. This design would require battery storage and would also require mounting the additional arrays over the parking area.

The following paragraphs give a description of the cell arrays and roof structure.

Cell arrays are set at 45° with the horizontal. A reflective surface is placed in front of each solar cell array to increase solar energy to the cells by as much as 50%. This material is an opaque highly reflective one such as aluminized mylar with intermittently spaced reflective glass windows to transmit natural clerestory type light from the north during daylight hours.

Light baffles are provided below the skylights to prevent the transmission of direct sun rays, and also to serve as light and duct carriers used in conjunction with the building electrical and mechanical systems. Gutters are located in the valley areas to drain roof water away from the cells.

Figure 5.3.6-G indicates a section through the cell arrays and reflector surfaces and Figure 5.3.6-H illustrates a section-perspective of the system viewed from above the roof line.

The purpose of the arrangement is to integrate the functions of the photovoltaic cell system into the building architecture utilizing the availability of natural light sources to augment the internal lighting demands. The usage of

SECTION THROUGH CELL ARRAY AND REFLECTOR

SECTION - PERSPECTIVE OF ROOF

Figure 5.3.6-H

roof overhangs, minimum glass areas and a well insulated building help to reduce normal heating and cooling loads imposed on the structure. A general section through the site, Figure 5.3.6-I describes the arrangement of buildings to the site, indicating cell and thermal arrays, and the location of the basement battery storage area.

For the "double-scale" option the photovoltaic cell array areas are 15,000 square meters, and the thermal collector array areas are 2,000 square meters. The electrical energy generated is up to 14,000 KWH per day, which is ample to supply the daily electrical demands of the shopping center. The battery storage room located below grade contains approximately 60 square meters. Figure 5.3.6-J is an overall perspective of the development indicating buildings, parking lots, and cell array areas.

5.3.6.5 Application of Photovoltaic Cells to Existing Facilities

Photovoltaic cell application to existing facilities requires the following considerations:

- The method of placement and structural attachment to the existing facility.
- Determination of areas of the existing site and buildings suitable for photovoltaic cell array application.
- Locations which would blend in and not detract from the architectural aesthetics of the development.
- Areas selected must minimize the inconvenience of interrupting the daily operations of the shopping center during their installation.

Selected areas of cell array application would be:

- Parking lots
- Roof areas

SECTION THROUGH BUILDING
AND COVERED PARKING

SCALE: 1" = 40'

Figure 5.3.6-I

Figure 5.3.6-J

- Building facias
- Shelter structures
- Sign pylons or other miscellaneous areas of application.

The above areas may possibly be expanded however, they basically cover the practical and available areas for photovoltaic cell application to existing developments.

Parking lots appear to offer an interesting possibility, particularly in existing facilities where cell arrays could be installed in phases without greatly disrupting the facility operations. Columns could be located between stalls to support the overhead structure which would also serve as a pedestrian and car shelter. (Refer to Figure 5.3.6-K.) The use of parking lots as possible candidate areas also offers the possibility of utilizing prefabrication methods for the structural system components required for the array and shelter supports. The major disadvantage of this option is the cost of the support structure, which must be charged to the photovoltaic system unless covered parking is an architectural design requirement.

Roof areas of existing structures also are promising if the roof has enough reserve structural capacity to support the wind and dead loads imposed from the addition of cell array areas and reflectors, and if roof area is not required for other uses. In the vast majority of commercial buildings, the roof is not an important visual element of the building design and is usually concealed by fascia. The visual appearance of the photovoltaic arrays is therefore unimportant when roof mounting is selected. The occasional need to re-roof or repair the existing roof may present problems such as the removal of cell arrays while this operation is taking place. This is particularly true in older installations.

Other available areas mentioned as possibilities could only serve as supplemental areas to roofs or parking areas since they constitute a small part of available space.

SECTION THROUGH
COVERED PARKING

Figure 5.3.6-K

In summary, the majority of commercial building designs provide considerable usable space for array mounting, and the architectural and structural requirements can readily be met, especially if these requirements are considered during the initial design of the building.

5.3.6.6 Architectural Impacts

In general, architectural impacts will be experienced in areas of mechanical, electrical, and architectural measures taken to minimize energy requirements. Also, impacts will be experienced in areas associated with accommodation of thermal and photovoltaic arrays in an exterior sense and with their required system components in an internal sense.

Energy conservation in building design leads to innovation in fenestration, lighting, ingress and egress, ventilation, infiltration, insulation, handling of internal loads, minimization of internal loads, and ingenuity in the treatment of necessary structural components for multi-purpose utilization. An example of the latter might be the use of thermal, photovoltaic, and reflector arrays mounted with evaporative coolers and/or other mechanical components, and utilization of their location to perform some of the structural and thermal functions which would be performed as conventional roofing materials. In these efforts, heavy reliance must be placed upon the judgment of the A and E design team for the adoption of measures which contribute to energy requirement reductions but which do not adversely impact facility utilization or profitability. Some measures for energy conservation will unavoidably increase acquisition cost and thereby court owner-developer antipathy if cost-recovery time becomes excessive.

Significant opportunities for optimization of design for minimum life-cycle cost exist, such as specification of insulation thicknesses and location, which contribute to space conditioning load calculations and the resulting size and costs (acquisition plus operation) of the space cooling and heating components (thermal arrays, thermal storage, water chillers, auxiliary heaters, etc.).

Application of photovoltaic power systems to proposed and existing shopping centers poses the following considerations and their resulting architectural impact on the development design:

- Consideration of the photovoltaic power system primarily as an external visually prominent one compared to conventional power supply systems.
- How the adaptation of photovoltaic power systems will influence the architectural design of the buildings and the scheduling of on-site construction work.
- Potential building and site areas which could be available to serve as areas of cell array installations.
- Ramifications of planning, zoning and fire codes and their affect on the installation of photovoltaic power systems.

The most important feature of the utilization of photovoltaic power systems is the aspect of external on-site power generation versus conventional central power plants which (excluding transformer stations) exhibit little visual evidence of their presence. It is necessary then to consider and integrate the cell arrays and supporting systems into the architecture of the development.

Roof areas while incorporating the cells and reflector surfaces, can also be made to function as a combination ceiling and roof system which would add and become a feature of the basic building architecture. The concept then becomes something more than simply applying the cells and reflectors to the roof surface.

The transmission of north light from properly glazed skylights would also serve to reduce the internal lighting load demand. This basic concept has been illustrated in Figure 5.3.6-G.

Consideration of potential areas of the building and site which could serve as cell and reflector array areas is another subject which will have significant architectural impact on the development. These areas could be:

- Roof areas
- Parking lots
- Shelter structures, car and pedestrian
- Covered mall areas
- Building facias

The above areas could be expanded to include other possible applicable areas such as on the south wall surface of high rise structures (if they are part of the development or other miscellaneous areas which might be available).

Roof areas and parking lot areas appear to be among the most logical possibilities of those areas mentioned above, since they provide the greatest and most easily utilized areas for cell and reflector arrays. Roof areas are generally extensive and relatively unencumbered with generally level surfaces and with the only loss of available space being that relatively small space dedicated to mechanical equipment.

Parking lots offer other excellent possibilities with parking space requirements increasing as the result of the adoption of more stringent zoning and planning laws.

Areas given to parking and driveway requirements can amount to a significant portion of the shopping center site as evidenced by Figure 5.3.6-L which indicates minimum legal parking requirements in various major cities located throughout California. These cities have been selected for illustrative purposes only, and give a representative picture of parking lot to building area ratios, indicating significant variations in requirements. Figure 5.3.6-M

Figure 5.3.6-M

Tabulation of Auto Spaces/Sq. Ft. of Rentable Areas

Name	Location	Rentable Area	Parking Spaces	Rentable Area Per Parking Space
Bergen Mall	Paramus, New Jersey	1,700,000	8,400	203
Black Horse	Audobon, New Jersey	82,000	693	118
Capital Court	Milwaukee, Wisconsin	793,763	5,435	145
Cross Country	Yonkers, New York	968,000	5,200	186
Eastland	Covina, California	752,000	5,000	150
Eastland	Detroit, Michigan	899,737	8,300	108
Garden State Plaza	Paramus, New Jersey	1,150,000	6,300	184
Glendale	Indianapolis, Ind.	493,311	3,365	146
Hillsdale	San Mateo, California	702,227	3,000	233
Lloyd Center	Portland, Oregon	1,200,000	8,490	141
Mayfair	Milwaukee, Wisconsin	1,100,000	6,000	184
Mid-Island Shopping Plaza	Hicksville, L.I., N.Y.	911,000	6,000	152
Mondowmin	Baltimore, Maryland	475,000	4,000	118
Old Orchard	Skokie, Illinois	918,438	6,000	153
Pala	San Jose, California	38,000	210	181
Roosevelt Field	Long Island, N.Y.	1,150,000	7,000	165
Southdale	Minneapolis, Minn.	670,000	5,200	129
Valley Fair	San Jose, California	505,849	2,700	188
Wildwood	Milwaukee, Wisconsin	698,000	4,300	162
Waialae	Honolulu, Hawaii	152,652	1,055	144

Low 108/cars/Rentable Sq. Ft. Detroit Michigan - High 233 cars/Rentable Sq/ Ft. San Mateo, California
 Ref: Gruen, Shopping Towns, U.S.A. - Rienhold Publishing G. N. Y.

represents various tabulations of automobile spaces/square ft. related to rentable areas in existing shopping centers located throughout the country. Variations occur from a low of 108 square feet of rentable area to as much as 233 square feet of rentable area per auto space. Square feet of floor area to parking space ratio can vary widely as is demonstrated in the examples. Often, only the minimum required legal spaces are provided, and other times an ample reserve number of car spaces are provided. Usually reserve spaces are provided in the larger regional shopping centers, with smaller developments providing only the legal minimum number of parking spaces. It appears that even minimum lot areas can supplement roof areas to provide adequate areas for photovoltaic cell arrays.

Other areas available for array application such as covered mall areas or shelter structures present additional opportunities for incorporating the photovoltaic cells into the architectural design. These areas, however, constitute the minority of space which can be utilized.

Ancillary support areas such as the battery storage room, and hot and chilled water storage tank areas can be located below grade.

A discussion of the architectural impacts of photovoltaic power systems would not be complete without the consideration of the influence of planning and zoning laws and their net resulting effect. The use of cell arrays as automobile shelter structures appears to be the only area which could be affected by building, planning, and fire codes. Aside from the legal setback lines and the encroachment of dedicated yards required to achieve allowable building areas, the parking structures could be constructed as indicated in the perspective, Figure 5.3.6-N. The governing factor would be the type of construction to be used to avoid the usage of sprinkler systems or fire walls as normally required by building and fire codes for less fire resistive structures. To achieve the required areas, precast concrete frames could be utilized or the usage of a sprinkler system incorporated into a less fire-resistive type of structure.

PARKING LOT APPLICATION

COVERED PARKING APPLICATION

COVERED MALL APPLICATION

APPLICATION OF PHOTOVOLTAIC CELLS TO SHOPPING CENTERS

In order to minimize installation costs, it is desirable to take advantage of factory prefabrication whenever possible. Prefabricated components are usually less expensive than similar components build up on site; in addition, their use reduces total construction time and may facilitate obtaining plan approvals and permits from local authorities. It appears that the particular array design developed for the model shopping center is well suited to prefabrication, and it also appears that commercial buildings in the categories found to be best suited to the application of photovoltaic systems are also well suited for the use of integrated, prefabricated roof structures incorporating the arrays and associated wiring, skylights, etc. Typical building structures in these categories are simple and highly standardized, and presently make considerable use of prefabricated structural components.

In the following sections on component specifications and system costs, the application of prefabrication to reduce costs has not been taken into account because time available did not permit consideration of the many factors involved in determining the optimum size and design of prefabricated roof modules suitable for a wide variety of building applications. The potential for cost savings in this area should be assessed in future studies.

The basic size and configuration of photovoltaic cell arrays can be utilized to produce imaginative architectural concepts by incorporating the inherent physical characteristics of the system into the basic building architecture. The resulting net effect then offers the promise of ample variety with an almost unlimited means of integrating the power system into new and existing shopping center developments.

5.3.7 System Performance Specifications

For the "proposed" option design, the outline specifications for the more critical and/or lesser developed major components of the shopping center mechanical and electrical systems are defined in preliminary fashion in this section. It is the objective of this effort to provide a basis for

cost-estimating and to illuminate areas of mechanical and electrical design where departures from historical practice can result in significant energy reduction in a successful shopping center of the future. The components whose outline specifications are thought pertinent to this effort include:

- Photovoltaic Arrays
- Reflecting Surfaces
- Flat Solar Thermal Absorbers
- Concentrating Thermal Absorbers
- Thermal Transport Fluid
- Thermal Storage
- Absorption Chiller
- Electric Storage (not required for proposed system)
- Lighting

In the pages following, specifications are written for each critical component in the light of engineering judgement and the understanding of requirements developed to date for a shopping center utilizing photovoltaic conversion of solar energy to a maximum extent, and providing maximum energy conservation through design without sacrificing comfort, attractiveness, or profitability of the commercial enterprise. It should be kept in mind that individual specifications will be impacted in varying degrees by departure from this design philosophy (such as greater dependence upon utility power, for example). Further, the interrelationship of specifications which results from mutual consistency discourages independent change in most cases.

Photovoltaic Array Specifications

Item: Silicon Cell Arrays

Quantity: 750

Size: 5 meters x 2 meters

Voltage: 240 volts nominal

Current: 4.6 amperes nominal

} Standard test conditions

Construction: Glass in metal frame, caulked, sealed and waterproof

Cooling: Natural convection

Insulation: 600 volts minimum

Life: 30 years to 10% degradation

Weight: 140 Kg maximum

Reflecting Surfaces Specifications

Item: Solar specular reflectors

Quantity: 2,725

Size: 4 ft. x 10 ft. (1.22 meters x 3.04 meters)

Materials: Aluminized mylar over 1/2 inch waterproofed plywood

Reflectivity: 0.75

Life: 10 years to 10% degradation

Solar Thermal Absorbers Specifications

Items: (A) Flat fixed solar thermal absorbers

(B) Flat fixed concentrating solar thermal absorbers

Quantity: 200 each

Size: 2.5 meters x 2 meters

Thermal Transport Fluid: Therminol 55

Maximum Temperature: (A) 275°F; (B) 400°F

Efficiency at 100°F Ambient: (A) 0.60; (B) 0.40

Covers: Double layer fiberglass "Sun-Lite" or equivalent

Absorbers: Selective-surfaced Pyrex annular

Absorptivity - 0.80 minimum (visible spectrum)

Emissivity - 0.10 maximum (far infrared)

Heat Traps: Borated glass annular absorber covers

Concentrators: 5:1 anodized aluminum sheet parabolic trough;
Item (B)

Frames: Double walled aluminum, fiberglass insulated

Waterproofing: Caulked, sealed, and waterproofed

Heat Transfer Fluid Specification

Item: Transport Fluid for Thermal Energy

Quantity: Approximately 3,500 gallons

Manufacturer: Monsanto Industrial Chemicals Company

Trade Name: Therminol 55

Description: Liquid phase heat transfer fluid for non-pressurized
indirect heating to 600°F

Composition: Synthetic hydrocarbon mixture

Density: 7.40 lb./gal.

Flash Point: 355°F min.

Fire Point: 410°F

Coeff. of Expansion: 0.00085 cc/cc/°C

Sp. Heat at 300°F: 0.572 Btu/lb.

Viscosity at 300°F: 4.09 lb./hr. ft.

Vessel Specification

Item: Thermal Energy Hot Water Storage Tank

Quantity: One

Working Pressure: 150 psia

Working Temperature: 350°F

Construction Material: ASTM A-212

Capacity: 12,000 gallons

Dimensions: 9' diam. by 25' long

Heads: Flanged and dished

Nozzles: 150 lb R.F.

Level Indicator: Gage glass

Heat Exchanger: U-tube handle having 100 sq. ft. of heating surface

Code Requirement: ASME Code stamp

Testing: All pressure containing welds shall be radiographed.
Tank shall be hydrostatically tested.

Absorption Chiller Specification

Item: Four-stage lithium bromide chiller

Quantity: Single 500-ton unit

Manufacturer: Trane, York, Arkla, or equivalent

Refrigerant: Water

Absorbent: Lithium bromide

Coefficient of Performance: 2.5 under stated conditions

Inlet Temperature: 350°F to first generator

Outlet Temperature: 120°F from fourth generator

Absorbent Concentration: 40% into generators
55% from generators

Heat Transfer Fluid Flow Rate: 40 GPM maximum
10 GPM minimum

Chilled Water Outlet Temperature: 40°F

Refrigerant Flow Rate: 11.5 GPM maximum

Strong Absorbent Flow Rate: 30.5 GPM maximum

Weak Absorbent Flow Rate: 42.0 GPM maximum

Chilled Water Flow Rate: 400 GPM maximum

Condenser Cooling Water: 240 GPM maximum

Absorber Cooling Water: 600 GPM maximum

Electric Storage System (For "double scale" photovoltaic array)

Item: Electric Storage Batteries, Lead-Acid

Quantity: 200

Size: 116 plates

Voltage: 240 nominal

Capacity: 125 ampere hours (each)

Cycle Life: 2,500 cycles

Depth of Discharge: 0.80

Storage Efficiency: 0.75

Materials: Lead-acid

5 hr. Charge Rate: 25 amperes, 6,000 watts (each)

Lighting Fixture

Item: Lighting Fixture

Quantity: 3,100 (approximately)

Type: Fluorescent commercial-surface and recessed

Lens: Acrylic plastic

Lamps: Four foot and eight foot fluorescent

Ballast: High frequency exciter generating 20,000 hertz output from direct current input. Filament power not required

Dimming Capability: Yes

Ballast Efficiency: 95%

5.3.8 Acquisition Cost Estimates

This section describes an economic analysis of the photovoltaic shopping center constructed under the presumed 1985 state-of-art, which allows planning for fixed flat photovoltaic arrays becoming available at a cost installed of about \$100 per square meter of \$900 per peak kilowatt, about one-twentieth of current cost.

Based upon an annual average of 0.78 kWh per day per square meter of array area for 45° inclined fixed arrays with reflecting surfaces in a San Fernando Valley (Los Angeles) location, the annual reduction in energy from the utility central power station is roughly 285 kWh/m². This is worth about \$5.20 per year at present incremental rates for large consumers, or about \$14 per year at initial block rates.

The payback period for critical components may be estimated by imputed cost savings over alternative or conventional methods for lighting, cooling, powering, and heating. A major difficulty with this approach is that of separation of effects of the various measures for energy conservation, including architectural, electrical, and mechanical. Refrigeration cooling loads are relatively small due to reduction of internal loads through improved lighting efficiency and motor loads, for example. When such synergistic effects predominate, their separation and proper crediting is made difficult.

It is illuminating to grossly evaluate some of the salient design characteristics on a cost-worth basis. This will be attempted for photovoltaic arrays, absorption chillers, thermal arrays, and high frequency lighting systems. The proposed roof-top reflectorized photovoltaic array reduces utility electrical consumption by 2.09 million kWh annually. At power costs of 18.2 mills per kWh this represents a reduction in electrical energy costs of \$38,038. The acquisition costs of the photovoltaic system is estimated at \$777,000 or approximately \$104/m² of array. This cost does not include reflector replacement costs.

The "double-scale" system is much less attractive due primarily to the high cost of constructing the array support structure over the parking lot. The system cost incurred is \$2,700,000 or \$180 per square meter of array, while the first year's value of the resultant decreased use of utility energy is worth \$61,153.

A detailed break-down of the costs (per unit array area) of the photovoltaic system is:

	<u>Proposed System</u>		<u>"Double Scale" System</u>	
	<u>Unit Cost</u>	<u>Total Costs</u>	<u>Unit Cost</u>	<u>Total Costs</u>
Arrays:				
Purchase		\$ 55/m ²		\$ 55/m ²
Installation				
Cables & Elec. Hook-up	\$ 5/m ²		\$ 5/m ²	
Change in roof structure	16/m ²		8/m ²	
Parking Structure	0		69/m ²	
Install on roof	5/m ²		5/m ²	
Installation sub-total		26/m ²		87/m ²
Reflectors: (Excludes Replacement Costs)				
Purchase	9/m ²		9/m ²	
Install on Roof	6/m ²		6/m ²	
Reflector sub-total		15/m ²		15/m ²
Regulators & Rectifiers		8/m ²		5/m ²
Storage		0		21/m ²
SYSTEM TOTAL COST		<u>\$104/m²</u>		<u>\$183/m²</u>

Absorption chillers of 500 tons capacity are expected to have acquisition costs of about \$150,000, based upon extrapolation of data for 2-stage chillers to four stages. For an estimated average duty of 50% of capacity on an annual basis their use would avoid annual electric energy consumption of 2.2 million kWh worth \$40,040/year at \$0.0182/kWh. However it must be recognized that the solar thermal system in essence provides fuel for the absorption chiller. Therefore an evaluation of the cost effectiveness of the chiller would have to take into consideration an appropriate allocation of the solar thermal system cost.

Thermal arrays are expected to exhibit acquisition and installation costs of \$5 to \$10 per square foot (\$55 to \$110 per square meter), and reflecting surfaces used with the flat fixed thermal collectors about \$10 per square meter. The high-efficiency low-temperature collectors will provide 60 therms per year per square meter of useful thermal energy for space cooling and space heating. For future costs of thermal energy between \$0.20 and \$0.40 per therm (oil at \$15.00/BBL yields energy at \$0.30 per therm), the annual savings in energy cost is \$12.00 to \$24.00 per square meter of array. It is estimated that costs of insulated piping associated with the 2,000 square meters of thermal arrays occupying 3,500 square meters of roof area would be \$20,000 or \$10 per square meter.

High frequency lighting system promises to reduce energy for lighting by 15% to 20% over comparable 60 Hz systems, resulting in annual energy savings of about 850,000 kWh. It would appear that the added cost of high frequency lighting ballasts operating on direct current would probably be paid back after two years of operation, at an estimated cost of \$30,000 for lighting ballasts. If the rectifier cost of \$50,000 is charged to the lighting system, the pay back period is less than six years assuming 8% interest and a 5% escalation of energy costs.

During the course of study, FSEC prepared detailed cost estimates for electrical, mechanical, and architectural systems and components. (See Tables 5.3.8-A and 5.3.8-B.) In way of summary, it is illuminating to consider the difference in shopping center acquisition cost and the difference in operating cost between an advanced photovoltaic-powered shopping center and a comparable one constructed along the lines of current conventional design practice, and then to estimate a pay back period, or time to amortize the higher initial cost of the unconventional design through annual operational cost savings. To that end, the following lists the sources of added acquisition cost and their probable magnitude, as a function of photovoltaic system size. "Double scale" denotes a system capable of providing all the electric energy requirements of the shopping center with the average daily output of

Table 5.3.8-A
Acquisition Costs

<u>Component</u>	<u>"Double-Scale"</u> <u>Photovoltaic</u>	<u>Proposed</u> <u>Photovoltaic</u>	<u>Conventional</u>
<u>Land</u>	\$ 1,800,000	\$1,800,000	\$1,800,000
<u>Construction</u>			
Site Improvement	507,000	507,000	507,000
Structural	827,000	827,000	827,000
Architectural	2,011,000	2,011,000	2,011,000
Parking Structure	1,030,000	0	0
Construction Sub Total	4,375,000	3,345,000	3,345,000
<u>Mechanical</u>			
Thermal Arrays	230,000	230,000	0
Reflectors*	34,000	34,000	0
Transport Fluid System	57,000	57,000	0
Auxiliary Heating System	6,000	6,000	20,000
500 T. Absorption Chiller	172,000	172,000	0
750 T. Vapor Comp. Refrig.	0	0	225,000
Evap. Water Coolers	62,000	62,000	77,000
Cooling Water System	15,000	15,000	18,000
Chilled Water System	44,000	44,000	56,000
Hot Water System	24,000	24,000	24,000
Air Handling Equipment	81,000	81,000	101,000
Ducting & Air Distribution	444,000	444,000	555,000
Temperature Controls	57,000	57,000	57,000
Plumbing	144,000	144,000	144,000
Fire Protection	216,000	216,000	216,000
Mechanical Sub-Total	1,586,000	1,586,000	1,493,000
<u>Electrical</u>			
Photovoltaic Arrays	825,000	412,500	0
Reflectors*	510,000	255,000	0
Array Wiring	75,000	37,500	0
DC Regulator	16,000	8,000	0
Rectifier	50,000	50,000	0
Storage System	320,000	0	0
Power Wiring	225,000	225,000	150,000
Other Installation Costs	158,000	158,000	0
Lighting System	658,000	658,000	690,000
Electrical Sub-Total	2,837,000	1,804,000	840,000
<u>Total Cost</u>	<u>\$10,598,000</u>	<u>\$8,535,000</u>	<u>\$7,478,000</u>
Cost/ft ² , excluding land (250,000 ft ² building)	\$35.19	\$26.94	\$22.71
Acquisition cost difference	+\$3,120,000	+\$1,057,000	0

*Includes present value of replacement at 10 and 20 years.

Table 5.3.8-B
Shopping Center Cost Summary

<u>ANNUAL OPERATING COSTS</u>	<u>PHOTOVOLTAIC</u>	<u>CONVENTIONAL</u>
ELECTRICAL ENERGY (kWh)	2,740,000	13,500,000
@ 18.2 Mills/kWh	\$ 50,000	\$246,000
THERMAL ENERGY	2,000	12,000
MECH. SYST. MAINT.	83,000	75,000
ELEC. SYST. MAINT.	52,000	42,000
OTHER MAINT.	58,000	58,000
WATER	12,000	12,000
ANNUAL OPERATING COST	\$257,000	\$445,000
ANNUAL COST REDUCTION	188,000	
CAPITAL COST INCREMENT	\$1,057,000	
RETURN ON INVESTMENT*	16.9% (before taxes)	
<hr/>		
SOLAR ELECTRICITY TO LOAD (kWh)	2,090,000	
PHOTOVOLTAIC SYSTEM COST	\$921,000	
PRESENT VALUE OF SOLAR ELECTRICITY**	\$759,619	
COST OF ENERGY INVESTOR OWNED UTILITY	65.4 Mills/kWh Levelized 36.8 Mills/kWh Initial Year	JPL/ERDA/ EPRI METHOD (19

*Based upon returning initial investment after 30 years.

**[2,090,000 kWh] [\$.0182/kWh] [19.97 (present value factor)]

the photovoltaic arrays during the best seasons (March-April and mid July-mid September), and about 70% of the total annual energy requirement. The "proposed" system is more dependent upon utility power, providing somewhat less than half the annual shopping center electrical power, but appears to be more cost-effective. While contributing more than half as much useful energy, the smaller system increases cost by only about one-third as much as the larger system, while preserving the other beneficial energy conservation features.

The "proposed" photovoltaic solar power system contributes to energy conservation design measures in approximately the same degree as the larger system in spite of its lesser contribution to total annual electric consumption required by the shopping center. Collected energy is used more efficiently because storage losses are avoided, and first cost is reduced significantly by elimination of storage requirement and parking lot structures. As calculated in Section 5.3.2, the smaller system provides 2.09 million kWh per year of DC power. An additional 2.51 million kWh of DC are provided by rectifying (at 95% efficiency) 2.64 million kWh of utility power. In addition, 100,000 kWh of utility power are required for convenience outlets. Net utility-furnished energy saving compared with a conventional shopping center would be 10,000,000 kWh annually, compared with 12,000,000 kWh for the "Double-Scale" system. At \$0.0182 per kWh the return on investment (\$1,057,000 increased cost) is 17.8%. This return is computed after reducing the annual cost savings by an amount each year to return the capital investment at end of life.

In Table 5.3.8-B the value of the electrical energy produced is compared to the cost of utility power in two different ways. The cost of the photovoltaic system is estimated at \$921,000 according to the breakdown in Table 5.3.8-A (the photovoltaic system is defined to include all electrical items except internal power system wiring and the lighting system). The present value of utility electricity displaced, which is equal to the present value of solar

electricity produced, is calculated by multiplying the annual output of the photovoltaic system (2.09 million kWh) by the incremental utility electrical rate appropriate to the center (18.2 mills/kWh) as determined from 1974 tariffs, and by the present value factor of 19.781.

The present value factor is calculated assuming a 30-year system life, an after-tax cost of capital of 8%, and an escalation rate for utility electricity of 5% per year. Since the present value calculation is based on present electrical rates, it provides a cost comparison essentially from the viewpoint of the building owner. Because of special tax provisions applicable to real estate, the cost of capital for the building owner may be more or less than that applicable to a utility, but is most likely less. However, in this comparison the same cost of capital was used as in the JPL/ERDA/EPRI energy cost calculation.

The second method is the JPL/ERDA/EPRI method, using the baseline economic parameters to give a levelized fixed charge ratio of 0.1483. The levelized cost of energy from the solar photovoltaic system is therefore calculated at 65.4 mills/kWh. If electrical costs are assumed to escalate at 5% per year (the assumed general inflation rate), the solar photovoltaic system will be less expensive over its 30-year life if the electrical cost at the year of installation is more than 36.8 mills/kWh in 1975 dollars.

Using the present value method, the cost of the photovoltaic system is 22.4% greater than the present value of the cost of buying electrical energy from the utility. Using the fixed charge ratio method, the cost of electrical energy from the photovoltaic system would be twice the cost of utility energy over the system lifetime, assuming 1975 installation.

If the costs of the electrical and mechanical innovations are separated, it is seen from Table 5.3.8-A that mechanical systems designed for compatibility with photovoltaic systems are expected to add only \$93,000 to the cost of the

shopping center. Some of the added cost of thermal arrays, reflectors, heat transport fluid system, and absorption chillers (about \$499,000 total) is balanced by cost savings caused by a one-third reduction in cooling load due to reduced internal loads.

Annual operating cost reduction attributable to the mechanical systems constitutes the largest fraction of total energy conservation possibilities with the photovoltaic shopping center, although a significant portion of that fraction is due to DC motor variable speed control efficiency gains as well as reduced loads. It is clear that a beneficial impact of photovoltaic and D.C. electrical systems characteristics is felt by the reduced annual energy requirements for mechanical systems, similar to the impact upon the mechanical systems in acquisition cost penalty. Subject to the foregoing observations that a component-by-component cost-benefit analysis is distorted by synergistic effects, a gross characterization shows:

1. The photovoltaic "package" treatment for shopping centers can exhibit an annual return on investment of 15% to 25%, if energy is worth \$0.02 per kilowatt hour, and photovoltaic systems cost around \$100/m² installed.
2. The total photovoltaic system, including arrays, cabling, regulators, and storage system can exhibit an annual return on investment of about 5.6%, if energy is worth \$0.02 per kilowatt hour, and credit is taken only for the energy produced (ignoring the energy conservation credits), and if total system cost is around \$100 per square meter.
3. Mechanical systems exhibit an annual return on investment of about 100%, since they are the principle beneficiaries of energy conservation. About half of the total energy savings is due to the thermal array-absorption chiller marriage, and the balance is through the courtesy of the photovoltaic-electric system characteristics.
4. Electrical systems can be credited with significant independent energy savings at small increased acquisition cost (power and lighting systems, and rectifier). At an acquisition cost increase of about \$100,000, the power and lighting systems are expected to reduce annual energy consumption by 1.5 million kWh, worth \$30,000 at \$0.02 per kWh.

5. Architectural systems may be credited with annual energy savings in an amount equal to that for electrical systems, also at small additional cost, if the photovoltaic-array-bearing parking lot structure is not counted. This feature has some intangible values to a shopping center beyond its primary function of deploying additional arrays, so it is difficult to do a proper cost-worth analysis. However, a smaller photovoltaic system whose size is constrained by available shopping center roof area would avoid this difficulty. It would still present shaded skylighting opportunities which together with several other means of minimizing internal loads and external heat gains would allow architectural systems to contribute significantly to annual energy conservation at small cost.

5.4 RETROFIT APPLICATION

Introduction

In general, the issue of solar applications to existing building vs. application to new construction should always be decided in favor of new construction if the objective is to optimize cost effectiveness of the solar energy system. There are good fundamental reasons supporting this philosophy:

- 1) New construction offers opportunity for total design optimization for the intended site location, building function, climate, and solar energy hardware options.
- 2) New construction offers no (or at least fewer) constraints in the selection of options for energy conservation in design, and in selection of solar conversion process hardware.
- 3) New construction can make maximum utilization of the synergistic effects of improvements to lighting systems, mechanical systems, space conditioning systems, and solar energy conversion systems.
- 4) Costs associated with incorporation of innovation in design and construction of new facilities are almost universally less than those for retrofit of existing buildings involving demolition, clean-up, functional disruption, and difficult reconstruction.

Unfortunately, but realistically, application of solar technology to new construction suffers from the spectre of uncertainty and perceived risk. Without federal subsidy, no prudent developer would presently go much beyond providing for a few flat plate thermal collectors for warm water for his new

building. In the absence of long term experience with life cycle costs, maintenance requirements, potential hazards, and prospect of return on investment from potentially more effective (but presently more costly) options for solar energy conversion and utilization, investment capital cannot be attracted to innovative approaches.

Retrofit of existing buildings offers an opportunity for obtaining experimental data regarding performance, installation costs, reliability, maintainability, and effectiveness of a variety of on-site solar thermal and solar electric configurations. Retrofit applications must be carefully shown so that the data obtained can be generalized to new construction. Commercial buildings of the categories found to be appropriate for photovoltaic applications appear to offer fewer difficulties in retrofit applications than do other types of structures such as residences, because of greater standardization of design and construction. In this section, results of a study of a typical retrofit application to a commercial building are presented. It is shown that many of the design features developed for the shopping center can be adopted to a retrofit application, and that system costs can be achieved which are closely comparable to costs in new construction.

Retrofit Options

Engineering considerations establish a spectrum of options for retrofit, embracing a range of architectural, electrical, and mechanical system improvements for energy conservation, solar energy utilization, and their synergistic effects.

Before proceeding with the analysis of a specific retrofit design to reduce energy demand, the major retrofit options and their benefits will be described. It is to be expected that geographical differences in both energy requirements and solar energy availability will lead to wide geographical differences in preferred measures for retrofit to conserve energy and to utilize solar energy,

even for identical building functions. Differences in building function and utilization in terms of demand profiles add further complication to any attempt at generalization. Economic factors must also be considered, such as building age and remaining useful life, as well as the projected economics of utility furnished energy.

For our purposes, there are five main sources of electrical loads in buildings; lighting, air conditioning, heating, ventilation and internal loads. Although heating is not usually electrical, fuel or gas requirements can be reduced by alterations of the electrical system by synergistic effects. These loads can be reduced by partial or complete alterations of the architectural, electrical, and mechanical building systems.

Candidate areas for architectural improvements to conserve electrical and thermal energy include insulation, fenestration, and infiltration. The first two are impacted by retrofit for solar applications but energy conservation measures which reduce infiltration are not. Poorly sealed windows and doors, open windows, and frequently opened doors are wasteful of energy required for space conditioning; and in severe climates the energy conservation of reduced infiltration can be significant. However, no interface exists between retrofit for solar applications and measures to reduce infiltration, as it does for both insulation and fenestration improvements.

For sites in the more southern latitudes of the United States, a very beneficial effect of reduced roof heat gain in summer accompanies flat fixed arrays inclined at 45° , with reflecting surfaces oppositely inclined at 35° between the East-West oriented rows of collectors. The solar collector system therefore contributes to improvement in building insulation and reduces summer heat gain, leading to energy conservation in the operation of air conditioning systems. While such a configuration has small impact on winter heat loss, it may be observed that such loss is small in southern latitudes with mild winters.

In contrast, sites at more northern latitudes would derive less benefit from reduction of roof heat gain in summer, but would be more in need of reduction of winter heat loss. In addition, as illustrated by Figure 6.1.1-D, a relatively greater incentive exists for the use of tracking surfaces in northern latitudes. Therefore it may be concluded that the interface between solar collector systems and architectural systems, at least in the area of insulation retrofit, is more pronounced in southern latitudes.

The remaining feature which has a complex interface with solar energy systems for retrofit of existing buildings is that of fenestration. Generally, windows are located around the periphery of the building, and contribute to energy consumption and opportunities for energy conservation in several conflicting ways:

- (1) In some inverse fashion, window area impacts energy consumption for lighting load during daylight hours.
- (2) Lighting load directly affects energy consumption for summer air conditioning, but has an inverse effect upon winter demand for thermal energy, and
- (3) Windows increase building heat gain (summer) and heat loss (winter) by conduction, and are capable of providing daytime heat gain by transmitted radiation at all seasons, depending upon orientation with respect to sun angles throughout the day and upon degree of shadowing by awnings, overhangs, and recessing.

In the shopping center study (Section 5.3) skylighting is considered to be beneficial for reduction of lighting loads and air conditioning load. No doubt the selection of site and architecture (San Fernando Valley, single story) was responsible for this conclusion, and it would be hazardous to extrapolate to other climates and/or multi-story structures.

Numerous modifications to lighting systems may be considered for incorporation during retrofit for on-site photovoltaic arrays. In addition to potential reduction of artificial lighting intensity requirements by improvement in natural lighting in single-story structures, large improvements in lighting

efficiency (lumens per watt) are achievable through the utilization of direct current lighting systems with high frequency DC and through compromise with the color spectrum of artificial lighting (see Figures 5.3.2-B and 5.3.2-C).

Similarly, provision for direct current motors for pumps, fans, and blowers will lead to energy savings in their speed control for variable volume flows. It is anticipated that energy savings by this means will more than compensate for rectifier losses when the components are operated from utility power, even if no credit is taken for those periods of operation when solar photovoltaic assist is available. Depending upon the size of the photovoltaic system, there may even be periods when all motive power required could be met by the on-site conversion of solar energy.

Photovoltaic arrays of various types (fixed, tracking, concentrating, reflectorized, hybrid (thermal)) may be provided. By paralleling rectified utility power and photovoltaic output (each protected by a blocking diode) into a common bus used for lighting and motor loads, it is possible to insure that all of the on-site photovoltaic energy is utilized whenever it is available by matching the load (number of circuits) to the maximum photovoltaic capability and designing the photovoltaic arrays for a higher output voltage than that of the utility power rectifier. For example, if the photovoltaic arrays were configured for 240 volts and were connected to a common bus with 220 volts from the rectifier, all available on-site energy would be utilized as long as its voltage remained above 220 volts, and utility rectified energy would be excluded from the load (as long as the on-site capability matched or exceeded the load). During periods of obscurement and a photovoltaic capacity inadequate for the entire loaded circuit, its voltage would drop to 220 volts and the rectified power would make up the deficiency, but all available on-site energy would be utilized in sharing the load.

It is possible to consider the use of electrical energy storage when decision is made to go direct current for lighting and motors. If the rate structure favors off-peak consumption sufficiently to overcome storage losses (~25%) as well as the storage system life cycle costs, it would become economic to charge batteries at night or periods of minimum demand. However, it is not recommended to size a photovoltaic array so that its maximum capability exceeds the demand of the load to which it is connected, so storage systems are not justified by the presence of photovoltaic systems.

All mechanical systems requiring power in their operation for pumps, blowers, or fans can benefit from the use of direct current when most of their operation is part load. Since this situation occurs most of the time in variable-air-volume air conditioning systems, sizeable energy savings result from controlling motor RPM by control of field current.

Other mechanical systems changes which can be considered for solar energy retrofit are more closely related to the utilization of solar thermal energy than to the use of on-site photovoltaic energy. All are related to the use of solar thermal energy for space conditioning (cooling and heating). In brief summary, they include thermal storage, expansion tanks, thermal transport fluid, auxiliary heater, heat exchangers, absorption chiller, chilled water storage, and pumps and controls (see Section 5.3.5).

Much more significant reductions in energy demand are possible by retrofit of air conditioning equipment to eliminate vapor compression refrigeration machinery and to substitute a solar-powered absorption refrigeration system. Depending upon geographical and climatological variables of site location, annual electrical energy savings between one-fifth and one-half of total consumption can be expected for many classes of light commercial buildings. Additional savings in fossil fuel requirements for winter heating constitute an additional benefit for the solar thermal collector system needed to drive absorption chillers (see Section 5.3.3).

Fairly high collection temperatures are desired to allow absorption chillers to operate at a high coefficient of performance to minimize the collection area required. With collection temperature of about 300°F, a multi-stage absorption chiller will have a coefficient of performance (ratio of refrigeration effect to heat collected) of about 1.3 for two stages, 1.9 for three stages, and 2.4 for four stages. For a given refrigeration load, heat rejection equipment size and cost are also reduced as C.O.P. is increased. Two stage absorption chillers are currently available which will operate at 1.3 C.O.P. at the (derated) refrigeration load of 150 tons. Multi-stage absorption chillers are not available in ratings below 50 tons.

The extent to which these options can be employed in a retrofit installation will depend on the extent of the disruption of normal building operations which can be tolerated, and the economics of replacing existing with new equipment. If major reconstruction and interior refurbishment of the building is planned for other reasons, all of these options should be considered. In more usual cases, some will be ruled out.

It should be noted that commercial buildings typically are refurbished several times during the life of the structure, and that major components of the building mechanical and lighting systems have useful lives which are a fraction of the useful life of the structure itself. Therefore opportunities for retrofit are not as limited as it may first appear. In the particular case selected for consideration, replacement of vapor-compression with absorption refrigeration equipment was ruled out because the building plan did not provide a suitable location for absorption equipment to connect with existing ductwork. Battery storage was also ruled out for the same reason, and also because the shopping center design study had not established a convincing case for the inclusion of storage.

The other options were found to be easily incorporated into a major refurbishment of the building interior, as would normally occur at the time of a change of tenant. In particular, it was found that:

- (1) Structural strength of the existing roof was adequate to handle dead and live loads imposed by roof-mounted arrays, without additional bracing, and within existing building code requirements. Even if this were not the case, it appeared to be possible to design the mounting structure of the arrays to contribute to roof stiffness and to carry structural loads to exterior walls and interior columns, and to do this at a minor increase in cost.
- (2) Existing roof-mounted mechanical equipment could be relocated to provide a clear area for array installation with minimal change in existing power wiring and ductwork.
- (3) The existing air conditioning equipment, which utilizes several packaged vapor-compression heat pump units to supply both heating and cooling, could be retained if drive motors were replaced with DC motors. Since this equipment was approaching its end of life, replacement with more modern and efficient equipment of a similar type was indicated in any event.
- (4) Replacement of lighting fixtures, while not necessary because of deterioration of existing units, would make such a large contribution to energy savings as to be cost-effective in any event.
- (5) Disruption of present activities within the building (engineering design work is the present use) would be minimal.
- (6) Overall costs of installation were estimated to be comparable to new construction in this particular case. It appeared that large increases in installation cost (as compared to new construction) would be incurred only if major changes in building structure or mechanical systems were required. This was not necessary in the particular case studied, which appears to be a representative case.

We therefore conclude that, when photovoltaic system installations become cost-effective for new commercial buildings, a significant fraction of existing buildings will also become candidates for retrofit installations. It appears that retrofit installations will then be cost-effective if scheduled to coincide with major interior refurbishment. This will substantially increase the rate at which photovoltaic installations can be predicted to penetrate the commercial market.

5.4.1 Analysis of Application

For specific purposes of illustration, a 3,000 square meter building (~32,000 square feet) devoted to the light commercial activities of architecture and engineering, plus a small amount of light manufacturing, has been selected to investigate some of the practical problems of retrofit installation options. Located near the Los Angeles Airport, it is typical of fairly recent construction trends for type 5 occupancy throughout the country, although it is located in a seismic zone 3 and therefore, might tolerate less weight added to the roof; although representing slightly more rugged construction than might be found in less earthquake-prone areas.

Figure 5.4.1-A gives the essential external dimensions of this existing building. It may be noticed that the building is not particularly favorable from the standpoint of available roof area for a two-story building, since the second floor area is only half as great as the first floor, making the lower (first floor) roof undesirable because of afternoon shadowing. Since the desirable roof area for solar arrays is presently cluttered with mechanical equipment in the center, the available space is less than 1,000 square meters, unless the equipment is relocated. In this instance, the air handling units and vapor compression machinery are in need of replacement due to age, frequent malfunction, and maintenance needs, so its replacement and relocation could be done simultaneously.

Structurally, the second story roof load-bearing capability (ultimate) as a function of area over which the load is distributed varies almost linearly from $1,500 \text{ lb/ft}^2$ over a very small area (less than one square foot) to slightly less than 100 lb/ft^2 uniformly distributed over the structure. Steel roof girders span the width of the building on 24-foot centers, with the girders supported on columns to the foundation at several points along their span. Strapped between girders are 2 x 10 purlins on 24-inch centers, with a plywood and 110-lb felt roof. With a structural safety factor of 5 the

Figure 5.4.1-A. Typical Retrofit Candidate

corresponding load-bearing capability of the existing roof would vary between 300 lb/ft^2 for concentrated loads and 20 lb/ft^2 for fairly large distributed loads without excessive deflection or likelihood of roof damage. Side loads due to wind loading on solar array surfaces would be of little concern unless the wind loading on a large surface would have to be resisted by a small area of the roof in shear, as for a large tracking array on a vertical pylon extending to ground level. Likewise, the concentrated moment of such a configuration in high wind conditions (if the pylon were bolted to the roof) could be destructive. For 45° inclined surfaces exposed to wind but reacted by uniform added roof loadings, there are no special requirements for added structural strength as long as the array weight is less than 10 lb/ft^2 and the wind loading is less than 10 lb/ft^2 . For such a wind loading on 45° inclined arrays, a wind velocity of nearly 100 MPH would be required to necessitate spreading the wind load reaction over a roof area equal to array area. Candidate photovoltaic arrays will result in less than five pounds per square foot added to the roof weight.

The daily, seasonal, and annual electric demand and consumption characteristics of the building selected for illustration of retrofit options are as follows:

1. Lighting demand average is 30 watts per square meter for 60 hours per week, and 0.5 watts per square meter for 108 hours per week. The second floor (windowless) uses a maximum of 40 watts per square meter and the first floor 25 watts per square meter. Building peak demand is 95 KWE for lighting, and consumption is about 300,000 KWH annually. Lighting demand and consumption are fairly independent of season, and both are practically constant at their maximum values between the hours of 7 AM and 6 PM five days per week, with variable but lower values during weekend daylight hours.
2. Air conditioning (vapor compression) units totalling 100 tons capacity are capable of heat pump space heating by reversing the refrigerant flow to provide heat to the interior from the outside at a maximum rate of 960,000 BTU/hr under winter design condition. Total maximum electric demand is 100 KWE in either cooling or heating mode, including the power for ventilation through the single duct system. Experience with the space conditioning system indicates an annual consumption of about 100,000 KWE to supply 65,000 ton hours of space cooling and 4,200 therms of space heating.

3. Miscellaneous minor loads (exhaust fans, office equipment, convenience outlets) have a variable and unpredictable demand in the range of zero to 20 KW, with an average annual consumption of 20,000 KWH. Maximum demand from all sources (lights, space conditioning, and internal loads) is about 215 KW, and annual total consumption averages 420,000 KWH. The electric rate, including fuel cost adjustment and 10% city tax is currently \$0.0378 per KWH; resulting in an annual cost of purchased energy of approximately \$15,900.

Seasonal variation in rate of consumption is small due to the nature of building usage, space conditioning method, and the mild climate. Daily variation in consumption is that caused by the weekend and holiday decreases from a level roughly constant from Monday through Friday. Hourly variation is characterized by a very low level at night (6 PM to 6 AM), a precipitous rise to the 8 AM to 5 PM regular working hours, and a precipitous decrease to night time levels during the next hour or two. Average monthly consumption is 35,000 KWH, with a range of 30,000 KWH in cold months to 40,000 KWH in hot months. Average daily consumption is 1,150 KWH, with a range of approximately 30 KWH per day unoccupied to 2,000 KWH per day during heavy utilization on a hot day.

Annual insolation on the 1,000 square meter roof of the second story is about 1,800,000 KWH. Some is reflected, but the larger portion is absorbed, adding to the air conditioning load in summer. It is the purpose of this section to examine some of the options and combinations of options for utilization of some of this solar energy to conserve purchased energy. The options selected for evaluation of cost and effectiveness are:

- I. Reflector-augmented flat photovoltaic arrays inclined 45° facing south.
- II. Polar-axis tracking concentrators with photovoltaic conversion of the concentrated energy.
- III. Concentrating tracking thermal collectors for space conditioning in conjunction with a two-stage absorption chiller.

- IV. Addition of skylights for improved natural lighting of the windowless second floor.
- V. Use of direct-current, high-frequency lighting.
- VI. Lighting intensity reduction in non-essential areas (spot-lighting).

All except options V and VI are directly dependent upon solar energy conversion processes, and even V is indirectly related to options I and II through the output characteristics of photovoltaic cells. The four combinations of options investigated for effectiveness and economic constraints are either of the first two, with and without the third, combined with the remainder. In both cases the area available for solar hardware deployment is assumed to be 1,500 square meters, or 75% of total roof area.

If all available roof area were devoted to photovoltaics, configuration I would have 900 square meters of arrays and 1,125 square meters of reflecting surface. At 10% annual average cell efficiency, the system would make available annually 257,000 kWh of direct current towards the building demand, or 61% of the present total load. Configuration II (polar-axis concentrating trackers) under the same space constraint, would have 300 square meters of concentrator aperture, 30 square meters of cell arrays at ten suns concentration, and at 10% annual average cell efficiency would contribute 85,000 kWh or 20% of the present requirement. Provisions for active cooling and tracking would consume some power not needed for the fixed arrays, but if the saving in cell cost is much greater than the acquisition cost of concentrating, cooling, and tracking systems, the concentrating trackers could show economic advantage over flat fixed arrays (high cell cost scenario). Unfortunately, unless photovoltaic material costs are greatly reduced, neither configuration is likely to show any payback. Even in an economic environment of ten cents per kWh electric energy cost, flat fixed arrays would pay for themselves within ten years, if maintenance cost were zero and capital discount rate were 10%, only if the system installed cost per square meter of array (including reflector costs) were not greater than about \$175. The corresponding economic constraint on polar-axis concentrating collectors is

about the same, based upon concentrator total aperture area, but including cooling and tracking systems and their associated maintenance costs, provided array efficiency were not compromised by elevated cell temperature.

Under option III, if all available roof area were devoted to concentrating thermal collectors tracking about a north-south axis inclined at 35° ($\pm 10^{\circ}$ depending upon season) from horizontal, the annual collection of thermal energy would be 18,600 therms at average collection efficiency of 65% for a total aperture of 300 square meters. Average daily collection would be 51 therms, with a winter average of about 42 therms and a summer average of 60 therms. Maximum heating rate would be about 7.3 therms per hour, independent of season. The summer average would furnish 650 ton-hours of refrigeration per average day through a two-stage absorption chiller with a coefficient of performance of 1.3. If no other energy-conservation measures (options IV, V, and VI) were employed, the thermal collector system would be capable of meeting most of the space-conditioning requirements of the building for summer cooling and winter heating. A small standby heater would be required for extended cloudiness to assure the maintenance of storage temperature in the vicinity of 300°F .

For the example retrofit, options IV, V, and VI are calculated to reduce lighting energy requirements from the present 300,000 KWH annually to 70,000 KWH by better use of natural lighting in the second floor office and drafting areas (four skylights), by spotlighting the critical areas (desks, tables, drafting boards, work areas; comprising 20% of total area), by bringing fixtures closer to the work by a factor of two (suspended fixtures), and by use of 20 kHz, 220-V inverted direct current fluorescent lighting. In addition, the application of option III would result in complete elimination of the estimated 100,000 KWH present consumption of electric energy for space conditioning, so the potential exists for direct savings of 330,000 KWH annually by retrofit for energy conservation — a reduction of 80%. Summer cooling load is reduced nearly 50% by reduction of the internal heat gain.

from lighting and the roof solar heat gain due to shading by solar arrays in this case, making the absorption chiller duty cycle that much easier to achieve. In fact, much of the time in this climate the principal duty of the air conditioning system is to remove the waste heat from the wasted lighting, so that it now becomes possible to consider much smaller vapor compression machinery powered by photovoltaic energy for summer cooling and winter heating. It may be seen from the considerations discussed above that an all-photovoltaic (no thermal) roof mounted system - (Option I) - could handle the new lighting load and provide almost twice the current annual consumption for space conditioning in addition. Option II could handle the lighting load and provide part of the current annual consumption for space conditioning.

Option I is characterized by installed costs of \$130 per (array) square meter, including all costs of installation and wiring. It is assumed that arrays will be designed to furnish 240 volts to a common bus with 220 volt rectified utility power, when delivering design current to the design load under conditions of maximum insolation rate. Each line to the bus is protected by a blocking diode so the photovoltaic system will drive the load at all times that its voltage is greater than 220 volts. At times of solar illumination inadequate to drive the entire load, array output voltage will drop to 220 volts at the bus and the load will be driven by all of the array output and sufficient rectified utility power to meet the remainder of the demand. When array output falls below 220 volts all of the demand will be met by rectified utility power. In addition to the cost of array and wiring installation, Option I must bear the cost of the rectifier, which is assumed to be \$1,000 + \$40/kWE. Capacity of the rectifier depends upon the effectiveness of other options exercised, and in this case would range between 30 kWE (with absorption chillers) and 80 kWE (with smaller vapor compression reversible heat pumps).

Option II, with a space-constrained output of one-third of Option I (while employing only one-thirtieth of the cell area) is characterized in terms of installed cost by \$230 per square meter of concentrator aperture. The cost

per square meter installed includes those costs of concentrators, tracking mechanisms, and the cooling system. If Option III is included, the cooling system might be incorporated in the heat transfer loop of the thermal collectors to utilize the heat that would be rejected to atmosphere through an evaporative cooler if Option III were not exercised. In the absence of Option III the cooling system would be a simple arrangement of circulation pump, piping, and evaporative cooler for the low-vapor-pressure heat transfer fluid (Dow-Therm, Therminol 55, etc.), all confined to the roof. Power requirements for operation of the cooling system (circulation pumps and evaporator air blower) and for the tracking system are estimated at 3% and 2% of total photovoltaic output, respectively. This requirement is equivalent to a reduction in array efficiency of about one-half of one percent in an array system with 10% conversion efficiency.

Option III would entail the greatest complexity of retrofit. Although the roof-mounted (concentrating, tracking) thermal collectors would be less costly than those of Option II due to the absence of silicon solar cells at the focal area, they would be identical in configuration. Added complexity arises from the need for (hot and cold) thermal storage, circulation pumps, auxiliary heater, 2-stage absorption chiller, controls, evaporative cooler(s), water treatment provisions, and extensive runs of insulated piping. Budget estimates for a 50-ton absorption chiller capability at a C.O.P. of 1.3 include:

2-Stage Chiller, Installed	\$ 30,000
Collectors, 200 m ² at \$200/m ²	40,000
Thermal Storage	10,000
Auxiliary Heater (Gas)	1,000
Evaporating Coolers	5,000
Pumps, Valves, Controls, Piping	10,000
Miscellaneous	4,000
TOTAL	<u>\$100,000</u>

Because the air conditioning system needs replacement, the \$24,000 cost of an alternate system can be credited against amount.

Options IV, V, and VI would be expected to cost \$2,000, \$10,000, and zero, respectively, for four skylights, for 150 new suspended DC lighting fixtures with ballasts, and for reduced lighting intensity. The direct effects of these options is an annual reduction of 230,000 kWh worth \$8,700 at present rates. If no other options were exercised, but the reduced air conditioning load were handled with DC motors, additional costs of \$4,600 for a rectifier and \$5,000 for motors would be necessary. However, there would be energy savings of about 50,000 kWh annually from reduced cooling loads, worth of \$1,900 at present rates. Total costs of Options IV, V, and VI (about \$21,500) would be paid back in about two years of energy savings. To the extent that electrical rates may rise in the future, the savings and attractiveness of energy conservation measures will be more pronounced.

When solar energy options are added to energy conservation measures, the pay-off is less definable due to cost uncertainties. If either an Option I or Option II configuration could be installed for \$100 per square meter, about 300 square meters costing \$30,000 would suffice for either configuration to provide more than half of the remaining building electric energy required (150,000 kW annually) for lighting, space cooling and heating by vapor compression reversible heat pumps, and electric heating of domestic hot water. Only the convenience AC demand and back-up utility use during night and cloudy times would depend upon purchased energy. Even this could be minimized by electrochemical storage of two hundred kilowatt hours at a cost of about \$5,000. However, even at \$100 per square meter for either option, the annual worth of output is only \$3,780 at present rates, even if the arrays provided 100,000 kWh annual consumption. It is clear that cost of arrays must decline remarkably from their present levels ($\$1,500/\text{m}^2$) or utility rates must rise significantly before a case for economic attractiveness can be made for photovoltaics.

Summarizing the cost and effectiveness of the various options for retrofit, it is apparent that measures for energy conservation are much superior to alternate energy source utilization applied to the same old wasteful use of energy in building design and operation. In an economic environment of 5 cents per kilowatt-hour of purchased electric energy, the various options for avoidance of purchased energy cost may be characterized as follows (Figure 5.4.1-B); as they are applicable to one building size, type, and usage, in a specific location (Los Angeles), in a given economic environment. In Figure 5.4.1-B the options are treated as mutually exclusive, except that I or II depend on the presence of V for its rectifier, while the converse is not true. Also, the rectifier needed for options I, II, and V would be larger without options IV and VI.

5.4.2 System Design Description

Based on the preceding analysis of various design options, the following retrofit measures are adopted for the Los Angeles low rise office building:

- Clear second-floor roof of existing equipment to create 1000 m² of clear area for array mounting.
- Add 455 square meters of photovoltaic arrays and 562 square meters of reflectors, requiring 782 square meters of roof area.
- Replace lighting and AC motors with DC.
- Spot light work areas with suspended DC/20 kHz fluorescent.
- Reduce space conditioning capacity and replace existing packaged units with modern high-efficiency units.
- Add 90 kW rectifier to provide supplemental DC power from utility line.

The effect of these measures is to reduce peak electrical demand from 215 kW to 90 kW and annual use of electricity from 420,000 kWh to 150,000 kWh (see Figure 5.4.2-A). The estimated reduction in lighting load accounts for the

Figure 5.4.1-B

Comparison of Retrofit Options

OPTION	COST ⁽¹⁾	EFFECTIVENESS ⁽²⁾	C/E
I (300 m ² Flat Fixed Reflected Photovoltaic)	\$39,000	\$4,275 (Zero Maintenance)	9
II (300 m ² Tracking Concentrating Photovoltaic)	\$69,000	\$3,750 ((\$525 Maintenance and Operation)	18
III 200 m ² Thermal Conc. Tracking, -Stage Absorption	\$76,000 (Alternative System Costs \$24,000)	\$4,000 ((\$1,000 Annual Operation)	19
IV (Four 2.5 m ² Skylights)	\$2,000	\$2,000	1
V (150 Suspended DC Fixtures, 75 HP total capacity DC Motors)	\$20,000 (Includes 90 kW Rectifier)	\$4,000	5
VI (Eliminate Non- essential lighting)	Zero	\$7,500	0

(1) All costs of acquisition and installation (at \$130/m² and \$230/m² respectively for fixed and tracking photovoltaics).

(2) Annual cost savings; energy cost avoidance (at 5¢/kWh) less maintenance cost.

Figure 5.4.2-A

Retrofit of Light Commercial Building Consumption of Electricity

	<u>Before</u>		<u>After</u>	
	<u>Demand</u>	<u>Annual Consumption</u>	<u>Demand</u>	<u>Annual Consumption</u>
Lighting	95 kW	300,000 kWh	20 kW	70,000 kWh
Cooling	100 kW	65,000 kWh	50 kW	25,000 kWh
Heating	50 kW	35,000 kWh	50 kW	35,000 kWh
Convenience	20 kW	20,000 kWh	20 kW	20,000 kWh
Totals	215 kW	420,000 kWh	90 kW	150,000 kWh

major part of the reduction in electrical energy consumption. In turn, the major part of the reduction in lighting load is obtained merely by the use of more efficient lighting fixtures which provide high illumination levels only on work surfaces requiring these levels (drafting tables and desks). Lighting levels in hallways, conference and reception areas and storerooms have been reduced, and natural lighting from skylights has been utilized for area lighting. This lighting plan, although fully adequate for present work arrangements, would need to be changed whenever work areas are relocated, and therefore a less efficient lighting plan might be preferred if frequency re-arrangement of activities is anticipated.

The 455 square meters of reflector augmented array would provide 109,000 kWh of the 150,000 kWh per year of electricity used by the office building. The remaining 41,000 kWh would be purchased from the utility. The total generation of the photovoltaic array is estimated at 121,000 kWh annually, of which 12,000 kWh is not useful because it is generated at times (Sundays and holidays) when demand is small. The peak generation of the photovoltaic array is 73 kW, which is less than building load on a clear day. Thus no photovoltaic energy is dumped when the building is occupied, and this no-storage system supplies 73% of annual electrical energy requirements.

If a less efficient lighting system were preferred, the photovoltaic system design would remain the same (and the cost of solar-generated electricity would also be the same) but the fraction of the load served by solar energy would be reduced.

Figure 5.4.2-B shows the postulated specifications of the photovoltaic panels for the pragmatic retrofit design. The photovoltaic panels are inclined at 45° from horizontal and are installed in lengthwise rows (facing south), twelve in a row, so that each row is 96 feet in length, with the height of top of the rows being ~26 in. above the base. The reflector panels are

Figure 5.4.2-B

Array Specifications

Photovoltaic Panels:

Length	8 ft.
Width	3 ft.
Panel Efficiency	0.11
Max. Output (Std. Test Cond.)	245 Watts
(Reflector augmented)	356 Watts
Weight	80 lbs.
(Including aluminum frames)	

Reflector Panels:

Length	8 ft.
Width	3 ft. 8 in.
Reflectivity	0.75
Weight	45 lbs.

inclined oppositely at 35° from horizontal, facing north. A north-south row spacing of ~5.5 feet is selected to provide eight inches of exposed roof between the bottoms of alternate rows and their reflectors to provide access for installation and maintenance. Available roof area permits a maximum of seventeen rows of panels, or 204 individual panels, to occupy an area 90 feet x 96 feet, with adequate clearnace from the 18-inch parapet on all four sides. The resulting total photovoltaic array area is 4,896 square feet or 455 square meters. Maximum capability of this largest practical configuration is 73 kW at noon during April and August each year. Figures 5.4.2-C and 5.4.2-D illustrate the seasonal and hourly power and daily energy characteristics respectively, for the largest practical retrofit. Figures 5.4.2-E and 5.4.2-F compare these output characteristics with seasonal and hourly building demand and consumption.

The selected configuration of the photovoltaic array is illustrated in Figure 5.4.2-G consisting of seventeen rows of 3 ft. high by 8 ft. long panels, twelve in each row. Panels are connected in series to provide 240 V direct current. Parallel wiring of series strings to a bus in common with rectified 220 V utility power (each circuit protected by a blocking diode) allows full utilization of whatever photovoltaic energy is available, with maximum sharing of load with rectifier output. Maximum photovoltaic current is 260 amperes. Each panel is supported in a light-weight aluminum or steel sheet formed framing strip, as shown in Figure 5.4.2-H. Similar frames are employed for support of the aluminized mylar-covered plywood reflectors, and provision is made for bolting each panel to its structurally associated reflector at the apex, while the bases of each panel and reflector are pinned or bolted to wood or metallic strips fastened to the roof to distribute the loads. Total weight of each panel-reflector combination with required structure for roof attachment is estimated to be ~140 lbs., including wiring; distributed over ~44 square feet of roof area for a total added roof load of $\sim 3.2 \text{ lb./ft.}^2$ or ~28,000 lbs. uniformly distributed over the second floor roof.

Figure 5.4.2-C. Seasonal and Hourly Power - - - -

Figure 8.4.2-D. Maximum Daily Energy Conversion

Figure 5.4.2-E. Power Output - Demand Matching, Cloudless Day

TYPICAL 3,000 m² LIGHT COMMERCIAL BUILDING
LOS ANGELES AREA

Figure 5.4.2-F. Annual Ranges, Daily Consumption and P.V. Supply

Figure 5.4.2-G. Roof-Mounted Photovoltaic Array Configuration

Figure 5.4.2-H. PANEL INSTALLATION DETAIL

The reflector-augmented flat fixed photovoltaic array configuration selected for the pragmatic retrofit design imposes small roof loadings to the existing structure which are smaller than those of the existing mechanical equipment to be relocated. The purpose of this section is to determine the adequacy of the existing roof structure to resist the added stress of array weight and wind loads of flat fixed inclined photovoltaic arrays of 300 to 600 square meters, along with their associated reflector surfaces.

Concentrated load-bearing capacity of the roof is limited by the strength of the 2 x 10 purlins spanning 24 feet between girders and spaced on 24-inch centers. For maximum allowable stress in the purlins (about 1/5 of elastic limit stress), the minimum load (at the center of the span) would be about 400 lbs. Assuming conservatively that a concentrated load would be resisted by bending moment of single purlin loaded at midspan by a concentrated load P lbs.:

$$M = \frac{PL}{4} = 72 \underline{P} \text{ inch lbs, for 24 ft. span.} \quad (\text{Eq. 1})$$

The douglas fir purlins have a rupture modulus (MC/I) of 10,500 lb./in.² and an elastic limit fiber stress of 6,500 lb./in.² Using a design limit stress of 20% of the latter figure (1,300 lb./in.²),

$$S = 1300 = \frac{MC}{I} = \frac{72 \underline{P}c}{I} \quad (\text{Eq. 2})$$

Actual dimensions of the 2" x 10" purlins are $b = 1.5$ inches and $h = 9.5$ inches, so the cross section moment of inertia $I = 107$ in.⁴ Distance from the neutral axis to the outer fiber $c = 4.75$ inches, so $I/c = 22.6$ in.³ Substitution of these values in Equation 2 gives the desired value of P which results in the design limit stress:

$$\underline{P} = \frac{(1300)(22.6)}{(72)} = 408 \text{ lb.} \quad (\text{Eq. 3})$$

It is emphasized that the location of the concentrated load application P at the weakest point of the roof purlin, and the assumption that only one purlin resists the entire load, leads to significant conservatism in calculating concentrated load bearing capacity of the roof. Deflection of a single purlin under load would spread the load to adjacent purlins to some extent. Also, the limit load would still be only one-fifth of the elastic limit load and one-eighth of the ultimate load bearing capacity of the roof at its weakest point.

Uniformly distributed roof loads are similarly limited by the strength of the roof purlins, and may be calculated by substituting in Equation 2 the proper value of the bending moment (M) for uniform span-wise loading from:

$$M = \frac{WL^2}{8} = 10,368 W \text{ inch lb.}, \quad (\text{Eq. 4})$$

where W is expressed in pounds per inch, or

$$M = 864 W \text{ foot lb.}, \quad (\text{Eq. 4a})$$

where W is expressed in pounds per foot.

Since the purlins are on 24-inch centers, each purlin under a uniformly distributed roof loading of $w \text{ lb./ft.}^2$ is loaded at $W = 2w \text{ lbs./ft.}$ Therefore the uniform roof load $w \text{ (lb./ft.}^2\text{)}$ which results in the design limit stress of $1,300 \text{ lb./in.}^2$ in the purlin outer fiber is calculated from Equation 2:

$$S = 1300 = \frac{Mc}{I} = \frac{1728 w}{I/c} = 76.5 w$$

and

$$w = \frac{1300}{76.5} = 17 \text{ lb/ft}^2$$

The weight of the roof covering is not greater than 2 lb./ft.², so an additional uniform loading of 15 lb./ft.² would not exceed the design limit stress (one-fifth of elastic limit and one-eighth of ultimate).

Wind loading on the postulated array configuration is minimized by the low profile (less than 30 inches above the existing roof surface). For the 45° inclination, the horizontal and vertical components of wind force in the worst case of wind from the south at right angles to the array length are given by:

$$F/A \text{ (lb/ft}^2\text{)} = \frac{\rho V^2}{4}$$

Each component, resisted by a horizontal or vertical force, is one-half that of a vertical surface with the same area, and is determined by air density (ρ , slugs/ft.³) and velocity (V , FPS). For standard sea level air density of 0.002378 slugs per ft.³, the resulting horizontal and vertical forces array surface as a function of wind velocity are:

$V =$	25	50	75	100	125	MPH
$F/A =$	0.8	3.2	7.2	12.8	20	lb./ft. ²

In reality, only the first row of the array system feels the full force of the wind, which tends to be deflected upward, and subsequent rows downwind experience less wind pressure. Also, in high wind conditions, there tends to be some reduction from the pressure forces shown above due to upward deflection of the air from the building itself. The following sketch shows qualitatively the magnitude of such wind pressure reduction, along with the sheltering effect of the 18-inch parapet (next page).

5.4.3 Cost Analysis

A cost breakdown of the photovoltaic system is given in Table 5.4.3-A. The unit cost of the array modules, delivered on-site, is taken as \$0.50 per peak watt or \$55 per square meter, in accordance with ERDA 1985 goals. This works out to \$122.63 per module or \$25,017 for the 204 modules used. Other components and installation labor are estimated according to current costs. Net retrofit costs exclude replacement of air conditioning equipment, since this is required in any case.

Energy costs are calculated by two methods. Using the required JPL/ERDA/EPRI fixed charge ratio method with the recommended levelized fixed charge ratio of 0.1483, the levelized annual cost of ownership of the photovoltaic system is \$6774 (0.1483 times \$45,677) and the levelized cost of energy is 62.1 mills/kWh (\$6774 divided by 109,000 kWh of useful energy produced). If electricity is expected to escalate in cost at an annual rate of 5%, the initial cost of utility electricity at which installation of this system becomes cost-effective

Figure 5.4.3-A

Cost Estimate Summary

Photovoltaic System - \$45,677

P.V. System, Materials - \$32,337

204 Array Modules @ \$122.63	\$25,017
204 Reflector Panels @ \$30	6,120
2" x 2" Wood Sleepers, 2,500 ft	250
#10 AWG Insul. Conductor, 1,700 ft	100
#500 MCM Insul. Conductor, 100 ft	300
Electrical Conduit, Fuse and Switch Box	450
Misc. Hardware	100

P.V. System, Installation - \$8,740

Install Sleepers and Flashing	\$ 2,200
Install Panels	4,740
Connect Wiring	1,800
Supplemental Power - 90 kW rectifier	4,600

New Lighting System - \$10,000

Materials - \$6,300

150 D.C. H.F. Fixtures, Suspended	\$ 6,000
#10 AWG Insul. Conductor, 3,000 ft	200
#6 AWG Insul. Conductor, 600 ft	100

Labor - \$3,700

Demolition	\$ 1,300
Installation	2,400

Add Skylights - \$2,000

4 Skylights, Subcontract	\$ 2,000
------------------------------------	----------

Figure 5.4.3-A

(Continued)

Replace Air Conditioning Equipment - \$26,400

5 Heat Pumps, 10 Ton Each	\$20,000
5 D.C. Motors, 15 HP.	4,000
Installation Labor	2,400

Total Retrofit Cost - \$84,077

Net Retrofit Cost - \$57,677 (excluding air conditioning)

Photovoltaic System Cost: \$45,677

Solar Electricity to Load: 109,000 kWh/year

Present Cost of Utility Electricity: 37.8 mills/kWh

Present Value of Solar Electricity: \$82,280*

Cost of Electricity: 62.1 mills/kWh levelized*
(Investor Owned 35.0 mills/kWh initial year*
Utility)

*See Section 5.3.8 for discussion of calculation methodology.

is 35.0 mills/kWh. These costs are virtually identical to corresponding cost estimates for the shopping center, and thus confirm the conclusion that retrofit installations can provide energy at costs comparable to new installations.

Using the present value method as described in Section 5.3.8, and taking the present average utility cost of 37.8 mills/kWh as the incremental cost, the present value of the 109,000 kWh of useful generation is estimated at \$82,280, again assuming that the after-tax cost of capital to the building owner is 8% and electrical rates escalate at 5% per year. The use of the average rather than the incremental electrical rate in this calculation results in an over-estimate of the present value of the solar electricity produced, but the over-estimate is insignificant under the present tariff applicable to this building. However, because of the large fraction of the total energy requirement produced by the photovoltaic system and the consequent increase in peak to average demand ratio seen by the utility, a different tariff schedule might be applied if such installations became prevalent.

These cost comparisons are clearly more favorable to the photovoltaic system than were the comparable comparisons for the shopping center, because this building is much smaller and therefore is charged a much higher rate by the utility. Using the variable charge ratio method, the initial competitive cost of energy from the photovoltaic system (35.0 mills/kWh) is slightly less than the present cost of utility electricity (37.8 mills/kWh) and therefore this installation would be advantageous to the utility if photovoltaic arrays could be obtained presently at \$0.50 per peak watt. Using the present value method which, as discussed in Section 5.3.8, more accurately described the cost comparison from the viewpoint of the building owner, the cost of the photovoltaic system is only 56% of the present value of the reduction in utility costs attributable to the photovoltaic system, and therefore the installation would be a bargain if arrays could be obtained for \$0.50 per peak watt. In fact, on this basis the installation will save money for the building owner if array costs are less than \$1.22 per peak watt.

As in all other cost comparisons in this report, maintenance and replacement costs for the photovoltaic array have not been included in the cost analysis because no data exists by which a valid estimate can be made. These costs will be small if array modules can be constructed to have a useful life of 30 years with high reliability, as we were directed to assume at the inception of this study, and therefore our conclusions are not prejudiced by neglecting these costs. In our opinion, if these conditions cannot be met on-site applications of photovoltaic systems will not achieve public acceptance regardless of the initial cost of arrays.

5.5 CONCLUSIONS

5.5.1 Shopping Center

1. There are a number of significant opportunities for energy conservation in the design of architectural, mechanical, and electrical systems, which are enhanced by the use of roof-mounted photovoltaic systems. In evaluating the economics of photovoltaic application to a shopping center, it is proper to credit some of the value of these energy-saving innovations to the photovoltaic system.

2. The annual energy produced by the photovoltaic system is about one-third to one-fifth of the total reduction in utility energy consumption made possible by the use of photovoltaics plus the energy-conserving mechanical and electrical system designs made possible in part by the photovoltaic system's beneficial architectural impacts.

3. A conventionally-designed shopping center of 23,200 square meters (250,000 square feet) with vapor compression refrigeration air conditioning, gas or oil heating, and typical fluorescent and incandescent lighting would consume about 13,500,000 kWh annually plus about 42,000 therms of gas or oil for domestic water heating plus space heating. An unconventional design of a San Fernando Valley shopping center in 1985 could reduce gas or oil consumption by a factor of at least ten with solar thermal collectors, while at the same time reducing annual purchase of utility (A.C.) energy to about 2,740,000 kWh.

4. The solar-heated absorption refrigeration machinery could avoid the consumption of 6,000,000 kWh annually, with or without the presence of a roof-mounted photovoltaic system. However, its size and initial cost would be twice as great in the absence of the beneficial architectural and electric systems impacts of the roof-mounted photovoltaic system, require twice the solar thermal collection area, and exhibit only half the return on investment. This characteristic is due partly to reduced roof heat gain, partly to shaded skylighting, and partly to reduced internal lighting and motor loads by the use of D.C. equipment.

5. Development of a four-stage absorption chiller with a performance coefficient of 2.5 appears to be technically and economically feasible for large units, and requires solar thermal collectors operating at maximum temperature of 400°F (with auxiliary heating when required). The reduction in solar thermal collector area required for a fixed design refrigeration load would more than offset the higher cost of the four-stage chiller, and the total first cost of installed hardware would be quickly paid back by electric energy savings. The parallel development of high COP absorption chillers and of high temperature solar collectors should be considered for funding by ERDA.

6. Use of direct current for the high frequency lighting system permits 15 to 35% reduction in energy for the same lighting intensity by 60 Hz A.C. power, at small additional cost. Reduction to artificial lighting intensity by careful architectural use of natural lighting results in further energy savings, made possible by integration of roof-mounted photovoltaic and reflector arrays into the building structure. It is estimated that the combined effect of higher efficiency and lowered requirement will result in electric energy savings of about 2,000,000 kWh annually in lighting system operations.

7. Use of direct current for power systems makes possible additional electric energy savings by virtue of high efficiency in the speed control of electric motors in the 1 to 40 HP size range. Fluid pumps and air conditioning systems can benefit significantly from this characteristic in design for a wide operating range to meet large variability in requirements. It is estimated that energy requirement for power systems can be reduced by 1,500,000 kWh annually by

reduced loads and more efficient part-load operation. A significant credit for motor load reduction and efficient part-load operation must be given to the characteristics of the marriage of photovoltaic systems to the shopping center.

8. Flat, fixed, convection-cooled silicon cell arrays, augmented by fixing reflecting surfaces are preferred over tracking and concentrating arrays for shopping center applications, if array costs can be reduced to the order of \$50 per square meter.

9. Smaller photovoltaic systems could prove to be economically attractive to a greater degree than the size considered for the shopping center model.

10. The largest economically justifiable storage system is one of 25,000 ampere hours at 240 volts (about 6000 kWh), corresponding to the daily energy average requirement of the shopping center during the hours of darkness, and also the average maximum (summer) excess of daily capability over daylight energy requirement of the shopping center, for the largest photovoltaic system considered (2 MWE).

11. For reflector-augmented photovoltaic arrays, photovoltaic array space is about 58.3% of roof area for 7500 square meters of array. Maximum power at 10% efficiency is 139 watts per square meter of array around 27 April, and maximum daily energy collected (at 10% efficiency) is 1 kWh per square meter around 10 April.

12. Based upon roof area dedicated to arrays and reflectors, the configuration selected will deliver a maximum power of 100 watts per square meter and a maximum daily energy of 718 watt hours per square meter of (dedicated) roof area ($10,445 \text{ m}^2$). These figures may be compared to the projected requirement of 42 watts per square meter of floor area (peak demand) and 600 WH/m^2 daily consumption.

13. The model shopping center has a floor area of 23,200 square meters and a roof area of 18,500 square meters. If 80% of roof area is available for photovoltaic arrays and reflectors (allowing space for thermal collectors and mechanical equipment) the maximum roof-mounted photovoltaic output would be

8,600 kWh per day and 1.2 MWE. For a system of this size 1,000 kWh storage capacity would be required (about 4,000 ampere hours at 240 volts), costing about \$55,000, and the parking area covering could be eliminated.

14. A 1 MWE system without storage would result in a cost difference of only \$1,057,000 when compared to a similar conventional shopping center. The worth of annual energy savings would be \$188,000. A 2 MWE system, employing parking coverings and electric storage, would produce slightly larger energy savings but would entail a cost increment of \$3,120,000. Therefore the no-storage system is preferred.

5.5.2 Retrofit Applications

1. Although retrofit installations will usually involve more constraints and require more design compromises than installations in new buildings, they can be equally cost-effective. The retrofit market (in commercial buildings, at least) should be considered as open to photovoltaic systems whenever they become cost-effective in new construction.

2. The most likely candidates for initial installations of photovoltaic systems are smaller, low-rise buildings with open floor plans, occupied predominantly during normal office hours.

3. Careful attention to energy conservation measures improves the cost-effectiveness of photovoltaic systems in retrofit as well as new applications.

4. No-storage systems are likely to be preferred to systems involving storage to an even greater extent in retrofit applications because of the difficulty of meeting building and fire code requirements for battery storage rooms. Because the load in typical commercial buildings is nearly constant diurnally and seasonally, no-storage systems can provide a major fraction of electrical energy requirements.

5. Structural designs typical of low-cost commercial buildings can sustain the additional loads imposed by roof-mounted photovoltaic arrays provided that the load is properly distributed over the roof area.

6. Distribution of electrical energy in the form of 240 volts DC to building lighting and space conditioning loads is practical, cost-effective, and efficient.

7. Of all of the applications examined during this study, the application to commercial buildings appears to be most cost-effective if low cost non-concentrating arrays become available. This conclusion follows the fact that the load profiles of commercial buildings generally match the generation profile of photovoltaic arrays to a greater degree than the general utility load, and to a much greater degree than the residential load.

8. Application of concentrating arrays to commercial buildings is restricted by the lower packing factor (ratio of array aperture area to horizontal area required) characteristic of tracking arrays, and by the structural problems attendant upon the imposition of concentrated loads on the building roof.

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6.0 SIMPLIFIED DESIGN METHOD FOR ON-SITE APPLICATIONS

Using computer simulations to check our formulas, we have developed methods of estimating solar fractions of an on-site load from monthly average insolation data. Section 6.1 presents methods of estimating insolation for various array types for all parts of the continental United States. Loads are briefly discussed in Section 6.2.

Solar fraction formulas suitable for hand calculation from available monthly insolation data are given in Section 6.3. These formulas lead to design methods for sizing on-site solar power systems with utility backup.

The following section contains comparisons of solar fractions from computer simulations to those predicted with the formulas. The magnitude of the errors in prediction (average 8%, maximum 15%) due to the formulas compares quite well to the year-to-year variability in monthly insolation. The remaining sections of this chapter contain a summary of the design method and our recommendations for sizing on-site systems.

6.1 INSOLATION AND ARRAY OUTPUT ESTIMATES

6.1.1 Insolation Potential

The major variables influencing availability of solar energy are few in number: (1) geographic latitude, (2) season of the year, (3) hour of the day and (4) obscurement. The first three are unambiguous but interrelated and are treated below and in figure 6.1.1A. The fourth is important and is treated probabilistically for meteorological obscurement (except for the effects of atmospheric absorption and scattering which are accounted for in figure 6.1.1A). Cloud, haze, smoke and dust obscurement are treated separately in a statistical fashion for all parts of the continental United States (figures 6.1.1E 1-12). Obscurement by local topography or adjacent building structures is not considered.

Figure 6.1.1A

SOLAR FLUX DENSITY FOR CLOUDLESS CONDITIONS

The insolation on a cloudless day depends principally on the zenith angle of the sun, which is determined by the latitude, season and time of day. This angle may be calculated from the formula 6.1.1-1.

$$\cos \theta_z = \cos \lambda \cos \delta \cos \omega + \sin \lambda \sin \delta \quad (6.1.1-1)$$

Here λ is the latitude angle, δ is the solar declination angle, which may be calculated as

$$\delta = 23.45 \sin \left[360 \cdot \frac{284 + n}{365} \right] \quad (6.1.1-2)$$

n is the day of the year, with January 1 being day number one and ω is the hour angle (0 at noon, $+15^\circ$ at 1:00 p.m., etc.). The sun's zenith angle is the angle between the solar beam and the zenith (the complement of the solar elevation angle). Figure 6.1.1A shows clear day beam and diffuse solar intensity, as well as total insolation for a tracking and a horizontal surface, as a function of the zenith angle. Clear day direct insolation was calculated according to Hottel's 23 kilometer large model for one kilometer elevation (Solar Energy Vol. 18, No. 2). Diffuse insolation was estimated from Liu and Jordan's relation, modified to apply to instantaneous rather than daily insolation.

With this figure it is not difficult to estimate the clear day solar flux on a south facing surface in the northern hemisphere at any time of the day and year. For example, on May 2, the 123rd day of the year, the declination angle is 15.5° . At 2:00 p.m. at a latitude of 35°N , the cosine of the zenith angle is

$$\cos \theta_z = (.819)(.964)(.866) + (.574)(.267) = .837$$

For this cosine, the beam and diffuse components of insolation are .938 and .090 kilowatts per square meter, respectively. For a fixed array tilted south at an angle s from horizontal, the cosine of the angle of incidence of the solar beam is

$$\cos \theta_t = \cos (\lambda - s) \cos \delta \cos \omega + \sin (\lambda - s) \sin \delta, \quad (6.1.1-3)$$

and the total incident sunlight can be estimated by

$$\phi = DN \cdot \cos \theta_T + DF$$

In the example, for a panel tilted at 50° , $\cos \theta_T = .737$ and $\phi = .781 \text{ kW/m}^2$.

It should be added that clear day insolation is affected by elevation, water vapor, atmospheric aerosols and the variation of the sun-earth distance over the year. These are not taken into account in Figure 6.1.1A.

For design calculations, estimates are needed of clear day solar flux at noon, of the day length and of the amount of energy incident on an array month by month and over the year. Figure 6.1.1B shows the insolation at noon at the middle of each month as a function of latitude for various array types, based on the solar flux shown in Figure 6.1.1A.

The reflector-array configuration used for these calculations consists of a south-facing array tilted at ten degrees more than the latitude angle and a north facing reflector with specular reflectance .75, which makes an angle of 100° with the array. Array and reflector are of equal height, and unequal illumination of cells and end losses are neglected (the array is assumed to be long in the east-west direction). The formulas for calculating insolation on this type of array-reflector configuration are derived in Section 6.1.2. Design studies for the shopping center located at 34° latitude showed that this choice of tilt angles was optimal for a roof mounted array for an array to reflector price ratio of ten to one.

When the sun sets, the zenith angle is ninety degrees, so the sunset hour (half the day length) is

$$h_s = \frac{1}{15} \arccos (-\tan \lambda \tan \delta). \quad (6.1.1-5)$$

Figure 6.1.1C shows the sunset hour for the middle of each month for various latitudes.

The choice of array type depends on a comparison of the array output potential to cost. Figure 6.1.1D compares the potential annual insolation (based on

Figure 6.1.1 B1

SOLAR FLUX AT NOON - CLOUDLESS DAY
AT MIDPOINT OF MONTH

TRACKING ARRAY

HORIZONTAL ARRAY

Figure 6.1.1 B2

SOLAR FLUX AT NOON - CLOUDLESS DAY AT MIDPOINT OF MONTH

INCLINED ARRAY (TILTED AT LATITUDE ANGLE)

ARRAY WITH REFLECTORS (SEE TEXT)

Figure 6.1.1.B3

CLEAR DAY SOLAR FLUX AT NOON
ANNUAL AVERAGE

Figure 6.1.1C

SUNSET HOUR
AT MIDPOINT OF MONTH
UNITED STATES LATITUDES

Figure 6.1.1D.
POTENTIAL INSOLATION
(Year of Cloudless Days)

cloudless days) on various types of arrays for different U. S. latitudes. The advantage of nonhorizontal arrays increases with latitude. The following points should be noted, however. First, concentrating arrays will not collect diffuse insolation, and so will receive about 14% less insolation than shown. Second, for arrays with reflectors, the roof space they occupy and the size of the reflector must be considered. For example, the sunlight incident on a series of reflectorized arrays per unit of horizontal area is less than that on a horizontal array. Factors for converting insolation per unit array area to insolation per unit roof area for the configurations described above are given below. Also shown are ratios of reflector area to array area.

Latitude	<u>25°</u>	<u>30°</u>	<u>35°</u>	<u>40°</u>	<u>45°</u>	<u>50°</u>
<u>Insolation per unit roof area</u> <u>Insolation per unit array area</u>	.718	.653	.582	.508	.429	.347
<u>Reflector area</u> <u>Array area</u>	.811	1.000	1.233	1.532	1.938	2.532

Third, a series of tracking arrays which is not separated will lose insolation due to shadowing. This problem is discussed in Section 6.1.3.

The effect of weather at different locations can be estimated by applying obscurement factors to monthly cloudless day insolation estimates. Figures 6.1.1E 1-12 contain obscurement maps for each month for the continental United States. The graphs below the maps give cloudless day insolation as a function of latitude for several array types. The insolation at a particular location can be obtained by multiplying the cloudless day insolation by the meteorological obscurement factor. The maps in Figures 6.1.1 F-H, which show yearly incident solar energy on horizontal, inclined and tracking surfaces, were derived from the preceding figures. Data on monthly average horizontal insolation is also available from the National Weather Service for many U.S. locations.

Figure 6.1.1 E1
AVERAGES DURING JANUARY

Figure 6.1.1 E2
AVERAGES DURING FEBRUARY

Figure 6.1.1 E3.

AVERAGES DURING MARCH

Figure 6.1.1 E4

APRIL

Figure 6.1.1 E5

MAY

Figure 6.1.1 E6

JUNE

Figure 6.1.1 E7

JULY

Figure 6.1.1 E8

AUGUST

Figure 6.1.1 E9

Figure 6.1.1 E10

OCTOBER

Figure 6.1.1 Ell

Figure 6.1.1 E12

ANNUAL INSOLATION, kWh/M^2 , HORIZONTAL SURFACE

Figure 6.1.1 G

ANNUAL INSOLATION, kWh/M^2 , INCLINED SURFACE
(INCLINATION FROM HORIZONTAL = LATITUDE)

ANNUAL INSOLATION, kWh/M^2 , TRACKING SURFACE

Figure 6.1.1 H

6.1.2 Arrays with Reflectors - Formulas

The use of a large south-facing tilted solar array creates problems of structural integration and/or support. On a flat roof it is less costly and more convenient to put up a series of tilted arrays. However, one array then can shadow another, and so the arrays should be spaced to avoid this. Putting reflectors between the arrays permits the utilization of some of the energy which falls between the collectors. This makes up for shadowing and increases the output per unit array area. This section contains formulas for the calculation of the solar flux on a series of long south facing arrays with north facing reflectors.

6.1.2.1 Array Reflector Configuration

The shopping center design has a series of rows of long arrays tilted to the south facing reflectors tilted to the north.

Figure 6.1.2A: Array-Reflector Configuration

The symbols used in Figure 6.1.2A are:

- A width of the arrays
- R width of the reflectors
- D width of array-reflector row
- i array tilt angle
- β reflector tilt angle.

The geometric relationships between the widths and the angles are

$$A/D = \sin \beta / \sin(i + \beta) \quad (6.1.2-1)$$

$$R/D = \sin i / \sin(i + \beta). \quad (6.1.2-2)$$

6.1.2.2 Sun Position and Intensity of Beam Radiation

For a reflector system the sun's position is most easily described in terms of the shadow angle ϵ , the elevation of the projection of the sun in

the meridian plane, and the projection angle α , the angle of projection of the sun onto the meridian plane. These angles are shown in Figure 6.1.2B, which

Figure 6.1.2B. A South-Facing Surface and the Angles ϵ and α

also shows a surface tilted southward at angle s . The solar insolation on the surface is found by multiplying direct normal insolation by $\cos\theta_T$, where θ_T is the angle between the normal to the surface and the sun's rays. From Figure 6.1.2B, $\cos\theta_T = \cos\alpha \cos(90-\epsilon-s)$.

$$\cos\theta_T = \cos\alpha \sin(\epsilon+s),$$

where $\epsilon+s$ is the angle between the projection of the sun's rays in the meridian plane and the surface.

Formulas for α and ϵ are

$$\sin \alpha = \sin \omega \cos \delta \quad (6.1.2-3)$$

and

$$\epsilon = 90 - \lambda + \arctan \frac{\tan \delta}{\cos \omega} . \quad (6.1.2-4)$$

Here ω is the hour angle, λ is the latitude angle, and δ is the declination angle. Figure 6.1.2C shows the derivation of these formulas. The declination may be calculated from Formula 6.1.1-1.

6.1.2.3 Insolation on an Array with Reflectors

For the array configuration shown in Figure 6.1.2A the intensity of direct illumination is $DN \cdot (F_D + F_R) = DN \cdot F_D + DN \cdot F_R$, where DN is direct normal insolation, $DN \cdot F_D$ is the sunlight directly incident on the surface, and $DN \cdot F_R$ is the reflected sunlight incident on the surface. Figures 6.1.2 D-F illustrate the derivation of formulas for calculating F_D and F_R . In the figures projections of sun rays and reflected rays in the meridian plane are labeled SP and RP , respectively. The letter ρ denotes the specular reflectance of the reflector.

$$0 < \epsilon < 180 - i$$

$$F_D = \sin(\epsilon + i) \cos \alpha$$

Figure 6.1.2D. Direct Illumination of the Array

Figure 6.1.2C. Calculation of ε and α

To find the sunlight which falls directly on the surface, the beam component of insolation is multiplied by the cosine of the incidence angle, which was shown above to be the product of the cosine of the projection angle and the sine of the angle between the surface and the projection of the sunlight on the meridian plane.

Thus, for sunlight falling directly on the array,

$$F_D = \sin(\epsilon + i) \cos \alpha, \quad 0 < \epsilon < 180 - i \quad (6.1.2-5)$$

(See Figure 6.1.2D)

The factor for reflected light depends on the relation of the shadow angle ϵ to the reflector tilt angle β . The possibilities when the array does not shade the reflector, i.e. $\epsilon < 180 - i$, are illustrated in Figure 6.1.2E. Part of the array is shadowed if $\epsilon < \beta$. In this case the insolation on the array is reduced proportionally to the part of the surface which is shadowed. In Figure 6.1.2E1

$$\begin{aligned} F_R &= - \frac{K}{A} \sin(\epsilon + i) \cos \alpha \\ &= - \frac{K}{R} \frac{R}{A} \sin(\epsilon + i) \cos \alpha \\ &= - \frac{\sin(\beta - \epsilon)}{\sin(\epsilon + i)} \cdot \frac{\sin i}{\sin \beta} \sin(\epsilon + i) \cos \alpha \\ F_R &= \sin(\epsilon - \beta) \cdot \frac{\sin i}{\sin \beta} \cos \alpha, \quad \text{if } 0 < \epsilon < 180 - i, \quad 0 < \epsilon < \beta \quad (6.1.2-6-1) \end{aligned}$$

When the shadow angle is greater than the array tilt and the reflected rays go downward, only part of the array gets reflected light, but all light from the reflector is incident on that part of the array. (See Figure 6.1.2E2.) The reflected light relative to the whole array area is

$$F_R = \rho \frac{R}{A} \sin(\epsilon - \beta) \cos \alpha$$

6.1.2E1. Shadowing

$$0 < \epsilon < \beta$$

$$F_R = \frac{\sin i'}{\sin \beta} \sin(\epsilon - \beta) \cos \alpha$$

6.1.2E2. Reflection to Part of Array

$$\beta < \epsilon < 2\beta$$

$$F_R = \rho \frac{\sin i'}{\sin \beta} \sin(\epsilon - \beta) \cos \alpha$$

6.1.2E3. Reflection to Whole Array

$$2\beta < \epsilon < 2\beta + i' \text{ and } 90 + \beta$$

$$F_R = \rho \sin(2\beta + i' - \epsilon) \cos \alpha$$

6.1.2E4. Light Reflected away from Array

$$\epsilon > 2\beta + i', F_R = 0$$

6.1.2E5. Light Reflected away from Array

$$\epsilon > 90 + \beta, F_R = 0$$

6.1.2.E. REFLECTED LIGHT IF $0 < \epsilon < 180 - i'$

$$F_R = \rho \frac{\sin i}{\sin \beta} \sin(\epsilon - \beta) \cos \alpha \text{ if } 0 < \epsilon < 180 - i, \beta < \epsilon < 2\beta \quad (6.1.2-6-2)$$

When the reflected light goes upwards, all of the array gets reflected light uniformly. The angle between the projected reflected rays and the array surface is $2\beta + i - \epsilon$, as shown in Figure 6.1.2E3. Thus

$$F_R = \rho \sin(2\beta + i - \epsilon) \cos \alpha \text{ if } 0 < \epsilon < 180 - i, \quad (6.1.2-6-3)$$

$$2\beta < \epsilon < 2\beta + i - \epsilon \text{ and } \epsilon < 90 + \beta$$

If the shadow angle ϵ exceeds $2\beta + i$ or $90 + \beta$, the reflected light does not reach the array. (See Figures 6.1.2E4 and 6.1.2E5.) Consequently $F_R = 0$ in these cases.

It is possible that some reflected light reaches the array when the sun is behind it. Then part of the reflector is shadowed by the array. The reflected light may go downwards or upwards, as shown in Figures 6.1.2F1 and F2. In Figure 6.1.2F1, the portion K of the array sees reflected sunlight, so

$$\begin{aligned} F_R &= \rho \frac{K}{A} \sin(2\beta + i - \epsilon) \cos \alpha \\ &= \rho \left(1 - \frac{M}{A} - \frac{S}{A}\right) \sin(2\beta + i - \epsilon) \cos \alpha \\ &= \rho \left(1 - \frac{M}{L} \frac{L}{A} - \frac{S}{T} \frac{T}{A}\right) \sin(2\beta + i - \epsilon) \cos \alpha \\ &= \rho \left(1 - \frac{\sin(2\beta - \epsilon)}{\sin(2\beta + i - \epsilon)} \frac{\sin(\beta + i)}{\sin \beta} - \frac{\sin(\epsilon - \beta)}{\sin(2\beta + i - \epsilon)} \frac{\sin(\epsilon + i - 180)}{\sin(\epsilon - \beta)}\right) \\ &\quad \sin(2\beta + i - \epsilon) \cos \alpha \\ &= \rho \left(\sin(2\beta + i - \epsilon) - \sin(2\beta - \epsilon) \frac{\sin(\beta + i)}{\sin \beta} + \sin(\epsilon + i)\right) \cos \alpha, \end{aligned}$$

$$2\beta < \epsilon < 2\beta + \epsilon \text{ and } 90 + \beta$$

Figure 6.1.2F. REFLECTED LIGHT IF SUN IS BEHIND ARRAY,
 $180 - i < \epsilon < 180$

$$F_R = \rho \frac{\sin(\beta + \iota)}{\sin \beta} \sin \epsilon \cos \alpha \text{ if } 180 - \iota < \epsilon < 180, \beta < \epsilon < 2\beta \quad (6.1.2-7-1)$$

For the case illustrated in Figure 6.1.2F2, the reflection factor F_R is

$$\begin{aligned} F_R &= \rho K/A \sin(2\beta + \iota - \epsilon) \cos \alpha \\ &= \rho K/M A \sin(2\beta + \iota - \epsilon) \cos \alpha \\ &= \rho \frac{\sin(2(\epsilon - \beta))}{\sin(2\beta + \iota - \epsilon)} \cdot \frac{\sin(\beta + \iota)}{\sin(\epsilon - \beta)} \sin(2\beta + \iota - \epsilon) \cos \alpha \\ &= \rho \frac{2 \sin(\epsilon - \beta) \cos(\epsilon - \beta) \sin(\beta + \iota)}{\sin(\epsilon - \beta)} \cos \alpha \\ F_R &= 2\rho \sin(90 + \beta - \epsilon) \sin(\beta + \iota) \cos \alpha, \text{ if } 180 - \iota < \epsilon < 180 \quad (6.1.2-7-2) \\ &\quad 2\beta < \beta < 2\beta + \iota \text{ and } 90 + \beta \end{aligned}$$

Again, if the shadow angle exceeds $2\beta + \iota$ or $90 + \beta$, the reflected light does not reach the array and $F_R = 0$.

Solar cells connected in series produce electricity proportional to the insolation of the most weakly illuminated cell in the string. If the series strings in the array are oriented horizontally the effect of uneven direct illumination is small. However, if the series strings go from the top to the bottom of the array, the factor F_R should be reduced in cases E1, E2, F1 and F2. In the case of shading, E1, $F_R = -F_D$, and there is no output from the cells. In the other three cases $F_R = 0$, and there is no gain due to reflection.

6.1.2.4 Treatment of Diffuse Isolation

The distribution of diffuse solar radiation in the sky is dependent on weather conditions. On a clear day diffuse radiation is concentrated within a few degrees of the sun, but on a day when the sky is completely overcast it is nearly uniformly distributed. Moving cloud cover can produce very uneven and varying distributions.

For this calculation, diffuse radiation can be assumed uniformly distributed in the sky. In this case, the diffuse sunlight incident on an array with reflector is calculated as follows.

Diffuse insolation directly on the array is $F_1 \cdot DF$, where

$$F_1 = .5 \left(1 + \frac{\sin (\beta + i) - \sin i}{\sin \beta} \right)$$

Diffuse insolation reflected specularly to the array is $F_2 \cdot DF$, with

$$F_2 = \frac{\rho}{4} (1 - \cos (\beta + i)) \left[\frac{\sin i + \sin (\beta + i) - \sin \beta}{\sin \beta} \right] .$$

For $\rho = .75$, $i = 45^\circ$, and $\beta = 35^\circ$, $F_1 + F_2 = 1.04$.

6.1.3 Shadowing of Tracking Arrays

When tracking arrays are placed closely together, part of their potential output is lost due to shadowing. To simplify the analysis of this problem, a field of single axis tracking arrays, with their axes parallel to the earth's axis, will be considered. Such arrays have an insolation potential which is 96% of the potential of two axis tracking arrays. We will briefly discuss the separation of a series of east-west rows of such arrays, and the effect of east-west spacing on insolation potential.

Figure 6.1.3A illustrates the north-south separation of rows of solar axis tracking arrays. Their axes are inclined at an angle equal to the latitude angle, and so are parallel to the line joining the poles. If no shadowing is to occur on noon of December 21st, the shadow angle ϵ is $90 - \lambda + \delta$ or $90 - \lambda - 23.45$ degrees. The corresponding ratio of array length to the separation between arrays is shown in the figure. Some shadowing would still occur during the winter at times other than noon, but the effect on total insolation would be small.

Figure 6.1.3A

North-South Separation
Polar Axis Tracking Arrays

λ	25°	30°	35°	40°	45°	50°
D/A	1.383	1.541	1.753	2.052	2.498	3.221

($\epsilon = 90 - \lambda - 23.45$)

In the following schematic, which views adjacent arrays from the direction of Polaris (looking down parallel to the tracking axis) the spacing of axes in the east-west direction is defined in terms of multiples of the array radius about its axis of rotation. The sun angle γ is the complement of the hour angle ω . At the moment of unshadowing

$$\sin \gamma = \frac{2r}{d} = \frac{2r}{xr} = \frac{2}{x}, \text{ if } 2 < x < \infty. \quad (6.1.3-1)$$

When the array is partially obscured, the ratio of unshadowed area (ignoring the effect of the declination angle) to array area is

$$\frac{2r - S}{2r} = \frac{x}{2} \sin \gamma, \text{ if } \sin \gamma < \frac{2}{x}. \quad (6.1.3-2)$$

Figure 6.1.3B shows annual insolation potential as a function of x for various latitudes. The upper graph shows insolation on the whole array, while the lower graph shows insolation on unshaded halves of the array. If each half of the array contains one series string of cells, shadowing any cell in the string would substantially reduce the output of the whole string. Diffuse insolation is assumed not to be affected by shadowing.

Figure 6.1.3B

SHADOWING - POLAR AXIS TRACKING ARRAY ANNUAL INSOLATION - YEAR OF
CLOUDLESS DAYS - AS A FUNCTION OF EAST-WEST SEPARATION

6.1.4 Electrical Output

The efficiency of a solar panel varies with cell temperature and insolation, and with the way that panel output voltage is matched with the battery voltage. For cells with a base efficiency of 15% (under 1 kW/m^2 insolation at 28°C), an actual annual panel efficiency of 10% can be achieved, considering a cell packing factor of .74 for flat arrays with round cells, or optical and temperature losses for concentrating arrays. The variation in average ambient temperature over the year results in a corresponding variation of average cell temperature. Since cell efficiency falls .4 to .45% per degree Celsius, a difference of 50°F (28°C) between winter and summer temperatures would result in a twelve percent difference in array efficiency between the hottest and coldest month. About two percent of the winter efficiency gain could be offset by lower winter insolation levels, so monthly efficiencies would range from 9.5 to 10.5% for a ten percent efficient panel.

6.2 LOADS

Shopping centers and commercial buildings are particularly suitable for on-site solar power installations because of their steady daytime electrical demand, particularly for lighting. Because of these load characteristics, the power produced by solar arrays can be used directly whenever it is available, without waste or storage (except for weekends in commercial buildings). A factory or a hospital which had a steady load over 24 hours would also be favorable, but a smaller proportion of the total load could be met directly. In contrast, residential loads are concentrated in the late afternoon and evening, and for single residences, are intermittent, which makes them more expensive to serve with on-site solar systems.

On a seasonal basis the maximum potential output at noon of a solar array may vary little, as in the case of a tracking or inclined array, or may be higher in the summer in the case of a horizontal or reflectorized array. Thus a greater part of loads which are even through the year or which are higher in the summer can be met efficiently by solar power systems.

Although typical electrical demand profiles are shown in Section 5.2, the demand profile for any particular application should be estimated carefully based on the types of electrical equipment on site, the time patterns of building use, climatic factors and, in the case of retrofit, past utility bills.

The simplified load shown below was used to verify the solar fraction formulas given in Section 6.3. It approximates the form of a utility system or commercial building load.

6.3 DERIVATION OF DESIGN METHOD

Estimates of the energy provided by a solar power system can be obtained by considering incident solar energy and the efficiency of the array and power conditioning components. However, the amount of available energy which can be utilized by the load is less because solar output power which exceeds the load and/or storage capacity is dumped, and because solar power is used through storage rather than directly. This section describes formulas for estimating the utilization of energy provided by a solar power system. A system design method is developed based on these formulas for sizing the solar array, or the array and storage.

6.3.1 Systems without Storage

The formula for estimating the amount of solar energy which can be used directly, with no storage, is based on the following two considerations.

- (1) The total amount of solar energy used cannot exceed the daytime load.
- (2) If the solar array is so small that the maximum system power output never exceeds the power demanded by the load, no solar energy will be dumped. For larger arrays some dumping will occur.

We identify the following variables:

L_D	energy demanded by the load per day during daylight hours (kWh/day)
L	energy demanded by the load per day (kWh/day)
I	average solar energy incident on the array per day per unit area (kWh/m ² -day)
S_D	average solar energy per day used directly by the load (kWh/day)
A	array area (m ²)
η	system efficiency for energy used directly
$\phi_{\max}$	clear day noon insolation (kW/m ²)
h_s	sunset hour (half of day length) (hours)
ℓ_D	daytime power demand of load ($L_D = 2 h_s \ell_D$) (kW)

For tilted fixed arrays the local sunset hour may not be the same as the array sunset hour. However the local sunset hour should be used in these calculations for non-concentrating arrays, which receive diffuse insolation. The panel sunset hour should be used for fixed concentrating arrays. The system efficiency η includes an allowance for power conditioning losses as well as array collection efficiency, but not for storage or dumping losses. Clear day noon insolation, sunset hours and average insolation were discussed in Section 6.1 above.

The daytime load ratio, C , solar availability, Z , and direct solar fraction, F_D , are normalizations of the above variables relative to the load. Specifically,

$$C = L_D/L$$

$$Z = \eta I A / L \quad (6.3.1-1)$$

$$F_D = S_D/L$$

The first consideration above tells us that $F_D \leq C$. The second consideration leads to the definition of the maximum array size A_0 for which no solar energy is dumped. This no-storage no-dump array size satisfies the equation

$$\eta \varphi_{\max} A_0 = L_D \quad (6.3.1-2)$$

For the no-dump array size, the solar availability is

$$Z_0 = \eta I A_0 / L$$

It is not difficult to see that

$$Z_0/C = I/2 h_s \varphi_{\max}$$

The denominator represents daily solar energy if insolation were constant at its maximum value. The ratio of average insolation to this value shows the effects of both weather and panel orientation in decreasing solar energy from this hypothetical value.

The formula for the no storage solar fraction is

$$F_D = Z \quad \text{if } Z \leq Z_0,$$

$$F_D = Z_0 + \left[(C - Z_0)^{-1} + (Z - Z_0)^{-1} \right]^{-1} \quad \text{if } Z \geq Z_0. \quad (6.3.1-3)$$

Verification of the formula by computer simulations is described in Section 6.4. This fraction function has the reasonable mathematical properties of being continuous with a continuous derivative at Z_0 , increasing, and asymptotic to C as Z increases. A graph and sample fraction calculation are shown below.

Given

$$L = 100 \text{ kWh/day}$$

$$L_D = 58 \text{ kWh/day}$$

$$h_s = 6 \text{ hours}$$

$$\varphi_{\max} = 1 \text{ kW/m}^2$$

$$I = 5 \text{ kWh/m}^2\text{-day}$$

$$\eta = .1$$

$$A = 100 \text{ m}^2$$

Find F_D

Calculate

$$C = .58$$

$$L_D = 4.83 \text{ kW}$$

$$A_0 = 48.3 \text{ m}^2$$

$$Z_0 = .2415$$

$$Z = .5$$

$$F_D = .2415 + \left[(.3385)^{-1} + (.2585)^{-1} \right]^{-1} = .388$$

$$S_D = 38.8 \text{ kWh/day}$$

Calculate (Cont'd.)

Array Output = 50.0 kWh/day

Dumped = 11.2 kWh/day

Because of the relatively simple form of the solar fraction formula, it is not difficult to determine the array size for which the cost of solar energy is lowest. Let a (\$/m²-day) be the daily cost of the solar system per unit of array area and let c (\$/day) be the total of all fixed system costs which do not depend on the size of the array. Daily costs of system ownership may be found by multiplying the acquisition costs by the fixed charge rate, adding annual recurrent costs and dividing the total by 365. The fixed charge rate converts capital acquisition costs to the annual return that the equipment must earn to cover repayments. According to JPL's "The Cost of Energy for Utility Owned Solar Energy Systems" an appropriate fixed charge rate for a private utility, for a thirty year system lifetime is .1483. The fixed costs could hypothetically buy an additional amount of array of

$$A^* = c/a$$

square meters. This would result in additional availability of

$$Z^* = \eta I A^* / L.$$

If there are no fixed costs, minimum cost of solar energy is obtained with any array not bigger than A_0 . Otherwise, the array for which cost per unit of energy used is minimum can be determined from the formula

$$Z^{MSC} = Z_0 \left[1 + (1 - Z_0/C) (\sqrt{1 + CZ^*/Z_0^2} - 1) \right]. \quad (6.3.1-4)$$

In the previous example,

Given

Array Capital Cost = $\$100/\text{m}^2$

Fixed Capital Costs = $\$1000$

Fixed Charge Ratio = .1483

Recurrent Costs = 0

$a = \$.0406/\text{m}^2\text{-day}$

$c = \$.4063/\text{day}$

Calculate

$A^* = 10 \text{ m}^2$

$Z^* = .05$

$Z^{\text{MSC}} = .272$

$A^{\text{MSC}} = 54.6 \text{ m}^2$

$F_D = .270$

$S_D = 27.0 \text{ kWh/day}$

Array Output = 27.3 kWh/day

Dumped = $.3 \text{ kWh/day}$

Cost of System = $\$2.62/\text{day}$

Cost of Solar Electricity = $\$.096/\text{kWh}$

On-site no-storage systems may be designed according to Equation 6.3.1-4.

The solar fraction formulas in this section and Section 6.3.2 were developed and verified as calculating monthly solar fractions for a nearly level load, and annual fractions for a load which does not vary seasonally. It is not known as yet how best to apply them to the cases of unsteady loads during the day, to daily varying or to seasonally varying loads. Provisionally, for design purposes, we would use annual average values of L , L_D and I as well as h_s , η and ϕ_{max} , then derive the other variables and design array and storage sizes. To find the performance of the system we would calculate monthly solar fractions. For applications with distinctly different weekend loads, such as commercial buildings, separate weekend and weekday calculations would have to be made.

The solar fraction formula can be modified as follows if the load is intermittent rather than level during the day. If the daytime load can be characterized by two levels ℓ_D^1 and ℓ_D^2 , with a probability p of being at the first level and $1-p$ of being at the second, then $F = pF^1 + (1-p)F^2$, where F^1 , F^2 are fractions which correspond to each of the load levels and

$$A_o^L = \frac{\ell_D^i}{\phi_m \eta}$$

$$Z_o^i = \frac{A_o^i \eta I}{L},$$

$$\text{and} \quad C_o^i = \frac{2h_s \ell_D^i}{L}.$$

6.3.2 Systems with Storage

Analogously with the no-storage case, the solar fraction formula for a system with a given storage capacity is based on two considerations.

- (1) The maximum energy that the system can supply per day via the storage is equal to the storage capacity.
- (2) If the array is so small that it never generates more energy than can be used directly or go into store for overnight use, then all solar energy which is available will be used. Some dumping will occur for larger arrays.

For the storage case the additional variables needed are:

B = storage output capacity (kWh)

η_B = storage efficiency

S_B = solar energy delivered to the load via storage per day (kWh/day)

S = $S_D + S_B$ total solar energy delivered to the load per day (kWh/day).

Normalizing these quantities relative to the load gives the relative storage capacity, R , the fraction of the load met via the store, F_B , the total solar fraction, F , and the excess, E , of availability over direct use, as well as the stored energy availability Z_B . These are defined below.

$$\begin{aligned}
R &= B/L \\
F_B &= S_B/L \\
F &= F_D + F_B = S/L \\
E &= Z - F_D \\
Z_B &= \eta_B E = \eta_B (Z - F_D).
\end{aligned}
\tag{6.3.2-1}$$

The maximum no-dump array size, A_1 , corresponding to the second consideration above must be derived next. It is more complicated to do this for storage than for no-storage systems because in addition to the noon clear day insolation the shape of the day's insolation profile determines how much energy is available for storage. To make the calculation manageable, standard clear day insolation profiles shown in Figure 6.3.2A are used to approximate the hour to hour data. The upper profile, which is used for fixed arrays, implies that clear day insolation is $\frac{4 h_s \phi_{\max}}{\pi}$ or $.637 (2 h_s \phi_{\max})$ for such panels. The lower one gives clear day insolation of $.8 (2 h_s \phi_{\max})$ for tracking arrays. Figures 6.3.2B1-3 compare the standard clear day profiles (dashed curve) to profiles computed hour to hour by the methods of Section 6.1 for 35°N latitude.

The standard profiles are used to determine the following:

- (1) the array that would just fill the store on a clear day,
- (2) the storage capacity that would be just sufficient to hold the excess energy available from a particular array on a clear day, and
- (3) the one day cycle store and array that exactly meet the entire load on a clear day.

Formulas for these calculations are derived and summarized in Figures 6.3.2C1-2, which show solar availability and the daytime load for each array type. Some of these calculations involve iteration. Lower case letters are used for clear day variables.

The no-dump array A_1 for a storage system depends on (increases with) the storage capacity B , as long as B is smaller than the one-day cycle store B_c .

Figure 6.3.2A. Standard Clear Day Insolation Profiles

Figure 6.3.2.B1
 APRIL
 STANDARD INSOLATION PROFILES
 AND CLEAR DAY INSOLATION
 35° NORTH LATITUDE

Figure 6.3.2.B2

JUNE

STANDARD INSOLATION PROFILES

AND CLEAR DAY INSOLATION

35° NORTH LATITUDE

HOURS FROM NOON

Figure 6.3.2 B3

December

STANDARD INSOLATION PROFILES AND CLEAR DAY INSOLATION

35° North Latitude

Tracking

Fixed
Horizontal

Fixed-
Latitude Tilt

Fixed-
With Reflectors
 $i = 45^\circ$ $\beta = 35^\circ$

Hours From Noon

Figure 6.3.2C1

Clear Day Standard Insolation Formulas
(Angles in Radians)

$$\begin{aligned} z &\sim 1 \\ C &\sim p \pi/2 = \pi/2 \cos \alpha \\ e &\sim \sin \alpha - \alpha \cos \alpha \\ f_D &\sim 1 - (\sin \alpha - \alpha \cos \alpha) \end{aligned}$$

$$\begin{aligned} e &= \frac{2C}{\pi} (\tan \alpha - \alpha) \\ f_D &= \frac{2C}{\pi} \left(\frac{1}{\cos \alpha} - (\tan \alpha - \alpha) \right) \\ p &= \cos \alpha = \frac{C}{\frac{\pi}{2}} \end{aligned}$$

- (1) Given A, find the battery which just contains the excess over direct utilization on a clear day.

$$\cos \alpha = p = \frac{l_D}{A \phi_m \eta}$$

$$B/L = R = \eta_B e = \eta_B \frac{2C}{\pi} (\tan \alpha - \alpha)$$

- (2) Given B, find the array that just fills it on a clear day

$$\cos \alpha_0 = p_0 = \frac{C}{C + \frac{R}{\eta_B}} \frac{\pi}{2}$$

Iterate

$$\alpha = \arccos \left(\alpha + R \frac{\pi}{2C} \frac{1}{\eta_B} \right)$$

$$A_B = \frac{l_D}{\phi_m \eta \cos \alpha}$$

Figure 6.3.2C1

Continued

- (3) Find B_c , A_c that just satisfy the load on a clear day

$$\cos \alpha_o = p_o = \frac{C}{C + \frac{1-C}{\eta_B} \frac{2}{\pi}}$$

Iterate $\alpha = \arccos \left(\frac{\pi}{2C} + (1 - \eta_B)(\tan \alpha - \alpha) \right)^{-1}$

$$A_c = \frac{l_D}{\cos \alpha \varphi_m \eta}$$

$$B_c/L = R_c = \eta_B \frac{2C}{\pi} (\tan \alpha - \alpha)$$

Figure 6.3.2C2

Clear Day Standard Insolation Formulas

Tracking Array

If $0 < p \leq k$
 $k \leq \alpha < 1$

If $k \leq p < 1$
 $0 < \alpha \leq k$

$$e \sim k - p(1 - \frac{1-k}{2k} p)$$

$$e \sim \frac{k}{2(1-k)} (1-p)^2$$

$$f_D \sim p(1 - \frac{1-k}{2k} p)$$

$$f_D \sim k - \frac{k}{2(1-k)} (1-p)^2$$

$$z \sim k$$

$$C \sim p \quad e = C \left(\frac{k}{p} - \left(1 - \frac{1-k}{2k} p \right) \right) \quad e = C \left(\frac{k}{p} \frac{1}{2(1-k)} (1-p)^2 \right)$$

$$p = \frac{C}{z} k \quad f_D = C \left(1 - \frac{1-k}{2k} p \right) \quad f_D = C \frac{k}{p} \left(1 - \frac{1}{2(1-k)} (1-p)^2 \right)$$

(1) Given A, find B to contain clear day excess

$$p = \frac{l_D}{A \phi_m \eta}$$

If $p \leq k$,

If $p \geq k$,

$$B/L = \eta_B C \left(\frac{k}{p} - \left(1 - \frac{1-k}{2k} p \right) \right)$$

$$B/L = \eta_B C \frac{k}{2p(1-k)} (1-p)^2$$

Figure 6.3.2C2

Continued

(2) Given B, find A which just fills it on a clear day

If $B/L = R \geq \eta_B C(1-k)/2$,

$$p = \frac{2k}{1 + R/(\eta_B C) + \sqrt{(1 + R/(\eta_B C))^2 - 2(1-k)}} \quad p = 1 - \frac{2}{1 + \sqrt{1 + 2\eta_B Ck/((1-k)R)}}$$

$$A_B = \frac{\ell_D}{p\phi_m \eta}$$

(3) Find daily cycle array and storage

$$p = \frac{k}{1-k} \left((1 - 1/((1-\eta_B)C)) + \sqrt{(1 - 1/((1-\eta_B)C))^2 + 2(1-k)\eta_B/(1-\eta_B)} \right)$$

$$A_c = \frac{\ell_D}{p\phi_m \eta}$$

$$B_c/L = \eta_B C \left[(k/p) - (1 - p(1-k)/(2k)) \right]$$

If a store larger than B_c is filled to capacity not all of the stored energy could be used on the same day. Some energy would be dumped if the following day were clear. Consequently, for any store larger than B_c , the no-dump array A_1 is equal to A_c . An array of this size provides at most just as much energy as can be used up in one day.

The fraction attainable with storage B can now be calculated in terms of A_1 , $Z_1 = \eta I A_1 / L$, F_{D1} , and $Z_{B1} = \eta_B (Z_1 - F_{D1})$.

$$F = F_D + F_B$$

$$F_B = Z_B = \eta_B (Z - F_D) \text{ if } Z \leq Z_1$$

$$F_B = Z_{B1} + \left[(R - Z_{B1})^{-1} + (Z_B - Z_{B1})^{-1} \right]^{-1} \text{ if } Z \geq Z_1$$

The via storage fraction increases asymptotically to R as array size A increases. If $C + R$ is greater than unity, values of F larger than 1 are obtained for large arrays. This reflects the fact that a system with sufficiently large array and storage will meet the entire load. Figure 6.3.2D shows solar fractions as a function of availability. The upper drawing shows the destination of available energy for a large array, while the lower drawing shows the effect of increasing the storage size up to and beyond B_c .

To illustrate how (that) the formula can be used, consider an array of 150 m^2 and a battery of 55 kWh in the example of the previous section.

(a) Fixed Array - Use Figure 6.3.2C1

$$C = .58$$

$$R = .55$$

$$\eta_B = .75$$

Find A_1

$$(2) \cos \alpha_o = .281$$

$$\cos \alpha = .293$$

$$A_B = \frac{4.83}{(.1)(.293)} = 164.8 \text{ m}^2$$

$$(3) \cos \alpha_o = .324$$

$$\cos \alpha = .318$$

$$A_c = 151.7 \text{ m}^2$$

$$B_c = 47.9 \text{ kWh}$$

Find F

$$A = 150 \text{ m}^2$$

$$A_1 = 151.7 \text{ m}^2$$

$$A_o = 48.3 \text{ m}^2$$

$$Z_o = .2415$$

$$Z = .750$$

$$F = F_D + F_B = .445 + .75 (.75 - .445) = .674$$

(b) Tracking Array - Use Figure 6.3.2C2

$$I = 6.3 \text{ kWh/m}^2\text{-day}$$

Find A_1

$$(2) \eta_B^C (1 - k)/2 = .0435$$

$$p = .360$$

$$A_B = 134.1 \text{ m}^2$$

$$(3) p = .404$$

$$A_c = 119.8 \text{ m}^2$$

$$B_c = 44.9 \text{ kWh}$$

Find F

$$A = 150 \text{ m}^2$$

$$A_1 = 119.8 \text{ m}^2$$

$$A_o = 48.3 \text{ m}^2$$

$$Z_o = .304$$

$$Z_1 = .755$$

$$Z = .945$$

$$F_{D1} = .475$$

$$F_D = .497$$

$$Z_{B1} = .210$$

$$Z_B = .336$$

$$F = .497 + .302$$

$$= .799$$

EFFECT OF INCREASING STORAGE CAPACITY

Figure 6.3.2D. Solar Fractions

Given a particular battery, a formula can be derived which determines the array size which gives the lowest energy cost. Let A^* be the array that could be bought with the battery and fixed costs, where b (\$/kWh-day) is the daily cost of owning the battery.

Then

$$A^* = \frac{bB + c}{a}$$

and

$$Z^* = \eta IA^* / L.$$

The size of the minimum cost array can be found from

$$Z^{MSC} = Z_1 + \frac{R - Z_{B1}}{\eta(1-K)} \left[\frac{1 + \sqrt{1 + XY}}{X} - 1 \right] \quad (6.3.2-3)$$

where

$$K = \left(\frac{Z_1 - Z_0}{C - Z_0} + 1 \right)^{-2} \quad (6.3.2-4)$$

$$X = \frac{F_{D1} + R - K(Z^* + Z_1)}{R - Z_{B1}} \quad (6.3.2-5)$$

$$Y = \frac{\eta_B(1 - K)(Z^* + Z_1)}{R - Z_{B1}} - 1. \quad (6.3.2-6)$$

This formula is applicable when Z^{MSC} is close to Z_1 .

The one day cycle storage size is recommended as the design storage size. It is essentially an overnight store. While this capacity could potentially be cycled every night, any additional capacity would be cycled much less frequently. Computer simulation data presented in Section 6.4 verifies that the incremental contribution of storage capacity to solar utilization tends to fall off near the one day cycle storage size. (Figure 6.4G1-2).

The lower drawing in Figure 6.3.2D also shows that according to our formulas adding storage beyond one day cycle capacity increases the solar fraction very little. Accordingly, the design system would have a storage output capacity equal to B_c , and an array determined by Equation 6.3.2-3. Continuing with the previous example for a flat array with storage, a design system size is determined below. It should be noted that the design array sizes for both the no-storage and storage systems are very close to the corresponding no-dump array sizes. Therefore the no-dump arrays would give near-optimum systems.

Example:

$$\text{Design Battery} = B_c = 47.9 \text{ kWh}$$

$$R = .479$$

$$A_1 = A_c = 151.7 \text{ m}^2$$

$$Z_1 = .7585$$

$$Z_{B1} = .2344$$

$$F_{D1} = .446$$

From Equation

$$6.3.2-4$$

$$K = .1566$$

$$6.3.2-5$$

$$X = 3.111$$

$$6.3.2-6$$

$$Y = 1.710$$

$$6.3.2-3$$

$$Z^{MSC} = .8096$$

Given

Battery Capital Cost \$100/kWh

Find

$$b = \$.0406/\text{kWh-day}$$

$$A^* = 57.9 \text{ m}^2$$

$$Z^* = .2895$$

$$\text{Design Array} = A^{MSC} = 161.7$$

$$F = .716$$

$$S_D = 71.6 \text{ kWh/day}$$

$$\text{System Cost} = \$8.92/\text{day}$$

$$\text{Cost of Solar Electricity} =$$

$$\$.125/\text{kWh}$$

6.4 COMPARISON WITH COMPUTER SIMULATIONS

Monthly solar fractions were calculated by computer for the electrical load shown in Section 6.2, using hourly insolation data from 1962-63. The computer simulations were run for both horizontal and latitude inclined photovoltaic arrays, for five U.S. locations, and for a variety of array and storage sizes. Constant efficiencies were assumed for the array and storage. These were .1 for directly used solar power and .08 for power delivered via the store; that is, the storage efficiency was assumed to be .8.

The monthly no-storage fractions from the simulation described above for latitude tilted panels were compared to those predicted by formula 6.3.1-3 using a single daily average insolation value obtained from the same 1962-63 data. This comparison is made graphically in Figure 6.4A1 for Washington, D.C. for the months of January, April, July and October. The maximum and average prediction errors for four panel sizes in each location are shown below, for fractions which ranged from .125 to .641.

Location	Maximum Error	Average Absolute Error
Cleveland	.071	.014
Washington	.060	.025
Riverside	.062	.028
Phoenix	.037	.014
Miami	.028	.011

Solar fractions were also predicted for the year for these latitude tilt panels without storage. The results for 100 M² arrays are shown in Figure 6.4B.

Figure 6.4.A2 presents annual no-storage solar fractions for the five locations. The solid curve in the figure represents the solar fraction that would be predicted if all days were identical, and daily insolation on the fixed array had the form of a cosine function. It is interesting that all the data points lie reasonably close to this curve in spite of the different weather conditions in the five locations.

Figure 6.4 A1
MONTHLY SOLAR FRACTIONS - WASHINGTON, D.C. 1962

Figure 6.4 A2
ANNUAL SOLAR FRACTIONS - 1962 DATA

Figure 6.4-B

Annual Solar Fractions
100 Square Meter Arrays

Location	Data Year	Prediction	Simulation	Difference
Cleveland	1962	.318	.320	- .002
	1963	.339	.346	- .007
Washington	1962	.385	.361	+ .024
	1963	.409	.385	+ .023
Riverside	1962	.463	.426	+ .037
	1963	.468	.431	+ .037
Phoenix	1962	.471	.455	+ .016
	1963	.485	.466	+ .015
Miami	1962	.428	.421	+ .007
	1963	.434	.420	+ .014

However, the data points make it clear that locations with low average daily insolation have significantly lower solar fractions than other locations. For this reason, we abandoned the identical days model which is based only on average insolation. Instead we adopted the method described in Section 6.3, which considers both clear day and average insolation, and agrees better with the simulation data.

An attempt was also made to verify the method of calculating the no-dump array size for systems with and without storage. Figures 6.4C1-3 show whether or not dumping of energy occurred as predicted for the five locations. In the second table the array sizes used were the largest predicted never to dump energy, the average no-dump panel, and the smallest that would dump energy every month.

Nine systems with storage and with latitude tilted arrays were simulated in each location. Figure 6.4D shows predicted and computer calculated fractions for two array sizes with a forty kilowatt hour battery. The upper graph shows monthly fractions for Riverside, California, and the lower graph shows annual fractions. The largest error observed for annual fraction calculations was + .109 (13%), for an array of 400 M² with an 80 kwh store in Cleveland. When monthly solar fractions were calculated and averaged to give an annual fraction, the prediction error was reduced to + .010.

Another comparison analysis exercise was performed and is described below. For the horizontal arrays with storage, monthly solar fractions were predicted based on long term average monthly insolation data from weather service tables. Figure 6.4E1 shows this data compared to computer hour to hour simulation and shows a table of the insolation comparison. Figure 6.4E2 shows a comparison of the computer hour to hour simulation to the predictions based on the short-cut method using actual 1962-63 daily insolation. Annual solar fraction predictions for large horizontal arrays with storage based on long term average insolation are shown in Figure 6.4F. The predicted fractions calculated on an annual basis (labelled "Annual" in the figure) were higher than computer simulation results by an average of 6.6% and as much as 20.9%. When solar fractions were calculated month by month and averaged the results agreed very well with the simulation fractions. (Fractions predicted in this way are labelled "Monthly".)

Figure 6.4.C1
 Latitude Tilt Panels
 Months when Dumping Occurs
 No Storage

✓ Computer shows dumping ---- Prediction

Figure 6.4.C2
Comparison of Predicted and Simulation Dumping

- Horizontal Panel

No Storage

CLEVELAND

<u>Array</u>	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>
Never Dump												
Ave.				✓	✓	✓	✓	✓	✓			
Always Dump		✓	✓	✓	✓	✓	✓	✓	✓	✓		

WASHINGTON

	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>
Never Dump						✓						
Ave.			✓	✓	✓	✓	✓	✓	✓	✓		
Always Dump	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

RIVERSIDE

	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>
Never Dump				✓	✓	✓	✓					
Ave.		✓	✓	✓	✓	✓	✓	✓	✓	✓		
Always Dump	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

PHOENIX

	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>
Never Dump				✓								
Ave.		✓	✓	✓	✓	✓	✓	✓	✓	✓		
Always Dump	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

MIAMI

	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>
Never Dump					✓	✓		✓				
Ave.		✓	✓	✓	✓	✓	✓	✓	✓	✓		
Always Dump	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ Computer simulation shows some dumping

Figure 6.4.C3

HORIZONTAL ARRAY

SYSTEMS WITH STORAGE - 48 kWh

PREDICTED AND COMPUTER CALCULATED DUMPING

Figure 6.4 D1

MONTHLY SOLAR FRACTIONS - RIVERSIDE, CA. 1962

Figure 6.4 D2

ANNUAL SOLAR FRACTIONS - 1962 DATA

CLEVELAND 1962-63

MONTHLY PREDICTED AND COMPUTER CALCULATED SOLAR FRACTIONS
HORIZONTAL ARRAY

6-70

	LONG TERM AVE INSOL kWh/M ² -day	PERCENT DIFFERENCE OF ACTUAL FROM LONG TERM AVE INSOL	
		1962	1963
J	1.44	4.6	10.4
F	2.10	-17.9	8.3
M	3.63	-19.6	15.2
A	4.39	1.4	5.7
M	6.09	-9.7	-5.5
J	6.51	-7.3	.2
J	6.41	-12.7	-9.1
A	5.74	-3.1	-18.6
S	4.38	-19.6	-5.9
O	3.06	-24.5	.6
N	1.64	-28.7	-29.3
D	1.34	-14.1	.9

Figure 6.4 E1

CLEVELAND 1962-63

MONTHLY PREDICTED AND COMPUTER CALCULATED SOLAR FRACTIONS

HORIZONTAL ARRAY

Figure 6.4 E2

Figure 6.4-F

SOLAR FRACTIONS FOR LARGE HORIZONTAL ARRAYS
BATTERY 48 kWh

<u>Location</u>	<u>Array (m²)</u>	<u>Solar Fractions</u>			
		<u>Predicted</u>		<u>Simulation</u>	
		<u>Annual</u>	<u>Monthly</u>	<u>1962</u>	<u>1963</u>
Cleveland	290	.839	.749	.694	.744
Washington	284	.839	.780	.787	.818
Riverside	205	.883	.857	.842	.857
Phoenix	185	.966	.872	.847	.863
Miami	241	.882	.866	.877	.867

Finally, the solar fraction formula developed in Section 6.3 has a discontinuous derivative with respect to storage capacity at B_c , the one day cycle storage. In the formula, this discontinuity occurs because the no-dump array size increases roughly proportionally to storage capacity up to B_c , but then does not increase beyond A_c , the one day cycle array size. In an actual system the discontinuity reflects the infrequent use of storage capacity beyond the overnight size, which was the basis of selecting B_c as the design battery size. If the formula is correct, there should be a kink at B_c in the graph of a solar fraction as a function of storage size. Accordingly, because $B_c = 48$ kwh for the computer simulation load model, solar fractions were calculated by hourly computer simulation for battery sizes of 43 to 53 kwh and three horizontal array sizes per location. The results appear in Figures 6.4.G1-2. Some of the plots show distinct bends, others do not.

6.5 Summary of Method

Section 6.3 describes in detail a method of system design and of predicting solar fractions. Sample calculations are also shown. The design finds a system size which provides solar energy at close to least cost.

The determination of design array and storage size requires information on the system load and the load during daylight hours, the array type, the location, the system efficiency for energy used directly, and the efficiency of the store. Then average values of maximum clear day insolation, sunset hour and noon power demand of the load can be found. For a no-storage system, the design array size is slightly larger than one which would dump no energy on a clear day, that is, one for which the system electrical output at noon on a clear day just equals the load. The design system with storage is basically one which would just satisfy the load on a clear day. The design storage output capacity B_c can be determined by methods shown in Figure 6.3.1C1 or 6.3.1C2. The design array size is slightly larger than the one day cycle array A_c which is also derived in those figures.

Somewhat more efficient systems may be obtained with the aid of formulas

Figure 6.4-G2. HORIZONTAL ARRAY, 1962. EFFECT OF BATTERY SIZE NEAR OVERNIGHT BATTERY SIZE;
 $C = .58$, $B_c = 48$ kWh

BATTERY OUTPUT CAPACITY (kWh)

BATTERY CAPACITY (kWh)

Figure 6.4-G2. HORIZONTAL ARRAY, 1962. EFFECT OF INCREASING BATTERY SIZE NEAR OVERNIGHT BATTERY SIZE, $C = .58$, $B_c = 48$ kWh.

6.3.1-4 or 6.3.2-3 for no storage or with storage systems respectively. The use of these formulas requires information on the cost of system components and also the average daily insolation.

The solar fraction that would be obtained with the design system with storage can best be estimated by monthly solar fraction calculations.

Figure 6.5A lists design horizontal array and storage sizes for five locations for the system efficiency assumptions used in the simulation, and cost ratios $b/a = 1$ and $c/a = 10$. The solar fraction predictions are based on long term average insolation.

6.6 CONCLUSIONS

Solar fraction formulas have been developed which can predict the solar fraction of a given load that can be obtained with a on-site solar power system of a particular size. The formulas use monthly insolation data and require the aid of a hand calculator, and may eliminate the need for a computer simulation in design studies.

From the standpoint of system design the major conclusions of this chapter concern the recommended size of the array and storage capacity for on-site systems.

For systems without storage, any electrical generation in excess of the load is wasted. Consequently, it is recommended that the array size be selected so that noon-time clear day output equals the load. When there are significant fixed costs (system costs not associated with the size of the array), a slightly larger array size is optimal. This array size can be calculated using formula 6.3.1-4 .

If storage is provided for electricity generated on-site, its capacity can be sized to the overnight load. Any capacity in excess of this would be used very infrequently. The corresponding design array size is slightly larger than one which would fill the store on a clear day. Formulas for sizing the array and the store are given in Section 6.3.2.

Figure 6.5A

Design Photovoltaic Systems

Horizontal Array

Location	No-Dump Array (M ²)	Design Array (M ²)	Store (kWh)	Solar Fractions*			
				Predicted Annual	Predicted Monthly	Simulation 1962	Simulation 1963
Cleveland	62	69	-	.240	.237	.216	.230
	181	192	48	.683	.622	.582	.617
Washington	60	66	-	.240	.236	.248	.268
	177	188	48	.684	.637	.662	.711
Riverside	57	61	-	.311	.308	.315	.317
	167	177	48	.835	.805	.800	.813
Phoenix	57	60	-	.343	.339	.325	.332
	167	169	48	.920	.840	.834	.832
Miami	52	57	-	.274	.273	.269	.275
	153	161	48	.769	.746	.753	.758

*Solar fractions for the systems without storage were calculated for the no dump array size.

REFERENCES (Section 6)

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5. JPL - "The Cost of Energy from Utility-Owned Solar Energy Systems", a Required Revenue Methodology for ERDA/EPRI Evaluations, ERDA/JPL-1012-76/3, June, 1976.