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USE OF SOLAR ENERGY FOR LIGHTING OF OVERHEAD GUIDE SIGNS, ROADWAY LIGHTING, AND INTERSECTION TRAFFIC SIGNALS

Final Report

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16. ABSTRACT

The principal objective of this study was to demonstrate the technological and economic feasibility (or lack thereof) of photovoltaic powered systems for overhead guide sign lighting, roadway lighting, and traffic signalization.

A preliminary technical and economic feasibility study concluded that the first two applications were feasible, but that full-scale traffic signalization was not. In lieu of full-scale traffic signalization, the project developed a system to power flashing warning lights.

Photovoltaic systems were designed, constructed, field tested and evaluated for overhead guide sign lighting, roadway lighting, and powering of flashing warning lights.

All these systems were found to be dependable and economical for application at remote sites where a conventional power supply is not available. In addition, previous research has shown that roadway lighting can have a safety benefit at remote locations which have a high nighttime accident rate and that flashing warning lights have a safety benefit.

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SI (METRIC) UNIT CONVERSION FACTORS

The material contained in this report is presented primarily in terms of English units. The following factors may be used to convert the measures used in this report between the English units and the International System of Units (SI):

1 mile = 1.6093 kilometers

1 kilometer = 0.6214 miles

1 foot = 0.3048 meter

1 meter = 3.2808 feet

1 square foot = 0.0929 meters squared

1 meter squared = 10.764 square feet

1 inch = 2.54 centimeters

1 centimeter = 0.3937 inches

Celsius temperature = (Fahrenheit temperature - 32) x 5/9

Fahrenheit temperature = (Celsius temperature x 9/5) + 32

1 kilojoule = 0.000278 kilowatt-hours

1 kilojoule = 1000 watt-seconds

1 kilojoule = 0.949 British Thermal Units

1 British Thermal Unit = 1.054 kilojoule

1 gallon = 4.405 liters

1 liter = 0.227 gallons

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CHAPTER 1
INTRODUCTION

During the past ten years, there has been increasing concern by highway agencies over the growing cost of electric power. The principal uses of electric power by highway agencies are for illuminating overhead guide signs, for roadway illumination, and for powering traffic signals. All predictions suggest that the cost of electric power will continue to grow and at a rate which exceeds the general inflation rate.

One potential means of reducing the cost of electric power is to consider photovoltaic systems. Photovoltaic systems convert sunlight into direct current electrical energy. In a typical application, sunlight is collected during daylight hours, converted into direct current electricity, and stored in batteries. Photovoltaic systems (solar cells) first received major use in the 1960's to provide a source of power on satellites and spacecraft.

Terrestrial use of photovoltaic systems can be most effective in locations where the insolation (the amount of sunlight) is high. This occurs at locations in the lower latitudes where cloud cover is infrequent. The major arid and semiarid regions of the world - including the southwestern United States - have these characteristics.

The past five years have seen the entry of photovoltaic systems into highway engineering applications in the United States and some other countries of the world. The major advantage of photovoltaic systems for highway applications is that they can provide a power supply in remote locations which lack conventional power. It is not unusual to incur a cost of $10,000 to $20,000 per mile to extend conventional utility power lines. Alternative forms of power supply such as diesel generators are expensive in comparison to conventional power. As a result, photovoltaic systems can be practical and economical in areas which have high insolation (solar radiation) and which lack a conventional utility power supply.

There are at least ten applications of photovoltaic systems in highway engineering in the United States which are known to the authors. They are as follows:

- Lighting of overhead guide signs on freeways.
- Roadway illumination.
- Flashing warning lights.
- Permanent traffic counting stations.

- Railroad-highway grade crossing warning devices.
- A dust storm warning system.
- Irrigation controllers for roadway landscaping.
- Remote highway maintenance stations.
- Cathodic protection of bridge decks.
- Motorist call boxes.

Each of these applications is described in some detail in Appendix A.

This research project evaluated three applications of photovoltaic systems:

1. Lighting of overhead guide signs on freeways;
2. Roadway illumination; and
3. Intersection traffic signals.

As described later in this report, the research project concluded that use of photovoltaics for intersection traffic signals is not economical. However, the project did design and field test a system to power flashing warning lights. The following paragraphs present problem statements which describe why there is an interest in considering photovoltaic systems for these applications.

OVERHEAD GUIDE SIGN LIGHTING

The costs of installing, operating and maintaining overhead sign lighting have been increasing while monies available to highway agencies have been declining in real terms. For example, it was estimated in 1986 that the State of Arizona was spending an estimated $88,000 annually to power their overhead sign lighting systems (approximately 700 signs). Thus, there is a need to stretch dollars further.

A potential solution to this problem is to use an alternative energy source to power overhead sign lighting. Photovoltaics is one alternative energy source. However, there are questions about its technological and economic feasibility.

The problem, then, is to determine if a photovoltaic sign lighting system is technologically and economically feasible and can result in a reduction in agency costs while still providing for the needs of the motorist.

ROADWAY LIGHTING

The problem in the roadway lighting area is similar to that in the guide sign lighting area. Roadway lighting is used on arterial streets and freeways in urban areas and at selected locations in rural areas to improve nighttime safety. With continuing increases in electric power costs, public agencies have a continually growing burden in powering these roadway lighting systems.

Again, a potential solution to this problem is to use an alternative energy source to power the roadway lighting. Photovoltaics is one alternative energy source. Again, its technological feasibility must be proven.

A photovoltaic roadway lighting system may provide a solution to a different problem--nighttime highway safety at isolated rural intersections. Isolated rural intersections with high nighttime accident rates could benefit from roadway illumination. However, due to their location, remote from conventional power sources, roadway lighting has been an impractical countermeasure. Availability of a photovoltaic powered roadway lighting system might make it economically possible to provide roadway lighting as a nighttime accident countermeasure.

The problem then, in the roadway lighting area, is to determine if a photovoltaic roadway lighting system is technologically and economically feasible so that it can either reduce agency costs for existing roadway lighting systems or make possible the use of roadway lighting at remote high accident locations.

TRAFFIC SIGNALIZATION

A third major consumer of electric power for public traffic engineering agencies is traffic signals. The power requirements at a typical signalized intersection are far greater than those for lighting an overhead sign, for example. Therefore, it would be of interest to determine if a photovoltaic powered traffic signal installation would be technologically and economically feasible and have the very high reliability required to provide for motorist safety.

A simpler type of "traffic signalization" is the use of a flasher to provide a flashing yellow caution indication or to provide a flashing red stop indication at isolated intersections. Use of this type of device could be similar in application to the use of roadway lighting at remote high accident locations. The possibility of a photovoltaic powered flasher would be an accident countermeasure at this type of location. The problem, then, is to determine if a photovoltaic powered system of this type is technologically and economically feasible.

CHAPTER 2
PROJECT DESCRIPTION

For a better understanding of this report, it is important that the reader be familiar with the scope of the research project that was conducted. For that reason this chapter briefly describes each of the tasks undertaken in this research project.

The principal objective of this study was to demonstrate the technological and economic feasibility (or lack thereof) of photovoltaic powered systems for overhead guide sign lighting, roadway lighting and traffic signalization. The work effort in the project was subdivided into nine tasks as described below.

TASK 1. REVIEW EXISTING APPLICATIONS

Task 1 reviewed existing applications of photovoltaics for lighting of overhead guide signs, roadway lighting, intersection traffic signalization, and other photovoltaic applications which are not directly related to this project. Existing applications are described in Appendix A.

TASK 2. PRELIMINARY TECHNICAL AND ECONOMIC FEASIBILITY STUDY

Task 2 was a preliminary technical and economic feasibility study of the use of photovoltaic systems for lighting of overhead guide signs, roadway lighting, and intersection traffic signalization. In Task 2, the research team conducted a preliminary assessment of the hardware requirements for each of these photovoltaics systems and compared their capital and operating costs to costs of conventionally powered systems.

In addition to evaluating technical and economic feasibility, Task 2 determined the number of viable applications for lighting of overhead guide signs, roadway lighting, and intersection traffic signals in Arizona. In addition to existing roadway lighting, candidate sites for potential roadway illumination were identified. This effort concentrated on remote interchange or intersection locations having a relatively high nighttime accident record and unavailability of conventional power. An estimate was made of candidate locations for flasher type installations in remote areas. These sites are locations with relatively high accident rates that might benefit from more positive intersection control.

TASK 3. PREPARE INTERIM REPORT

An interim report was prepared documenting the findings of the preliminary study conducted in Tasks 1 and 2. The report presented the project team's evaluation of the economic and technical feasibility of using photovoltaics for powering lighting of overhead guide signs, roadway lighting, and intersection traffic signals. The interim report presented the team's assessment of each of these systems.

The interim report recommended applications for demonstration and testing in the succeeding tasks of the study.

TASK 4. PROJECT COMMITTEE REVIEW OF INTERIM REPORT

Task 4 provided the project committee the opportunity to review the interim report and evaluate the recommendations made therein.

TASK 5. DESIGN OF PHOTOVOLTAIC SYSTEMS

Task 5 designed systems for the applications selected for field testing. Task 5:

- Developed specifications for all photovoltaic components;
- Specified the number and size of photovoltaic panels and batteries based on weather data, the amount of solar insolation available at specific sites, and electrical requirements for all of the applications;
- Determined the most appropriate tilt angle of solar panels to maximize winter energy output; and
- Determined the most appropriate lighting equipment, lighting controls, battery charge regulators, performance monitoring systems, and troubleshooting procedures.

TASK 6. CONSTRUCT AND INSTALL SYSTEMS

In Task 6, test sites were identified, the systems were constructed (the hardware was acquired, assembled, and mounted), and the systems were installed at test sites.

TASK 7. TEST SYSTEMS

Following installation, each photovoltaic system was field tested in order to obtain meaningful information on reliability and maintenance requirements and to expose the system to seasonal extremes in environmental conditions. System performance was monitored.

TASK 8. PERFORM ECONOMIC ANALYSIS

In Task 8, a comprehensive economic analysis was performed for those applications tested in Task 7. Costs were compared with potential competing power sources. The economic analysis was comprehensive: costs included capital items, energy costs, and maintenance costs. In other words, a life cycle cost model was used. Economic analyses were conducted for both remote applications and replacement of existing installations using conventional power. Task 8 also determined the number of viable photovoltaic system installations for each application.

TASK 9. PREPARE FINAL REPORT AND RECOMMENDATIONS

This final report documents each of the tasks of the research study and the results of those individual task efforts. This report describes the technical and economic feasibility of photovoltaic systems as determined in this project. Recommendations to the Arizona Department of Transportation are included which indicate the types of photovoltaic system applications which should be pursued and the level of overall use of these photovoltaic systems in Arizona.

CHAPTER 3

TECHNICAL AND ECONOMIC FEASIBILITY STUDY

One of the initial efforts in this research project was to assess the economic and technical feasibility of each of the solar powered applications. This chapter documents the feasibility study.

Assessment of economic and technical feasibility began with a review of systems which had been designed and installed in other states. Appendix A provides a summary of these other systems. The following sections describe other aspects of the feasibility study.

OVERHEAD GUIDE SIGN LIGHTING APPLICATION

As summarized in Appendix A, other states have installed photovoltaic systems for lighting overhead guide signs. The sign lighting systems in New Mexico were installed at a total cost to the New Mexico State Highway Department of $5,500 per sign. Because the size of the system is dependent upon the size of the sign to be illuminated, this feasibility study estimated the system cost for an 8 foot high by 20 foot wide sign in Arizona to be $7,500. The estimate included the cost of 700 watts of photovoltaic modules, battery storage for four to five days of limited sunlight, regulators and conditioners, cabling, racks, and labor for field installation. The size of power supply was designed to provide adequate power for either a fluorescent lamp system (two 85 watt lamps) or a high pressure sodium lamp system (one 150 watt lamp). The power supply was scaled to operate a lamp for 14 hours per day, even in the winter when the amount of sunlight is much less than in the summer. Battery capacity for lighting loads of this kind is usually sufficient to provide energy for the load, without any replenishment from the photovoltaic modules, for three consecutive load cycles. In the southwestern geography, sunlight patterns will be intermittent but the photovoltaic modules seldom will produce zero energy in any one 24 hour period. Even on an average cloudy day, the modules will produce one-third or more of a "normal" amount of energy. A design that assumes no sunlight for three load cycles is usually sufficient to provide for at least four load cycles over limited sun days, and will often serve well for five such limited sun days.

This cost can be compared to the cost of a conventionally powered system. The recent study on "The Evaluation of Alternative Lighting Systems for Guide Sign Illumination" showed an initial cost of $1,160 for a fluorescent system to illuminate an 8 foot high by 20 foot wide sign. The relatively low $1,160 cost is misleading, however, if it is assumed that conventional power is available at the sign itself. If conventional power must be brought in even a short distance, it can add significantly to the cost. Conventional power brought in over longer distances can increase the cost substantially. For example, about seven years ago, ADOT considered using photovoltaics to light the I-10/U.S. 666 interchange. Supplying conventional power at this location would have cost about $20,000 to extend the power grid a distance of one mile.

Another aspect of the feasibility study was to determine how many locations in Arizona could benefit if a solar powered sign lighting system were available. An inventory of all overhead guide signs on the state highway system was reviewed and it was determined that there are approximately 18 overhead guide signs on the state highway system which are at remote locations where no conventional power supply is available. Beyond these existing locations, other applications would include installations for new overhead guide signs or possible use in refurbishing existing overhead guide sign lighting systems. Work in California has shown that, in some instances, retrofit with a photovoltaic powered system can be less expensive than refurbishing an existing conventionally powered system. If there are circuit failures in the power supply lines leading to the sign lighting system, it can be very expensive to pinpoint the location of the circuit failure and to either repair the existing circuit or lay new power supply lines.

ROADWAY LIGHTING APPLICATION

An important aspect of roadway lighting systems is the amount of power required to operate such a lighting system. The Arizona Department of Transportation uses high pressure sodium for all existing roadway lighting. To provide adequate illumination the most commonly used size of lamp is 150 watts. This size lamp is typically used by ADOT in rural areas and at signalized intersections. Occasionally ADOT uses 250 watt lamps at wide intersections. Four hundred watt lamps are used for continuous freeway illumination. In rest areas, 70 watt lamps are used by walkways.

A photovoltaic power source to provide winter operation for 14 hours per day for a 150 watt lamp would cost approximately $6,000. This estimate includes costs of 600 watts of photovoltaic modules, batteries for from four to five days of limited sunlight, regulators and conditioners, cabling, racks, and labor for field installation. Costs will vary depending on the assumptions regarding the sun energy that may be available on less than bright days.

A major advantage of nighttime illumination at intersections is that it can be effective in reducing night accidents. Therefore, there is a stronger and more obvious benefit for providing roadway illumination than there is for sign lighting.

Several studies have shown that intersection lighting can be effective in reducing night accidents. Walter and Roberts studied the effects of lighting at 47 rural at-grade intersections in Iowa. Results of the study indicated a 49 percent reduction in night accidents and a 52 percent reduction in night accident rate. Daytime accident rates at the same intersections fell 13 percent during the same period.

Lipinski and Wortman studied the effect of illumination by comparing accident data for 263 lighted and 182 unlighted intersections. Night accidents were significantly reduced at rural intersections when illumination was provided. In this before and after study the number of night accidents per year declined by 14.8 percent while the number of daylight accidents per year increased by 7.8 percent. The ratio of night accidents to total accidents decreased 22.8 percent, and the nighttime accident rate decreased 44.6 percent. It was found that the night accident rate was 45 percent less at lighted than at unlighted intersections.

Continuous lighting on rural highways without control of access is seldom used because these highways are very expensive to light for the relatively small traffic volumes that they carry. Cornwell and MacKay did find that lighting of rural highways can produce a significant reduction in injury accidents. In their study, a 49 percent reduction was found in "serious" accidents at 21 rural sites where lighting was installed. This reduction was significant at the 5 percent significance level. Significant reductions at 43 other rural sites were also found. At these locations, there was a 75 percent reduction in "fatal" accidents (significant at the 2.5 percent significance level) and a 37 percent reduction in "serious" accidents (significant at the 5 percent significance level). Sabey and Johnson evaluated 43 sites at rural locations before and after installation of new or improved street lighting. Although there were reductions in numbers of nighttime accidents, the reductions were not statistically significant.

Since use of photovoltaic power for roadway illumination is not economically competitive with conventional power where conventional power is available, the thrust of this effort was to identify locations which lack conventional power and which could benefit from roadway illumination.

To determine if there were candidate sites in Arizona which could benefit from intersection illumination, the ALISS accident record system was employed. Data were obtained for both intersection type accidents and for accidents on one-mile segments of the state highway system.

For intersection accidents, data were obtained for interstate route intersections (primarily ramp terminal locations), state routes, and U.S. routes. The listings of intersection accidents provided by the ALISS system presented intersections in descending order by accident rate; accidents occurring at dusk, during darkness, or at dawn were noted. The accident data provided by ALISS covered a four-year period from January 1, 1982 through November 30, 1985.

The accident data were reviewed for the following criteria:

1. "Night" accidents accounting for at least 50 percent of the accidents at the intersection location. (This indicates a relatively high level of nighttime accidents; statewide, only 33 percent of all accidents occur during "night" conditions.)

2. The number of "night" accidents in a four year period greater than or equal to four.

Forty-seven intersections were identified which met the above criteria. Further work was done to determine if conventional power was available at these intersections. From an inventory of signalized intersections in the State of Arizona, it was determined that some of these locations are signalized, and hence, that conventional power is available. Further, based on the location of the intersections in urban areas, it was judged that other locations are probably illuminated at this time. It was found that there may be as many as 17 of these intersections that may not have conventional power available and may not have existing illumination. These 17 locations are candidate sites for photovoltaic powered roadway lighting. It is important to note that there are undoubtedly additional candidate sites on local (non-state) roadway systems. Local roadway systems, however, were not included in the accident data.

It was recognized that ADOT has guidelines for highway illumination (included in the Traffic Engineering Policies, Guides, and Procedures) which have more stringent criteria for intersection illumination than those used above. For intersections on conventional highways, those guidelines state that lighting may be considered when there is an average of three or more accidents per year under conditions other than daylight over the most recent three year period. Seven of the 47 intersections identified did have three or more "night" accidents per year. However, these locations are either signalized or have conventional power available.

In addition to intersection accidents, the ALISS system was also used to review accident experience on the entire state roadway system by one-mile segments. This review was conducted to identify any additional locations which might benefit from roadway illumination.

One-mile segments of the state highway system were reviewed using criteria similar to those employed for intersections:

1. "Night" accidents accounting for at least 50 percent of the accidents on the one-mile segment.

2. The number of "night" accidents in a four year period greater than or equal to four.

A total of 126 one-mile segments of the state roadway system met the above criteria. Fourteen of these 126 locations had at least eight nighttime accidents and were at locations where conventional power is probably not available. Additional work is necessary to pinpoint the locations of accidents within these one-mile segments and to determine if the nighttime accident problem at these locations has potential for correction by roadway illumination. Once again, it must be emphasized that these sites represent only the state roadway systems and additional sites certainly exist on local roadway systems.

One of the locations identified using this approach was an interstate rest area where five nighttime accidents occurred in a four year period. This rest area is at a location where conventional power is not available. ADOT's guidelines for highway illumination state that "Illumination may also be considered for rest areas along freeways and their diverging and merging ramps." This is one instance where a photovoltaic powered roadway lighting system could satisfy a need which meets current ADOT criteria. The research team recommends that ADOT install photovoltaic powered roadway lighting at this location.

TRAFFIC SIGNALIZATION APPLICATION

When the Arizona research project was initiated, it specified that full intersection traffic signalization would be one of the applications to be evaluated. One conclusion reached in the feasibility study was that providing a photovoltaic power supply for full intersection signalization was neither practical nor economically feasible. This conclusion was presented in a July, 1986 Interim Report and concurred with by the Arizona Department of Transportation. As an alternative, the possibility of providing power for a flashing beacon - an application with a much smaller power requirement - was evaluated.

An investigation of existing applications found that no jurisdictions had used a photovoltaic system to power full scale intersection signalization, although one agency had used solar power for a flasher mounted on a warning sign. The power requirements for a typical signalized intersection are quite high when the multiple intersection approaches and the multiple signal heads facing each approach are considered. The total power requirement is in the range of 1200 to 1300 watts, including the controller. Unlike a lighting system, signalization must operate 24 hours a day, increasing the daily power requirement to about 30 kilowatt hours. The 1200 to 1300 watts power requirement compares to about 160 watts for sign lighting or roadway lighting systems. A further stringent requirement for a signalization system is that it must be nearly 100 percent reliable.

The cost of a photovoltaic power supply to operate traffic signals at a typical intersection (1200 to 1300 watt power requirement) for 24 hours a day was estimated to be $60,000. This cost is substantial, and it would be very unusual to have no conventional power available near an intersection requiring signalization. A conventional power supply line would have to be extended many miles to exceed the cost of the photovoltaic power supply. For this reason, the preliminary investigations focused on a simpler type of signalization -- a flashing beacon.

FLASHING WARNING LIGHT APPLICATION

A system to operate a 150 watt flashing beacon, 24 hours a day, was estimated to cost $7,000 (150 watt is the standard lamp size for a 12 inch signal head; 135 watt lamps are also available with the same lumen output). Flashing beacons can result in a reduction in accidents at rural intersections. A 1970 North Carolina State University study of accidents before and after installation of flashing beacons at stop sign controlled rural intersections showed a significant decrease in accident rates. A 27 percent reduction in intersection accidents was observed, with much higher accident reductions at three-legged (65 percent reduction) and channelized (47 percent reduction) intersections.

A California study showed the following changes when flashing beacons were installed at stop sign controlled intersections: 1) Total accidents decreased 43 percent; 2) Property damage accidents decreased 34 percent; 3) Injury accidents decreased 51 percent; 4) Fatal accidents decreased 80 percent; 5) Both daytime and nighttime accidents decreased by 43 percent and 46 percent, respectively.

To identify intersections that might benefit from flashing beacons, the ALISS accident records were reviewed to identify intersections meeting all of the following criteria.

1. Accident rate greater than or equal to 2.0 accidents per million entering vehicles. (ADOT generally considers intersections having an accident rate of greater than 2.0 to be an intersection with an unusually high accident rate.)

2. Approach volume greater than or equal to 500. (The accuracy of the approach volume on very low volume roadways is questionable, as it can result in misleadingly high accident rates. Therefore, intersections with very low approach volumes were not considered.)

3. Total number of accidents in a four year period greater than or equal to four.

A review of all intersections in the state highway system identified 39 locations which met the above criteria. A comparison of these locations with a list of signalized intersections showed that some of the 39 are currently signalized. Locations of some of the other intersections are in urban areas where conventional power is probably available. Considering these factors, there may be as many as nine locations which meet the above criteria which are not signalized and do not have conventional power available. These nine locations are potential sites which could benefit from a flashing beacon. Additional locations likely exist off the state roadway system.

The research team recognizes that the Arizona Department of Transportation does not routinely use flashing warning lights and that they are used by ADOT only when lesser traffic control devices have been unsuccessful. Potentially, the locations mentioned above may be locations where lesser traffic control devices have been (or would be) unsuccessful. The use of flashing warning lights at these locations should be considered.

CHAPTER 4
DESIGN OF PHOTOVOLTAIC SYSTEMS

As a result of the technical and economic feasibility study, three photovoltaic systems were selected for design, construction and field testing.

The three systems were designed to serve as direct replacements for existing electric utility power supplies. This was so that their loads could be served by the electric utility if at any time the photovoltaic systems became inactive. The photovoltaic installations served as a basis of field experience for ADOT personnel in construction and maintenance of photovoltaic systems.

A photovoltaic system designed without backup from the utility would be simpler and more efficient. However, reliability of an all dc system operating in that mode has not yet been proven. If consideration is to be given to more extensive use of photovoltaic systems in ADOT sites, dc systems should be investigated.

The designs, then, were based on use of traditional lamps and fixtures, without modification. Ballasts were unchanged, and controls were the same.

The systems were all designed so that four consecutive nights of operation could be powered from battery storage. The systems could thus continue to operate in a "worst-case" scenario of three consecutive cloudy days.

COMMON DESIGN SPECIFICATIONS

Certain features of the photovoltaic system design are common to all three photovoltaic applications. These common features are presented in this section. In the three sections that follow, features which are unique for each application are described.

Primary components of each system are the photovoltaic modules. An illustration of a typical 40 watt photovoltaic module is shown in Figure 1.

In addition to photovoltaic modules formed into an array, each system also has lead acid batteries with a charge controller, an inverter, and the connected load. The components are noted in the block diagram of Figure 2. The array transforms solar energy into

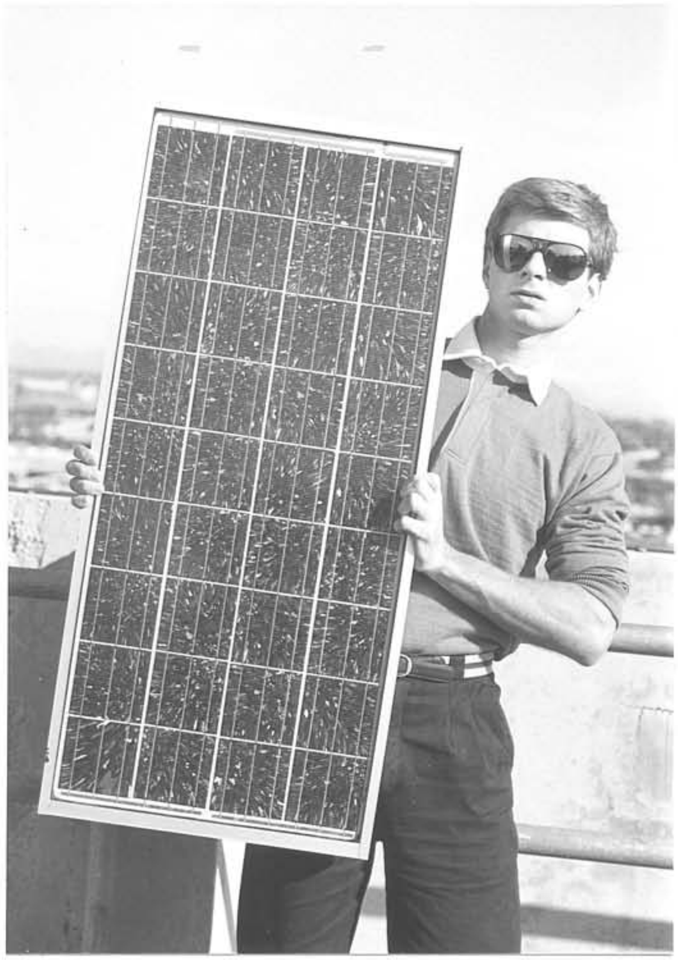


Figure 1. Typical 40 Watt Photovoltaic Module

electrical energy, which is stored in the batteries if its immediate use is not required. The charge controller prevents overcharging or excessive depletion of batteries. The inverter converts the dc energy to an ac form which is somewhat comparable to utility energy.

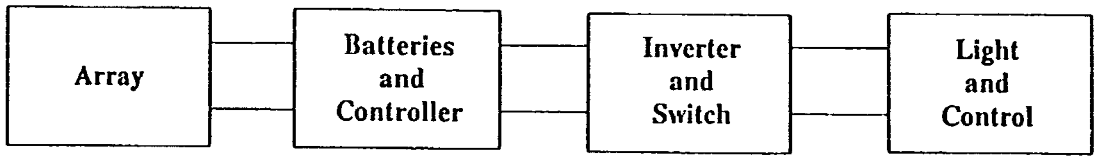


Figure 2. Schematic of Photovoltaic System

The detailed interconnection of the system is shown schematically in Figures 2a and 2b. Note the diodes that prevent battery discharge through the photovoltaic modules in periods of low sunlight.

Each array consisted of small photovoltaic modules interconnected through flexible conduit, using #12 Cu, THHN wire. Array circuitry depended on the vendor's particular hardware. The number of photovoltaic modules depended on the wattage of the modules that were selected. The voltage of each module was compatible with a nominal 12-volt system. Thus, the photovoltaic modules, protected by blocking diodes, were formed into a 12-volt system with the battery bank and charge controller.

The battery bank consisted of sealed lead acid batteries with negative plates of lead calcium, each rated 13.5 volts, 54 amp hour capacity to 10.5 volts with a 48-hour discharge rate. Each battery was capable of 1000 cycles to 50 percent depth of discharge and 500 cycles to 80 percent depth of discharge, at a 6-hour rate. The batteries were expected to have a 5-year life if the maximum depth of discharge did not exceed 25 percent. Battery interconnects were #4 Cu. For the designs described in this report, the batteries provided sufficient storage capacity to power the load over a period of four nights in the event that the intervening three days were to have limited solar insolation. It should be noted that these lead calcium batteries are capable of withstanding much more severe electrical abuse, discharging more often and to greater depths of discharge than those commonly used in automotive or industrial applications. They are structurally more sound and they will absorb more physical abuse and thermal cycling than those that are used for backup in fixed stations.

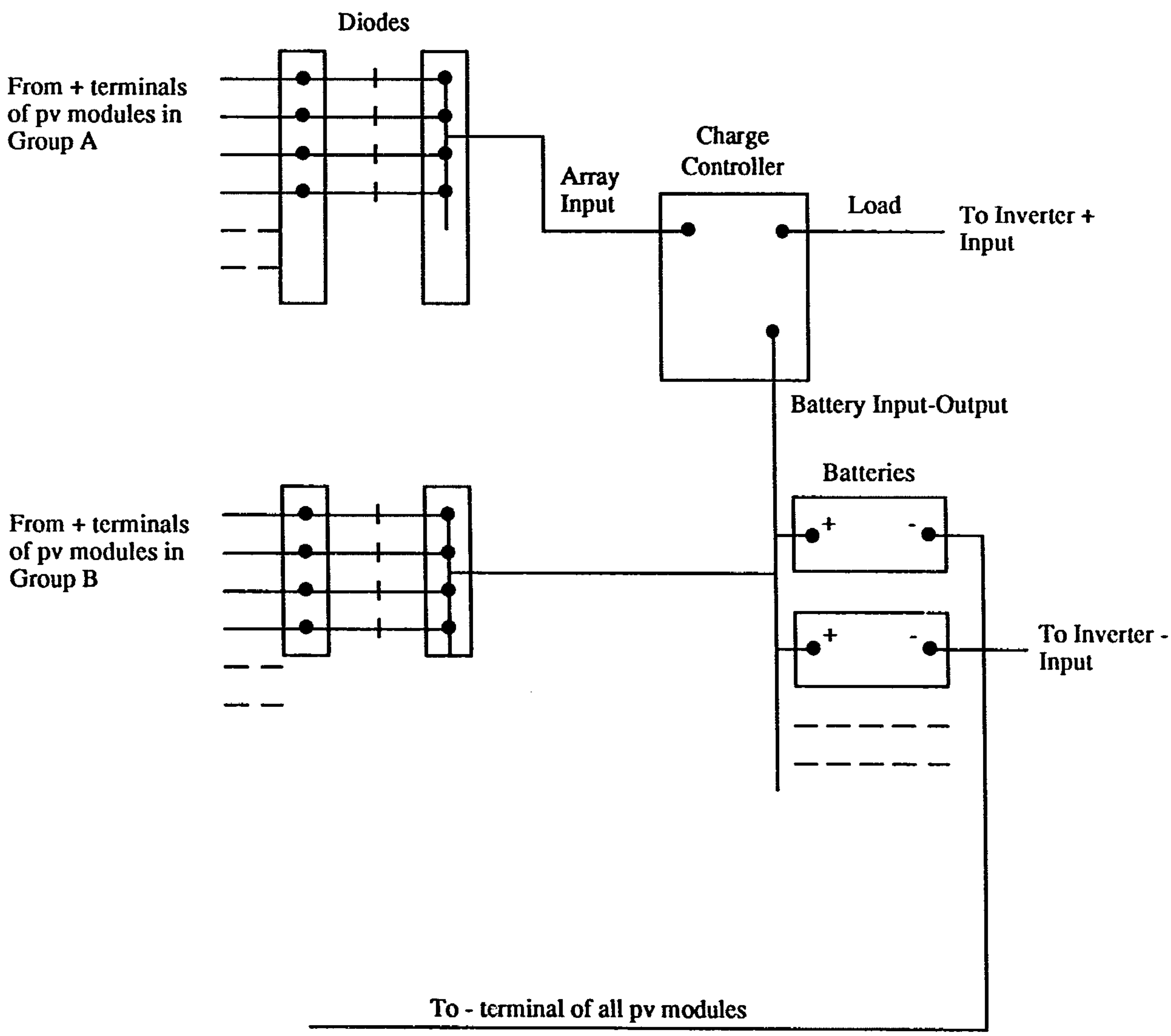
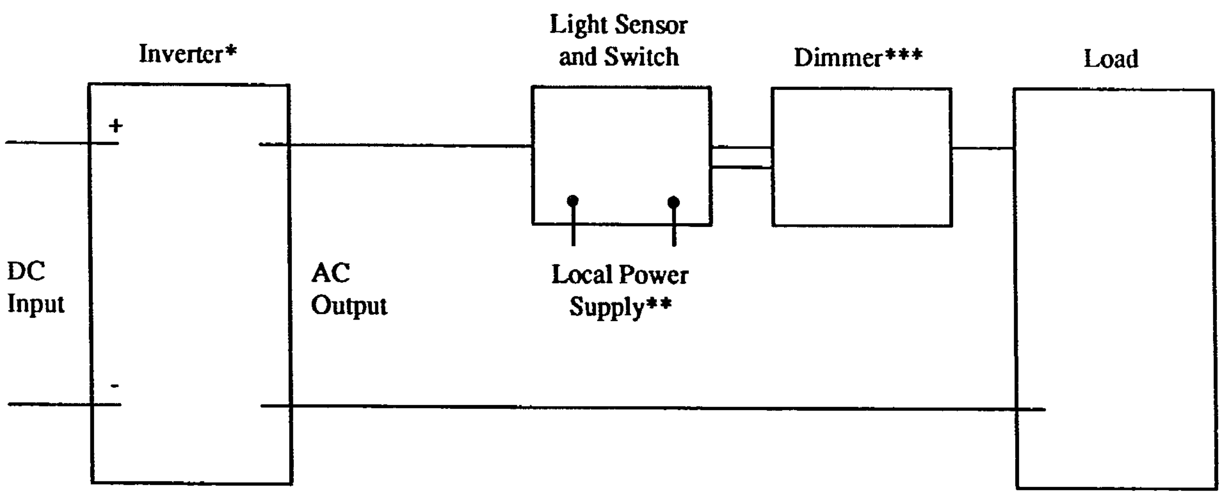


Figure 2a. Electric Circuit Details, DC System



* Load sensor disconnected for unit that supplies any continuous load, i.e. the flasher

** The inverter output can serve here, if the load is continuous; for time scheduled loads, this should be an independent source, from the battery bank.

***The dimmer is used only for the flasher

Figure 2b. Electric Circuit Details, AC System

The charge controller specification depended on the photovoltaic modules selected, but it was capable of regulation to prevent overcharge of the batteries. Not all modules were routed through the controller, allowing for equalizing current flow and also saving in the sizing of the controller.

An inverter served to interface between the batteries and the lighting load. It was rated at 500 watts 12 volts dc input, 120 volts 60 Hz output with a modified sine waveform. Inverter wiring was #6 Cu, THHN on the dc side, and #12 Cu THHN in flexible conduit on the 60 Hz side. A switch permitted choice of inverter power or utility power to the light fixture. If a failure of the photovoltaic power supply occurred at the test site, the lighting system could be manually switched to the utility power supply.

The array structures in the project were custom designed for each particular installation site. The array structure detail depended upon both the dimensions of the photovoltaic modules selected and the structure to which each was mounted. The structure was fabricated primarily from hollow aluminum square and rectangular tubes (2 inches x 2 inches, 2 inches x 3 inches and 2 inches x 5 inches). Module attaching bolts were plated and compatible with the aluminum structure and the module framing materials.

Photovoltaic panels were installed with a tilt angle of 50 degrees from the horizontal, facing south. The 50 degree tilt angle was used because it optimized performance of the solar panels during the winter months - the time of year which is critical for system performance. The winter is critical because there are fewer hours of sunlight to collect solar energy and more hours of darkness requiring nighttime illumination. Tolerance in tilt angle was +/- 5 degrees. East-west orientation was +/- 10 degrees from south.

These tolerances are very acceptable because, within these ranges, there is almost no impact on the amount of energy produced by the solar panels. These liberal tolerances greatly simplify installation in the field. This high tilt angle favored the December-January period for energy production from the array. That period was the time of greatest load for the street and sign lighting systems. See the fourth page of Appendix B.

The inverter, charge controller, diodes, and switch were enclosed in a NEMA 3R enclosure. The batteries were placed on a shelf shaded by the array. The shelf was not closed or weatherproofed, allowing easy ventilation of any hydrogen escaping from the batteries.

For purposes of system testing, performance was monitored by measuring the state of charge of the batteries. A termination suitable for a dc voltmeter was installed to measure the state of charge of the batteries.

The system components had expected lifetimes approaching 20 years, except for the batteries, which experience shows are limited to a life of about five years. Inverters and controllers are designed by manufacturers to have a 20 year life if they are not abused. They are, however, subject to severe damage if abused. Because there is limited experience with inverters and charge controllers in photovoltaic systems, there is some question about their actual life.

The design specifications for the electrical elements in the systems are derived as follows:

1. The period of greatest energy need of the load is determined. This period coincides with the time of least energy availability from the sun. The daily energy need of the load is then determined for that period.

2. The energy losses in supplying that load, in the inverter and in the batteries, is added to that load determined in item 1 above. (Distribution copper losses are usually small.) The inverter is chosen for maximum daily efficiency. Generally, for a given load requirement, the inverter efficiency will vary directly with dc voltage level. Therefore, the inverter that can supply the ac load, that operates with minimum tare load losses, and operates from larger dc voltages will be chosen. Tare losses can be minimized, for cyclic loads that are periodically zero, in inverters that incorporate load sensing circuits so that the inverter is energized only when the load requires it.

   The inverters were considered to be essential components of these experimental systems. Their use allowed for the photovoltaic system to be interchangeable with the traditional utility system. However, it should be noted that some lighting fixtures are available with ballasts that operate directly from dc. In a system committed to operate from the photovoltaic source only, a more efficient (smaller) system can be implemented without the inverter.

3. Battery capacity is then determined as being four times that daily requirement noted in item 2 above. This is that smallest battery pack that will be discharged to no less than 25 percent of rated capacity over those load periods during which low sunlight may occur.

4. The photovoltaic array is then determined as that array that can supply the load determined in item 2 above, with some margin determined from the designer's experience. The array rating can be minimized by choosing a south facing array, tilted from the horizontal so as intercept the maximum sunlight during the period of maximum load. See the fourth page of Appendix B for quantitative data in that regard.

OVERHEAD GUIDE SIGN LIGHTING

At the time this study was conducted, the Arizona Department of Transportation used fluorescent lighting for guide signs. The fluorescent fixture used by ADOT included two 85-watt lamps and a low power factor ballast. It operated from a 120 volt, 60 Hz power supply. Total power consumption by this fixture was measured at 177 watts in a recent study on alternative lighting systems for guide sign illumination. During December and January, the season critical to a photovoltaic system's energy development, the light is on 14 hours per day.

For the test site at State Routes 87 and 587, the photovoltaic powered sign lighting system was designed to power one fluorescent fixture. To power one fluorescent fixture, the photovoltaic array was designed to have a minimum rating of 780 watts at 25 degrees Celsius (77 degrees Fahrenheit) and in sunlight of 1000 watts per square meter (92.9 watts per square foot). Array circuitry consisted of twenty 40-watt modules.

The design required ten lead acid batteries of the type described in the preceding section. Fifteen batteries were actually installed in the field to provide an improved probability of performance.

This photovoltaic system was also designed to accommodate the new high pressure sodium sign lighting system which ADOT has recently adopted. This system has a total power requirement of 196 watts (150 watts for the lamp, the remainder for the ballast). At 196 watts, the system design is slightly oversized (10 percent) for use with the fluorescent fixture.

For the test site on State Routes 87 and 587 south of Chandler, the array structure permits the modules to be mounted on the primary sign structure on the back side of the sign.

In summary, the overhead guide sign lighting system required the following:

Photovoltaic modules	800 watt
Batteries	10
Charge controller	20 amp
Inverter	500 watts, 12 volts dc input 120 volts 60 Hz output

The approximate cost of the above hardware, plus miscellaneous features, was:

Photovoltaic modules	$4,000
Batteries @ $75 each	750
Charge controller	400
Inverter	600
Enclosures, wiring structures, etc.	500
	$6,250

ROADWAY LIGHTING

The roadway lighting luminaire is a 150-watt, 120-volt, 60 Hz high pressure sodium lamp and fixture. It was assumed to operate 14 hours per day in winter months.

This system design is essentially the same as the system described for the overhead sign light. As noted above, the system for the overhead sign light was designed to serve either a fluorescent or a high pressure sodium light source. The following equipment was required for the roadway lighting system.

Photovoltaic modules	800 watt
Batteries	10
Charge controller	20 amp
Inverter	500 watts, 12 volts dc input 120 volts, 60 Hz output

Eighteen batteries were actually installed in the field to provide an improved probability of performance. The test site for this application was on the southwest corner of State Route 87 and Riggs Road. The structure for support of the array and the other components were not originally in place at this location. The utility pole supporting the roadway luminaire was supplemented with a second utility pole to provide a structure for support of the array.

Costs for hardware were:

Photovoltaic modules	$4,000
Batteries @ $75 each	750
Charge controller	400
Inverter	600
Enclosures, etc.	500
	$6,250

FLASHING WARNING LIGHT

The research team designed systems to power both a single flashing warning light and a double flashing warning light. A flashing warning light is a 135-watt incandescent lamp operated from a 120-volt, 60 Hz power supply, 24 hours per day with a duty cycle of 50 percent.

Operating from a photovoltaic source through an inverter in the same fashion as the overhead sign light, the system detail for a single flashing warning light would be as follows:

Photovoltaic modules	440 watts
Batteries	7
Charge controller	10 amp
Inverter	500 watts, 120 volts, 60 Hz

Hardware costs would be estimated as:

Photovoltaic modules	$2,200
Batteries @ $75 each	525
Charge controller	400
Inverter	600
Enclosures, etc.	450
	$4,175

This cost estimate is less than that estimated in the feasibility study (page13) due to more accurate information on the size needed for this system.

A DOUBLE FLASHING WARNING LIGHT

A double flashing warning light is basically two of the single flasher systems and was the one that was installed for field testing. Small savings can be achieved in a double flashing warning light by having one inverter and one charge controller serve two lamps. Installation costs would also be reduced.

The approximate cost of the hardware, plus miscellaneous features, was:

Photovoltaic modules	$4,400
Batteries 14 @ $75 each	1,050
Charge controller	400
Inverter	600
Enclosures, wiring, etc.	500
	$6,950

For field testing, an existing set of two flashing warning lights at the State Route 87/587 junction were used. The flasher is located approximately 210 feet from the sign structure used for the overhead guide sign lighting application and the photovoltaic array for the flashing warning light system was mounted on the overhead sign structure. Power was provided from the array to the flasher via underground wiring. Wiring sizes for the ac side were larger than the previously described systems to allow for the longer run, underground, to the flasher location.

It can be noted that all of the installed systems used an inverter rated at 500 watts. This was the smallest unit of the required quality that was available in the marketplace. It is also noted that the dc input was only 12 volts. Greater system efficiency can result if an inverter becomes available with: (a) about 300 watts rating; and (b) dc operating voltage greater than 12 - such as 24 or 48 volts.

The inverters were purchased with a load-sensing system that prevented energy drain when the load was off. This feature was deactivated on the flashing warning light system, because the flashers operate continuously. The load-sensing system was deactivated on the other two systems because easier ways of performing the function were available. The load switch was moved to the input side of the inverter.

The inverters also had a load-shedding control that prevented excessive drain of the batteries. This system was also deactivated because it duplicated a similar function in the charge controller.

CHAPTER 5
CONSTRUCTION AND INSTALLATION OF SYSTEMS

All three systems were installed for field testing at sites on Arizona State Route 87 approximately six miles south of Chandler. The roadway lighting system was installed on the southwest corner of State Route 87 and Riggs Road, and was mounted on two utility poles. The overhead guide sign light system was mounted on an overhead guide sign structure at the junction of State Routes 87 and 587. This sign structure also supported the system for the flashing warning lights. Underground wiring ran from this point to the flashing warning lights located about 200 feet away.

Construction of the support structure for the photovoltaic modules, batteries, and other electrical components was found to be labor intensive. This operation consisted of cutting and drilling aluminum tubing, bolting it together and attaching modules. Wiring of the system was also found to be labor intensive. These tasks were accomplished before moving the system to the field site.

Installation of the systems in the field required special labor, and equipment in the form of a crane and a bucket truck. Because each system was unique in its design and personnel had no previous experience in system installation, there was a learning curve in installation. As was the case with construction of the support structure and wiring, installation was found to be labor intensive.

Based upon the experience in construction and installation, the research team recommends that ADOT purchase installed systems for future applications of photovoltaics. Use of contractor labor and equipment would be a more effective use of ADOT resources than using ADOT personnel for assembling and installing these systems.

Figure 3 shows some of the special equipment that was used during installation of the roadway lighting system. Figures 4 and 5 illustrate installation of the arrays for the overhead guide sign light system and the flashing warning light system.

Completed installations are shown in Figures 6 (roadway lighting system), 7 (sign lighting and flashing warning light system) and 8. Figure 8 shows the flashing warning lights that are powered by the photovoltaic system; the photovoltaic array is in the left background.

Figure 3. Installation of the Roadway Lighting System

Figure 4. Installation of the Array for the Flashing Warning Light System and the Sign Lighting System

Figure 5. Detail of Structure Used for the Flashing Warning Light System and the Sign Lighting System

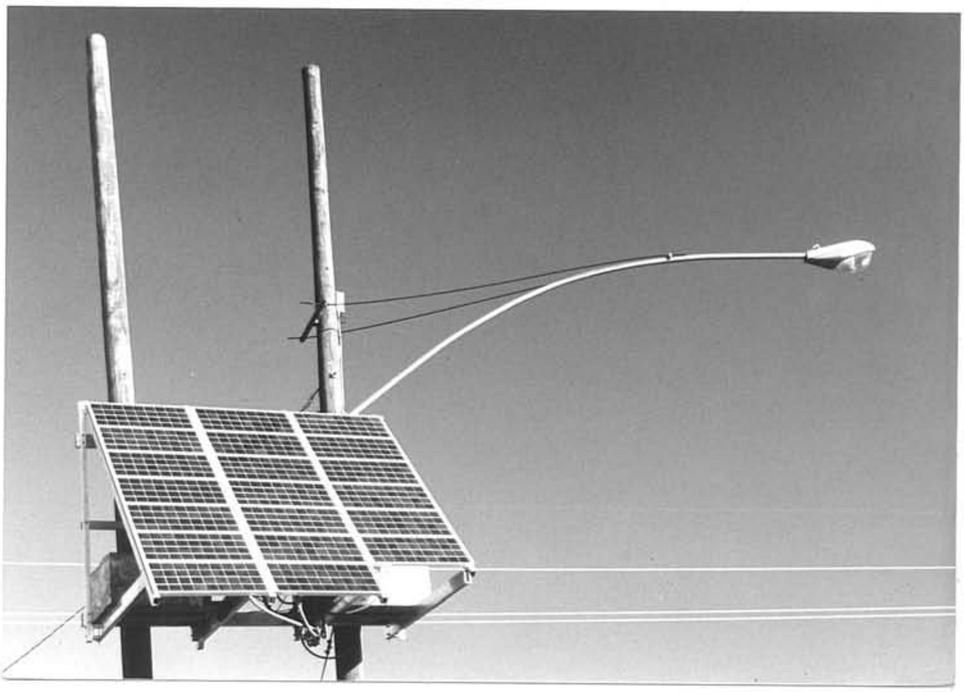


Figure 6. Completed Roadway Lighting System

Figure 7. Arrays for the Sign Lighting System and the Flashing Warning Light System

Figure 8. Flashing Warning Lights Powered by the Photovoltaic System

CHAPTER 6
FIELD TESTING

As noted earlier in this report, the intent of these first photovoltaic power systems was to provide systems that could substitute as directly as possible for electric utility supplies. Early field testing began, then, with each load and load control in an unmodified configuration. The standard photocell control for originating system changes with sunlight, their surrounding switching circuitry - including dimmers for the warning lights - were left intact. These dimmers were fabricated by ADOT personnel and provided a reduced power to the load by insertion of a diode circuit that effects half-wave rectification of the ac voltage input.

In the overhead guide sign and roadway lighting systems, the standard photocell acted as a load and kept the inverter turned on regardless of the need for light. Even in the summer months when the photovoltaic systems provide greatest energy and when the lighting system basic loadings were low, the losses caused by the photocell loads became cause for concern.

An early design change in the photocell control system was then initiated. Photocells and associated switching functions that operated from the 12-volt dc supply, rather than from the 120-volt ac supply, were a major goal. Such switching systems could save up to 40 percent of the no-load (tare) losses in the inverters and prevent cycling of their load sensors.

Attempts to locate photocell systems that might have been developed and tested for use in the recreational vehicle market proved unsuccessful. A local design effort was mounted, an effort that has produced what is expected to be reliable hardware. Prototypes are now in the field, but there has not been sufficient test time to make conclusions regarding reliability. That testing should continue.

No problems have been encountered with the traditional dimming controls, the rectifying systems used for the flashing red warning lights. It may be that more efficient dimmers can be developed, but to date no effort has been applied to that task. However, it is clear that the dimmer system now used causes no problems with the inverters or associated parts of the photovoltaic systems.

The charge controllers for the lead acid batteries have proved to be less than ideal. The charge controllers are intended to control the current from the photovoltaic array so as to maintain the maximum permissible state of charge of the batteries for the sunlight that is available, considering also the load imposed on the batteries. Charging current is permitted when the array produces it and when the batteries require it. The controllers also incorporate a load disconnect feature that operates if the battery state of charge becomes low enough to jeopardize the lifetime of the batteries, to below 10.5 volts.

The charge controllers have operated continuously since first installation, and no electrical or mechanical failures have occurred. However, their sensitivity to state of charge, or lack of it, is of concern. The existing charge controllers do not maintain the batteries in a maximum state of charge. Once the batteries reach a maximum state of charge, the array is then switched off. The controller will not switch the array back on until the state of charge of the batteries has deteriorated to mid range, thus jeopardizing the ability of the system to meet the next load cycle adequately. It is technically feasible to reduce this sluggishness in response, and an effort should be made to correct that feature in those controllers or to obtain more sensitive units from other suppliers.

However, field testing has validated the reliability and serviceability of the major system components. The photovoltaic arrays have caused no electrical or mechanical concerns. The poles supporting the roadway lighting array did lean a few degrees when they were loaded with the array, batteries, and other equipment. The lean increased the effective tilt angle of the modules. No serious reduction in energy production occurred, but the glare from this overextended array did reflect into traffic lanes at midday. Until the lean was corrected with guy wires, the array was covered and the system was inoperative.

The batteries themselves have caused no problems. Mounting them 20 feet above ground proved effective in preventing theft and vandalism. This also facilitated the side venting of hydrogen gas from the batteries. Shading of the batteries from direct sunlight is very important, wherever they may be mounted: heat is a special problem, and it must be limited.

Maintenance of the major units in the photovoltaic systems has not been a problem overall. The sealed batteries used in field testing do not require periodic addition of water. The high mounting of the solar panels has likely resulted in less dust accumulation than would have resulted from mounting them on the ground. Prior experience with solar panels indicates that dust accumulation results in very minor losses in performance (2 to 3 percent). Thus, washing of the panels is not required.

The peripheral components (charge controller, inverter, and photocell control) should be tested further, and an effort should be made to continue their development.

CHAPTER 7
ECONOMIC ANALYSIS

REPLACEMENT OF EXISTING CONVENTIONALLY-POWERED SYSTEMS

Chapter 4 presented the hardware costs for each of the three systems field tested in this project. Generally, the installation cost for a system will be equal to the total hardware cost minus the cost for the photovoltaic modules. Estimated initial costs for each of the systems tested in this project are presented below. It should be emphasized that these costs will vary depending upon geographic site, lamp wattage to be served, and other parameters. Most hardware components are expected to have a 20 year life. The batteries are an exception; their expected life is five years.

	Hardware Cost	Installation Cost	Total Cost
Overhead Guide Sign Lighting	$6,250	$2,250	$8,500
Roadway Lighting	6,250	2,250	8,500
Flashing Warning Light	6,950	2,550	9,500

At these costs, photovoltaic power systems cannot be economically justified in retrofit situations unless some very special consideration pertains. Energy costs from photovoltaics cannot compete with costs from electric utilities if reasonable capital costs are assessed against photovoltaics, and if the utility drop is available at little or no cost.

NEW SYSTEMS

The relative economics of photovoltaics versus a conventional power supply is highly site-specific and greatly dependent upon the required size of the photovoltaic system. Although broad generalizations can be made here, a separate analysis should be made for each individual application that the user wishes to consider. The analysis does not need to be highly detailed or time consuming, and the relative economics are fairly easy to determine.

The utility extension costs are usually dominant in consideration of economic factors. The capital costs of a photovoltaic system are also dominant in that choice. Oftentimes, the cost of energy as purchased from the utility is relatively small. The cost of energy from the photovoltaic array, after initial investment costs are accounted for, is an estimate of maintenance and replacement costs of the shorter-lived parts of the photovoltaic systems-- the batteries are dominant in that determination. If the utility charges per year for energy use are balanced roughly with the yearly replacement cost of the photovoltaic system components that most often need to be replaced, a quick comparison of the initial cost of the photovoltaic system with the initial cost of the utility system connection is sufficient to make the determination. If: 1) utility energy charges are high and photovoltaic system component replacement costs are relatively low, and 2) the initial cost for a photovoltaic system is less than the initial cost for a utility line extension, then a photovoltaic system is the more economical choice.

With utility line extension costs in many remote regions priced at $20,000 per mile or more, photovoltaic systems warrant consideration in the event electrical energy is needed for any extended period. Even for short-term energy needs, photovoltaics can compete with internal combustion drives if the modularity and portability of photovoltaic systems are given proper weights. Inherent in all of the economic calculation is the fact that small energy-conserving loads favor photovoltaic system use. Large loads may favor utility line extension.

CHAPTER 8
RECOMMENDED SPECIFICATIONS FOR PHOTOVOLTAIC SYSTEMS

Those photovoltaic systems that would be considered economically feasible at this time or in the near future will be those that would be installed in a location not now served by a utility's distribution system, where the cost of extending electric utility lines is prohibitive. In these situations the likely competition to photovoltaic power are replaceable batteries, wind generators, internal combustion engine driven generators, geothermal energy conversion systems, and hydro power. Photovoltaic systems operating in conjunction with an electric utility are usually demonstration systems implemented to gain experience with the technology and to improve the technology. Demonstration systems are often developed in anticipation of a future time when electric utility energy is expected to increase in cost and when photovoltaic systems are expected to cost less. Photovoltaic systems may compete with electric utilities in 5 to 15 years, depending on many difficult to predict factors affecting utility costs and photovoltaic system costs.

A photovoltaic system may be a power system standing alone, with no backup. That configuration was the only one considered in this study. But there may be systems in which a hybrid arrangement, with a motor generator for backup, may be more feasible and perhaps should be considered. Hybrid systems could be very attractive at locations where sunlight is unpredictable, where the system load is erratic, or where maintenance personnel can easily monitor the system's state and take corrective action in the event of low system capability.

In setting specifications for a stand-alone photovoltaic system, the major factor is energy, its form, and its schedule of use. The energy output, if well known without numerous contingencies, can be the basis for a minimum cost, lowest maintenance system. Coupled with knowledge of sunlight incident to the project's location and its expected time schedule, a system can be defined that best takes into account the temperature, wind conditions and other factors that affect efficiency and safety. System specifications generally define system output, define system input, and set any specific physical constraints to be accommodated and codes to be followed.

SYSTEM OUTPUT SPECIFICATIONS

The voltage, current, waveform, and power factor of the electrical load in steady state and during the startup transient must be set. The schedule of use for significant periods of the day or night and for significant periods of the year must be set. Lighting loads may be ac or dc. Dc loads are favored, because the power system can be simpler, more efficient, and more reliable. Many lighting loads are more severe in the short days of winter months. Generally, higher voltage levels are preferred to improve efficiency and reliability. Many loads, ac and dc, will invariably have large starting inrush currents which must be accounted for in system design and protection. But all lighting appliances have a similar, lower tendency to require higher starting current.

If the system must be operable for every day of the year without fail, the specification must be emphasized. If an outage can occur without catastrophe, however, the design can be much less costly.

The lowest cost, most reliable system will be one that supplies dc loads. Inasmuch as most system users are schooled to work with utility-supplied ac equipment, much could be gained in photovoltaic system utilization by reasonable exploitation of dc-operated appliances -- some available off the shelf from suppliers of recreational vehicle hardware. However, current exploitation is limited by current traffic control device specifications which prescribe standard designs for lamps, signal heads and lighting fixtures.

Thus, the system output specification is set after a very careful determination of the load. The energy load must be minimized by selecting the most efficient loading devices. The load form that is served with the least processing of the dc inherent in a photovoltaic system not only improves efficiency but also improves reliability. But if the energy form must be ac, its voltage, current, power factor, and susceptibility to waveform distortion must be indicated.

The system output specification is best noted by specifying the loading devices and their specific needs in the form and quality of power. Tolerances in each of the measures of power quality should be set. The schedule of use of each load, by typical day and by calendar season, must also be set. Whether the photovoltaic system will include the control system that schedules the use of the loads should be noted.

SYSTEM INPUT SPECIFICATIONS

The system input is sunlight. For flat photovoltaic arrays, the sunlight can be directly from the sun or it may be reflected from some surface and may enter the photovoltaic module at almost any angle. For concentrator arrangements, the lenses or equivalent light processors essentially ignore light that does not enter from the direction of the sun. Considering the state of the art of concentration systems and the potential needs for photovoltaic systems in the next few years, the concern should focus on flat photo arrays and their ability to convert total incident light.

Flat plate modules are rated at basic levels of light and at benchmark temperatures of the cells. The module output varies almost linearly with incident light, but the module's performance is seriously and adversely affected by cell temperature. Cell temperature is a function of sunlight, air temperature, and air movement (wind) that may convect the heat away from the cell and the module.

Given the general geographic area in the region, the light that is likely to be incident for any likely physical mounting of the module can be easily determined. Appendix B summarizes the data for a location in Phoenix. Light will generally be more intense in the clearer atmospheres away from the desert floor, but it may be interrupted more often by clouds. The lower temperatures at points of higher elevation will significantly improve conversion efficiency over those recorded for Phoenix.

The mounting of the modules, their orientation to the horizontal, to the south, to the east or west of south, and the possibility for even partial shading by adjacent structures must be known. The possibility of changing the module mounting with season must be noted. Because air temperature and movement changes from ground to elevated locations on some local structures, the constraints on module structure and its location must be set.

In summary, the macro and micro geography of the site must be set. If known, the sunlight, temperature, and wind profiles should be noted. Any possibility for module mount changes with season or any possibility of module shading must be noted. Additionally, an estimate must be made and noted as to the number of consecutive days of cloudy weather that could occur at the site, so as to refine the energy storage requirement set originally by the load profiles.

OTHER CONSTRAINTS

The specifications regarding the structural strength of the arrays, the wind loading during extreme weather, the snow loading, if likely, the electrical codes considered to be applicable, the battery compartment's ventilation of hydrogen to prevent fire hazards - any special environmental concerns - should be noted. One concern noted only in our recent experience is the possibility of light reflection from the array into oncoming traffic during certain seasons at certain times of the day.

If the components of a system are to be purchased and later assembled for use by ADOT, the system specifications above are the proper beginning. The storage capacity, storage controls, power conditioner (if used), and module requirements can be set. The recommendation, however, is that a system be purchased to perform the load functions at a specific location, unless ADOT prefers to develop the expertise in-house to design the interior details of systems. That expertise would become worthwhile if numerous photovoltaic applications are contemplated. The in-house talent and interest is surely at hand. An understanding of the detailed design can begin to be developed by a careful review of Chapter 4 of this document.

CHAPTER 9

CONCLUSIONS

Photovoltaic systems have been and are being used on an experimental basis for a wide variety of highway engineering applications. In some states, applications such as solar powered traffic counting stations have advanced from experimental stages to routine use.

Use of photovoltaic power supply is practical and economical in selected situations. Generally, the amount of available sunlight must be high, and conventional electric power supply should be unavailable. A photovoltaic power supply is more practical when the power requirements are relatively small. Photovoltaic systems are impractical when power requirements are large, as is the case for full scale intersection signalization. Fixed, or usually fixed, arrays are technically and economically feasible for installation at load sites away from electric utility lines. Photovoltaic systems are generally not competitive at locations with readily available conventional electric power. However, at remote sites where conventional power is not readily available it may cost $20,000 per mile or more to extend utility lines. In cases like these photovoltaics may have strong economic advantages.

The major components of photovoltaic power systems are reliable and could be maintained by ADOT crews without a major new investment in personnel and training. Photovoltaic systems have maintenance needs that only slightly exceed those of conventional systems.

Additional development is required in some control mechanisms.

In selected instances, photovoltaic powered systems provide a safety benefit that would not otherwise be available. Illumination of remote highway intersections which have a high night accident incidence, for example, can result in accident reduction.

CHAPTER 10
RECOMMENDATIONS

Testing of the photovoltaic systems as they are presently configured should continue in order to demonstrate the reliability of major components and the ease with which the systems can be maintained.

It is recommended that the Arizona Department of Transportation pursue a variety of photovoltaic applications. At the current time, photovoltaic system use can be economical under certain conditions and thus provides an immediate benefit. The long term trends in the relative costs of photovoltaic power supply and utility power supply indicate that photovoltaic systems will become more attractive and have wider economical application in future years. It would be to ADOT's advantage to gain experience with photovoltaic systems so that it will be able to develop new applications as opportunities arise.

ADOT could pursue any of the photovoltaic applications described in Appendix A. The most widely used application is power supply for permanent traffic counting stations. This appears to have potential for remote Arizona locations, and could provide an opportunity to install permanent counting stations at locations that thus far have been impractical. Power supply for motorist call boxes also has potential for Arizona. In 1987, ADOT expressed some interest in installing motorist call boxes on Interstate 19 between Tucson and Nogales.

It is recommended that ADOT consider installing the three types of systems tested in this project at selected locations. As stated in Chapter 3, there are:

- Approximately 18 overhead guide signs on the state highway system which are at remote locations where no conventional power supply is available.
- Seventeen intersection locations on the state highway system which are candidate sites for photovoltaic-powered roadway lighting.
- One interstate rest area that does not have a conventional power supply and which had five nighttime accidents in a four-year period.
- Up to nine intersection locations which could possibly benefit from a flashing beacon (warning light).

In addition to the above, there are also potential applications on local roadway systems.

As stated in Chapter 8, ADOT should develop specifications for photovoltaic systems which stipulate system input and output and other constraints but do not specify the "interior" of the system. In addition, ADOT should purchase "installed" systems which will be put in place in the field by the vendor or contractor. These strategies will minimize the burden on ADOT's manpower resources.

If only a small number of photovoltaic installations are contemplated, a photovoltaic system configuration that mimics the utility and supplies ac to the site is recommended. This configuration would require a minimum of new lighting appliances and controls on inventory and would only marginally extend maintenance personnel.

If ADOT chooses to implement a larger number of installations, it is recommended that dc systems be developed and/or specified. Photovoltaic systems with dc output should be installed and dc appliances placed in inventory. The dc systems will cost less and will be more reliable.

CHAPTER 11
RECOMMENDATIONS FOR FURTHER STUDY

A photovoltaic powered system is expensive and competes poorly when large energy uses are necessary. The potential of photovoltaic systems for lighting applications would be enhanced if lighting loads and energy requirements could be reduced, and if systems could be made to more efficiently maximize the conversion of energy into light. These possibilities need further study.

New standards for lighting, based upon research, should be considered. Given that photovoltaic system cost is very sensitive to the required power output, existing lighting standards may provide only marginal increases in effectiveness for major increments in system cost. A lower level of illumination may be justified. Research should be conducted to determine if new standards for lighting could be developed that would have little or no detrimental effect on safety while allowing for significant reductions in the power requirements.

More efficient systems can be developed which use dc rather than ac and which use dc at higher voltage levels than are now being utilized. Use of dc presents the possibility of eliminating the need for an inverter. Systems of this type should be studied, tested and validated.

Identification of other lighting appliances available in the marketplace which will perform the required function more efficiently and with a reduced power requirement is needed.

APPENDIX A
PHOTOVOLTAIC APPLICATIONS IN HIGHWAY ENGINEERING

Ten applications of photovoltaic systems in highway engineering are described in this appendix.

GUIDE SIGNS ON FREEWAYS

As of early 1988, four states have installed experimental systems for guide sign lighting--California, New Mexico, Arizona, and Florida. The sign lighting systems - two each in California and New Mexico - have been in place since 1984. The California and New Mexico sign lighting systems were developed and installed by a private company, Kyocera International Incorporated. One system in Arizona was installed in early 1987, and one system in Florida was installed in late 1987. The California system is located in a climate which has significantly more cloud cover than those in Arizona and New Mexico and, therefore, was designed to provide battery storage to last through ten cloudy days.

These installations have demonstrated that photovoltaic powered sign lighting systems can operate successfully. Experiences in both California and New Mexico have been good. There have been relatively few reliability problems in these four systems. New Mexico had a problem with cold weather (minus 23 degrees C.) affecting the ballast in the lighting system, but this problem was resolved. Routine maintenance is minimal; New Mexico (Reference 2) has reported that only occasional hydrometer testing and watering of the wet-cells have been required. Occasional cleaning of the solar panels improves system performance, and water must be added to the batteries occasionally. The annual energy savings at the two California signs is about 1220 kilowatt-hours.

The New Mexico systems were installed at a total cost to the New Mexico State Highway Department of $5,500 per sign. Comparable cost for a conventionally powered fluorescent sign lighting system would have been $1,160 if a conventional power supply were available at the site.

ROADWAY ILLUMINATION

The authors are aware of photovoltaic roadway lighting systems in at least three states--California, Arizona, and Hawaii. The California installations are used for area lighting in Park-and-Ride lots and have low pressure sodium luminaires. Arizona's test installation is used for lighting a rural intersection, and uses a traditional high pressure sodium lamp. Parking lot illumination is the purpose of the system observed in Hawaii; it also powers a low pressure sodium lamp. A number of manufacturers of photovoltaic systems market systems for area lighting. Many of these systems are down-scaled from those that use conventional power, and do not provide the same level of light output.

FLASHING WARNING LIGHTS

Arizona has developed and installed a system to power a flashing warning light as described in this research report. The system powers two red flashing warning lights which are used to draw the motorists' attention to a stop sign. These flashing lights operate 24 hours a day.

A second warning light application exists in Zion National Park in the State of Utah. At that location, the flashing warning lights accompany signs at each end of a one mile long two-lane tunnel. The sign message reads "WARNING DO NOT ENTER TUNNEL WHEN RED LIGHTS ARE FLASHING." The system is activated by radio control when an accident occurs in the tunnel, when an overheight vehicle becomes stuck in the tunnel, or when an oversize vehicle is being escorted through the tunnel. Since the power demand of this infrequently operated system is low, the size of the photovoltaic array and the size of battery storage is relatively small. Use of a photovoltaic system was ideal in this situation, because the tunnel is located in a remote section of the park which is far from utility lines. Extension of utility lines would have detracted from the scenic beauty of the park.

Private companies have also developed photovoltaic powered flashing warning lights and market them for a variety of uses. Traffic engineering professionals have expressed concern that many of these devices do not provide the level of brightness needed to meet existing standards for traffic control devices.

PERMANENT TRAFFIC COUNTING STATIONS

South Dakota has received more recognition than any other state for its use of solar powered traffic counting stations. The authors also have observed systems of this type in Utah and in Mount Ranier National Park in the State of Washington. In 1982, ten out of 49 continuous count automatic traffic recorders in South Dakota were powered by solar energy (Reference 26). South Dakota's research concluded that a photovoltaic power supply is cost effective and reliable for this purpose. Experience indicates that a solar powered system will pay for itself within three years. For the remainder of a system's 20 year life, the annual operating costs are about one-fourth the cost of conventional electric power.

RAILROAD-HIGHWAY GRADE CROSSING WARNING DEVICES

In 1979, the State of Alaska installed a solar powered system for flasher signals at a railroad-highway grade crossing (References 1, 10). This system is unusual, because at this northern latitude (63 degrees North) there are very long hours of sunlight in the summer and very short hours of sunlight in the winter. Fortunately, there are fewer train operations per day at the site in winter, and the system provides adequate power supply in all seasons. A cost analysis indicated that this system was more cost effective than the throw-away battery bank system it replaced. As a result, solar powered systems were installed at three additional sites.

DUST STORM WARNING SYSTEM

One of the earliest applications of solar energy to highway applications in the United States was as the power supply for a unique dust storm warning system. Portions of the low desert in the State of Arizona have occasional dust storms. High winds blow dirt and dust through the air; this sometimes results in extremely limited visibility and dangerous driving conditions similar to those associated with dense fog. During the 1970's, a system of dust storm warning signs was installed on rural Arizona freeways to warn motorists of impending reduced visibility. When the potential for a dust storm was high, the message on these signs would be changed from a passive message to a warning message. Solar power was used at one of these warning signs to charge up batteries. The power supply was used for the radio remote control of the sign and for changing the message on the sign. This system was installed in 1977.

IRRIGATION CONTROLLERS FOR ROADWAY LANDSCAPING

The California State Department of Transportation (Caltrans) is testing the use of solar energy to power automated irrigation controllers and irrigation systems (Reference 25). Caltrans has over 28 square miles of landscaping, and much of it requires irrigation. Solar energy is also being used to power temporary irrigation systems, which irrigate plants until they become established. Caltrans estimates that over its 20-year life, a system of this type will save $500,000.

REMOTE HIGHWAY MAINTENANCE STATIONS

The largest highway application of solar energy in the United States appears to be at the Caltrans Caples Lake maintenance station in the rugged Sierra Nevada mountain range (Reference 25). This location is remote and far from utility lines. Until 1985, the station's electrical power was provided by two diesel generators which used 40,000 gallons of diesel fuel a year. About 15,000 gallons of propane was used each year for space heating and heating water.

In 1985, a large photovoltaic system was installed which now provides most of the heat and light at the maintenance station. Although a generator still provides a backup in the event of cloudy weather or high power demand, diesel fuel consumption is now only about 4,000 gallons per year.

CATHODIC PROTECTION OF BRIDGE DECKS

Reinforcing steel in concrete bridge decks tends to corrode, particularly in locations where salt is used for snow and ice removal. Corrosion can be retarded by use of cathodic protection, a method by which a small electric current is passed through the reinforcing steel. A photovoltaic system is used at one location on the George Washington Parkway in Virginia to charge batteries which provided the electric current for the cathodic protection.

MOTORIST CALL BOXES

Motorist call boxes have been installed on selected portions of freeway in the United States. A call box is a telephone-like device located at the edge of the shoulder at approximate intervals of one mile. Motorists with flat tires, mechanical problems, no fuel, or other problems can use the call box to summon assistance. In California, 24 call boxes on the Benicia-Martinez Bridge near San Francisco are run by solar power (Reference 25).

OTHER POTENTIAL APPLICATIONS

At least one other application of solar power has been proposed, although it has not been implemented. It is a system for detecting and warning overheight vehicles that there is a low clearance overpass ahead. A system of this type was proposed at the site of a low clearance overpass at a remote location in New Mexico (Reference 21). The system would detect overheight vehicles and actuate a dynamic sign issuing a warning message.

APPENDIX B
SOLAR INSOLATION IN THE PHOENIX, ARIZONA AREA

The amount of electricity which can be produced by a photovoltaic array is directly dependent upon the amount of solar energy which reaches the earth's surface. The amount of solar energy is called solar insolation, and it can be defined as the amount of energy per square meter (kWh/m^2 or kJ/m^2) falling on the earth's surface.

Solar insolation varies from one geographic location to another and varies at a single location by the time of year for four reasons:

1. Solar insolation varies with the height of the sun above the horizon. Lower latitudes receive more insolation than high latitudes.

2. Similarly, at a given location solar insolation varies with the season of the year. In summer, the sun is higher above the horizon and solar insolation is greater.

3. Solar insolation also varies by season because of seasonal weather patterns. Some months have more cloudy weather than others.

4. Some locations have more cloudy weather than others. The southwestern deserts have less cloudy weather than the northern Pacific coast. The higher elevations of Arizona have more cloudy weather than the low desert areas.

Each of the photovoltaic systems described in this report was designed based upon solar insolation in the Phoenix area. The following pages present data on Phoenix area solar insolation.

The amount of solar energy which can be captured for use depends upon the orientation of the collector (photovoltaic panel). The variation of sunlight in Phoenix with collector orientation is summarized in the following pages. These base data apply for the typical meteorological year, and account for the energy that would be input to flat plate photovoltaic modules directly from the sun and reflected from clouds and from the earth. Energy profiles are presented for the year as a whole and for each month of the year.

Two of the systems designed in this project experience maximum loading in periods of shortest days (December and January) when daily insolation is lowest. Therefore, the photovoltaic array must be sized to accommodate those critical periods. Fortunately, the array geometry that maximizes array output in December also provides adequate array output in all other months of the year so that geometry need not be adjusted through the year.

Based upon solar insolation data, the most appropriate tilt angle to maximize array output in December is 50 degrees. An array tilted at 50 degrees from the horizontal, oriented due south, will collect energy as follows:

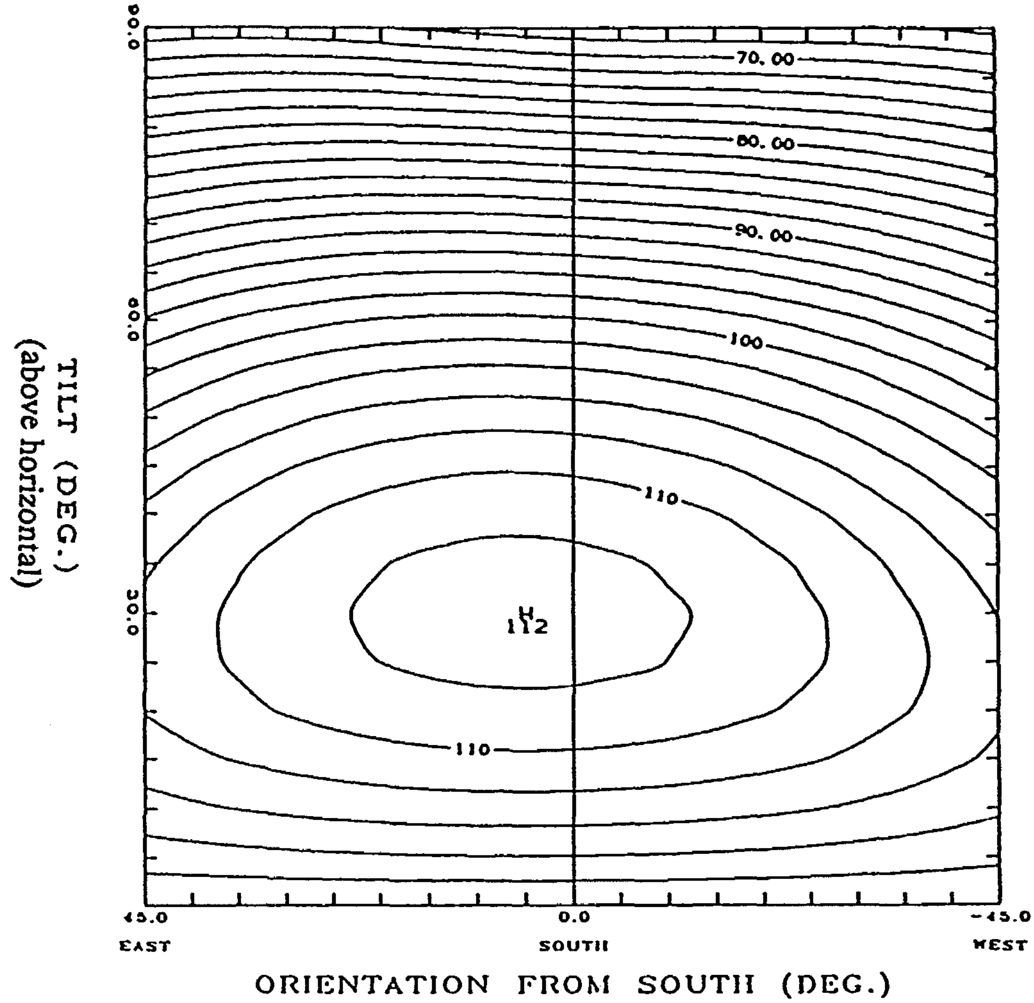
Daily Energy in kWh/m^2

January	5.2
February	5.3
March	6.1
April	5.9
May	5.3
June	5.0
July	4.9
August	5.2
September	5.6
October	5.8
November	5.5
December	4.9

These numbers are derived from the energy profiles, and have been rounded to two significant figures to emphasize their lack of precise application to a specific month of a specific year. The profiles point out clearly that tilt angle and east-west orientation are not critical, and that the array support structure need not be constructed with special care for these considerations.

TMY.* PHOENIX–AZ

ISOENERGY LINES FOR FIXED ARRAY



TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 6547544. (per year)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

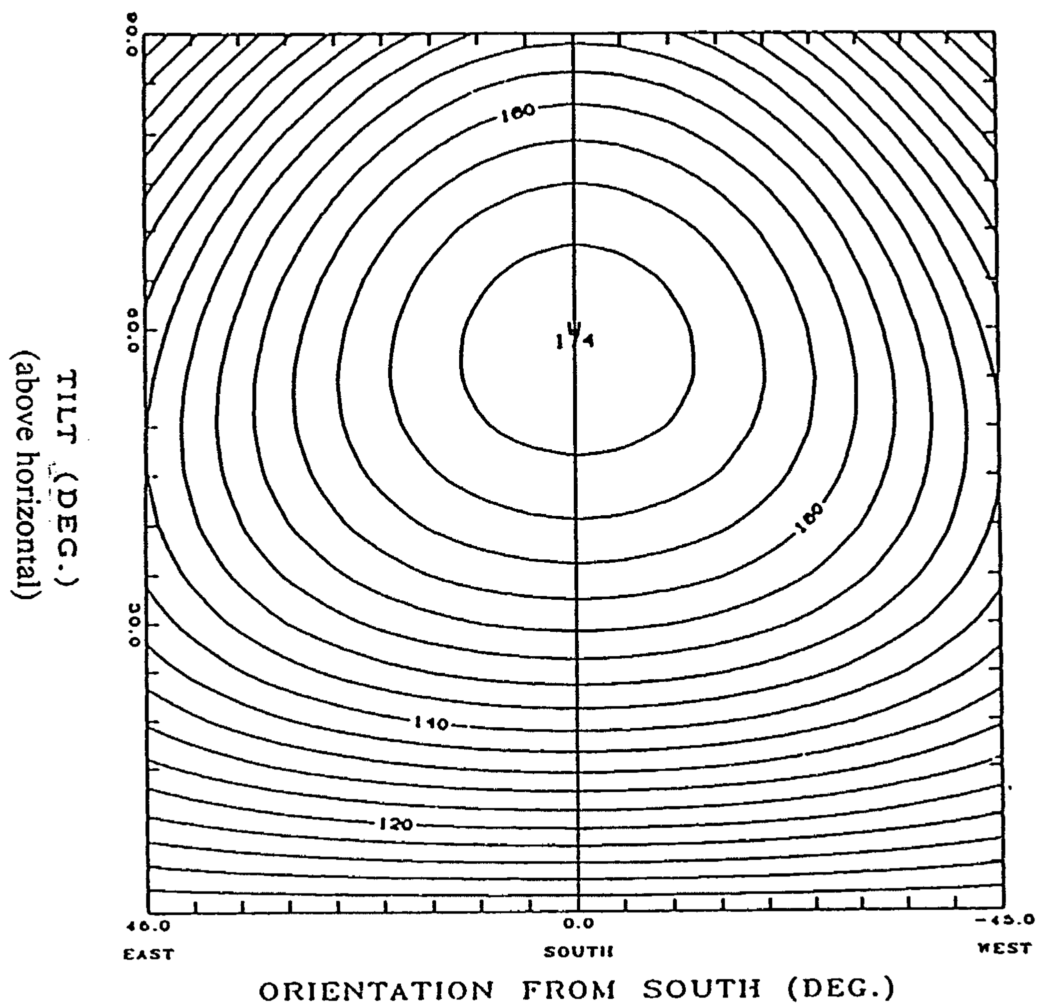
The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array. For example, an array with an orientation 5 degrees east of south and with a tilt of 30 degrees would receive 112 percent as much energy as a horizontal array.

* Typical Meteorological Year

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ JANUARY

ISOENERGY LINES FOR FIXED ARRAY



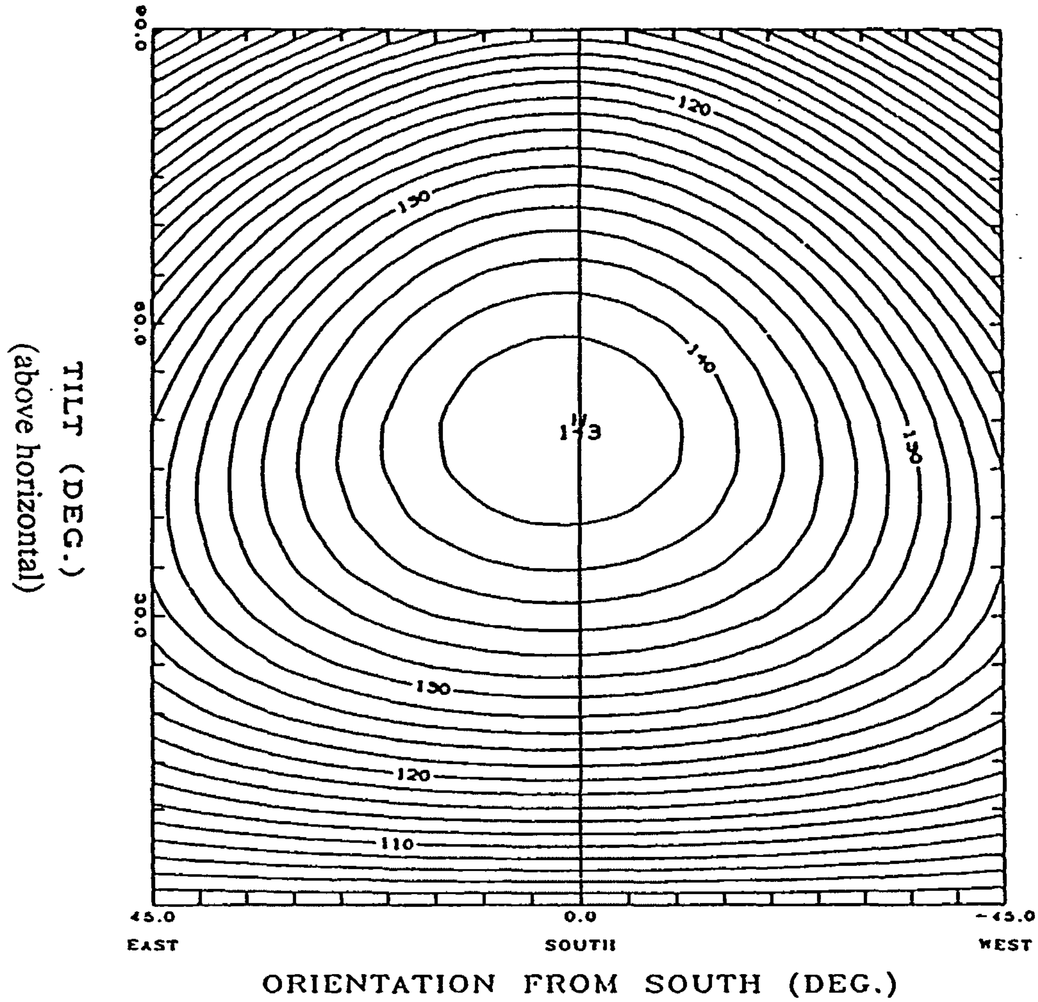
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 321366. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M² OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ FEBRUARY

ISOENERGY LINES FOR FIXED ARRAY



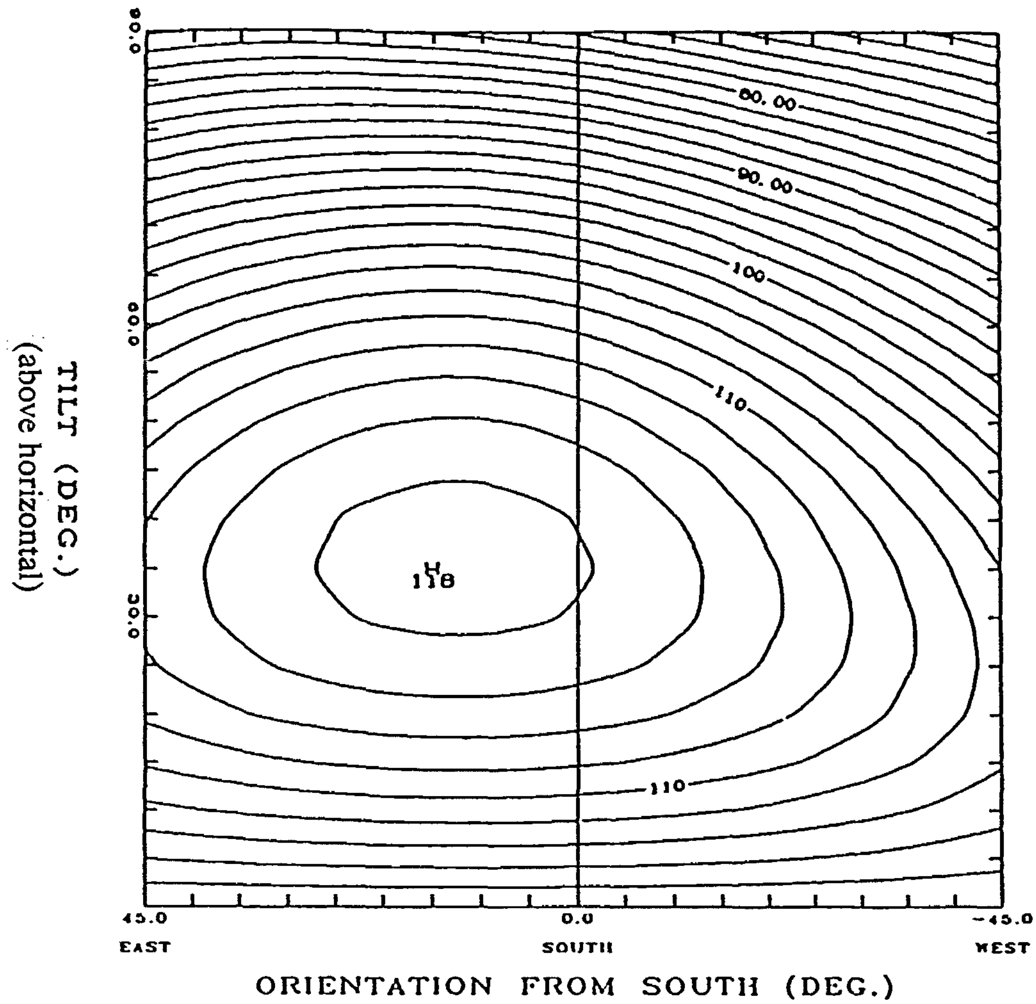
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 400812. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M² OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ MARCH

ISOENERGY LINES FOR FIXED ARRAY



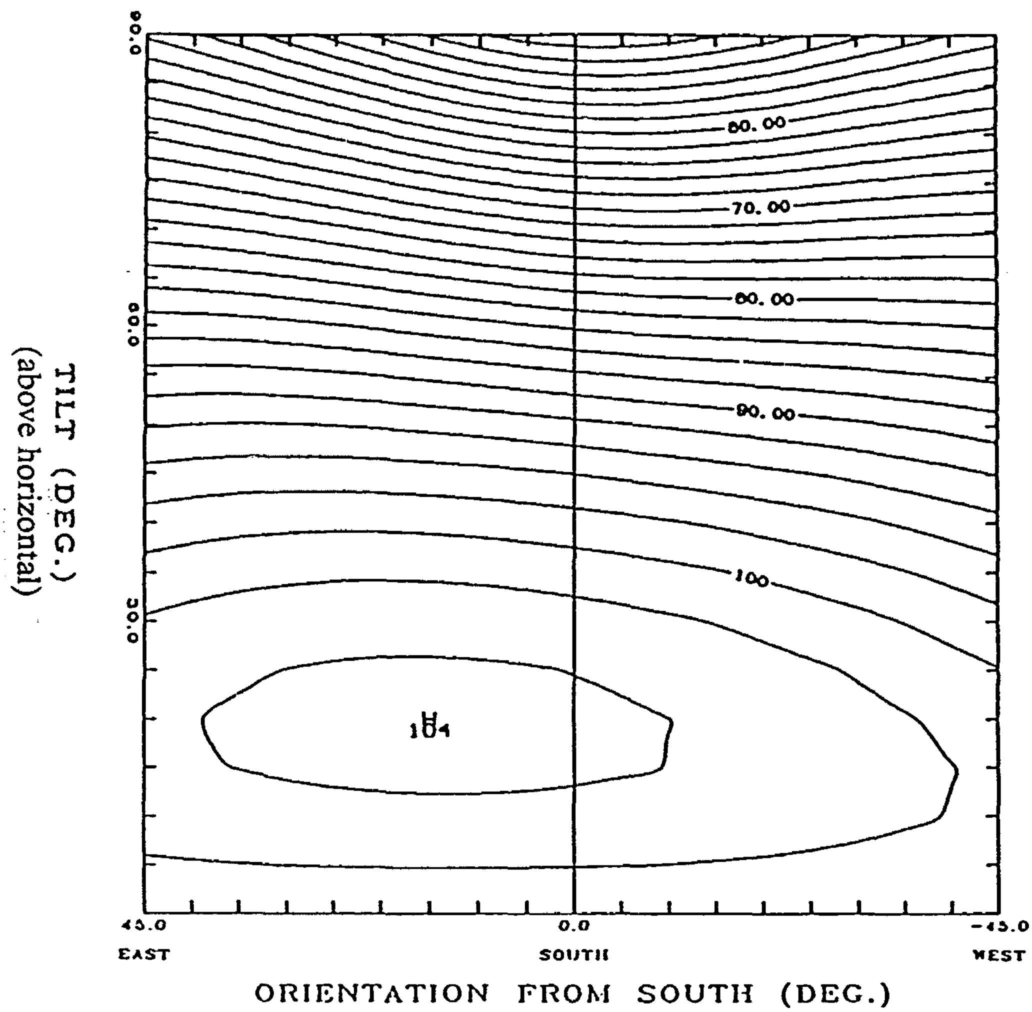
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 673560. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M² OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ APRIL

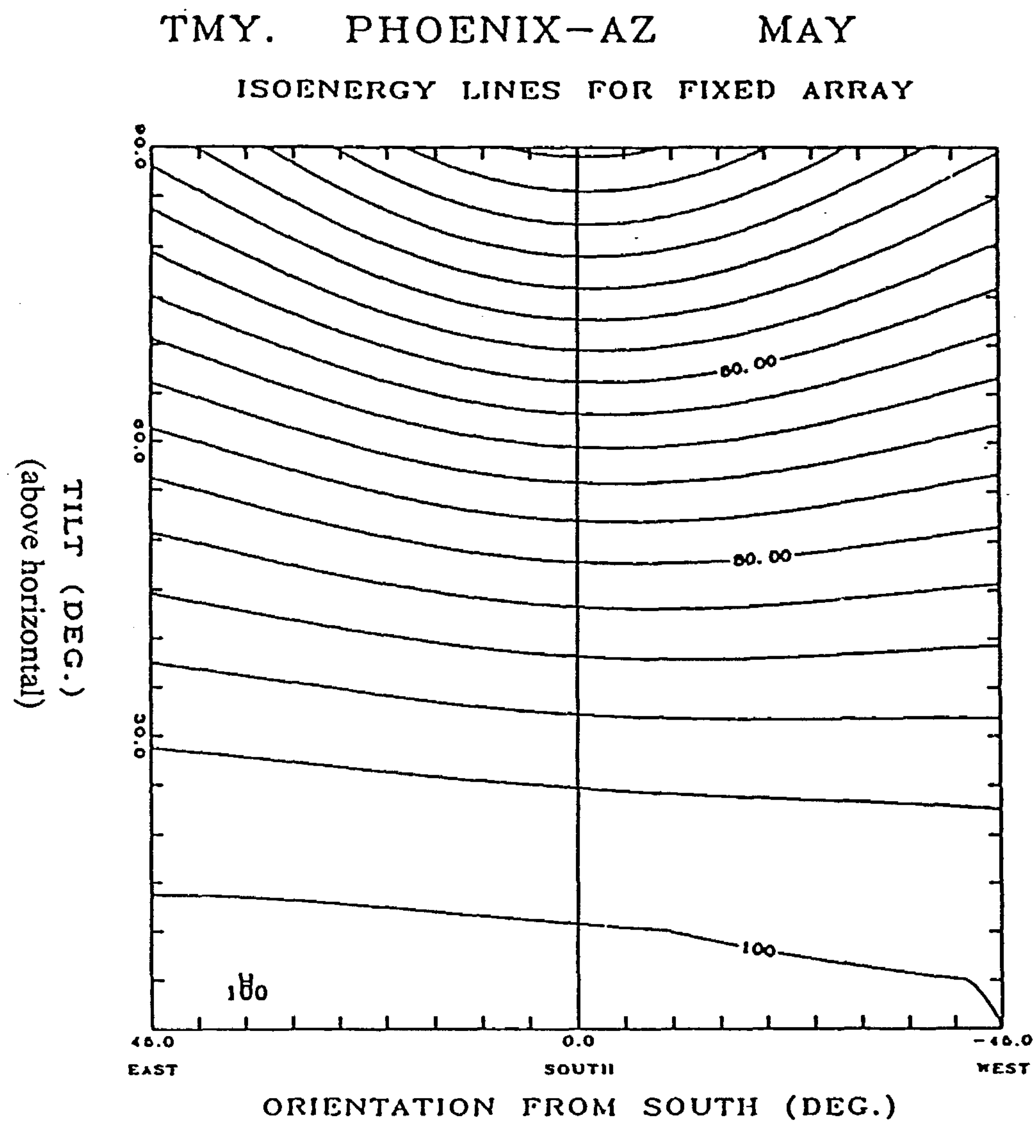
ISOENERGY LINES FOR FIXED ARRAY



TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 685685. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M² OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared



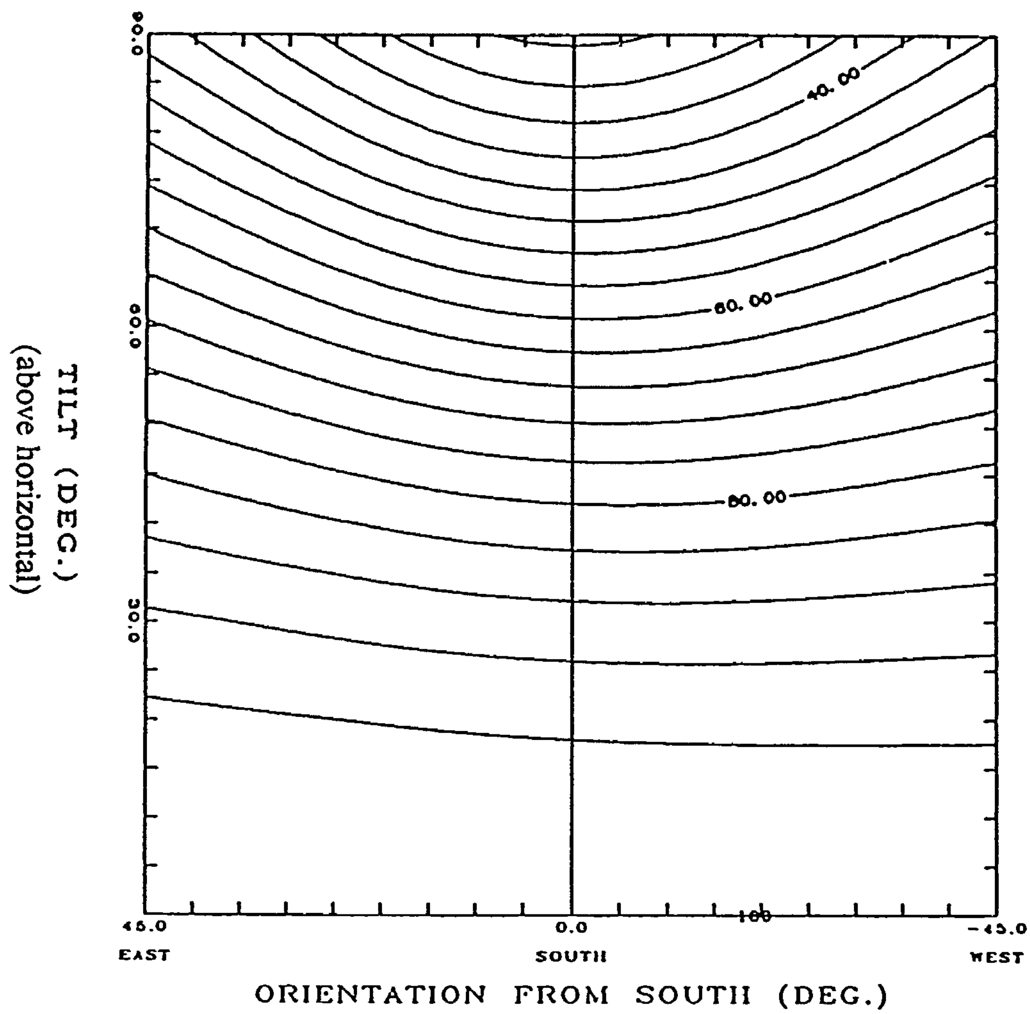
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 791398. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ JUNE

ISOENERGY LINES FOR FIXED ARRAY



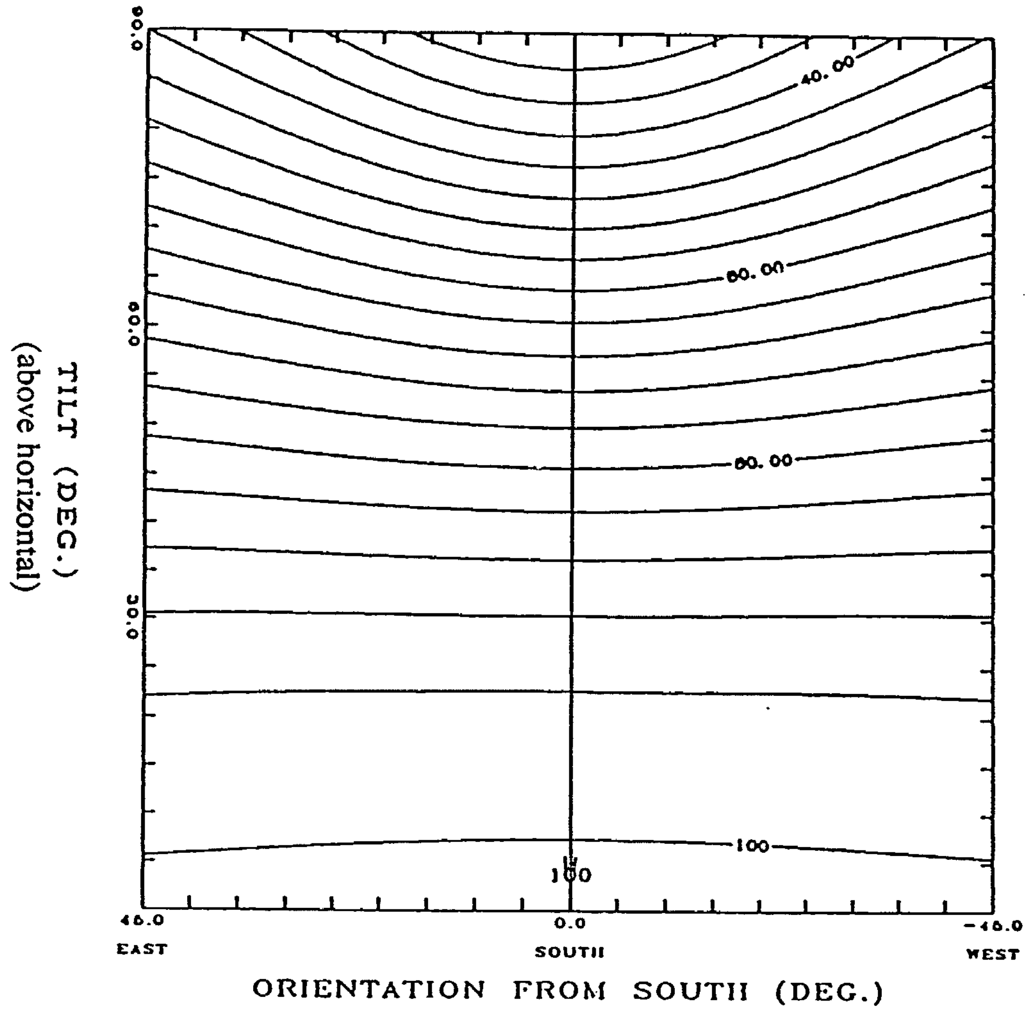
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 746223. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ JULY

ISOENERGY LINES FOR FIXED ARRAY



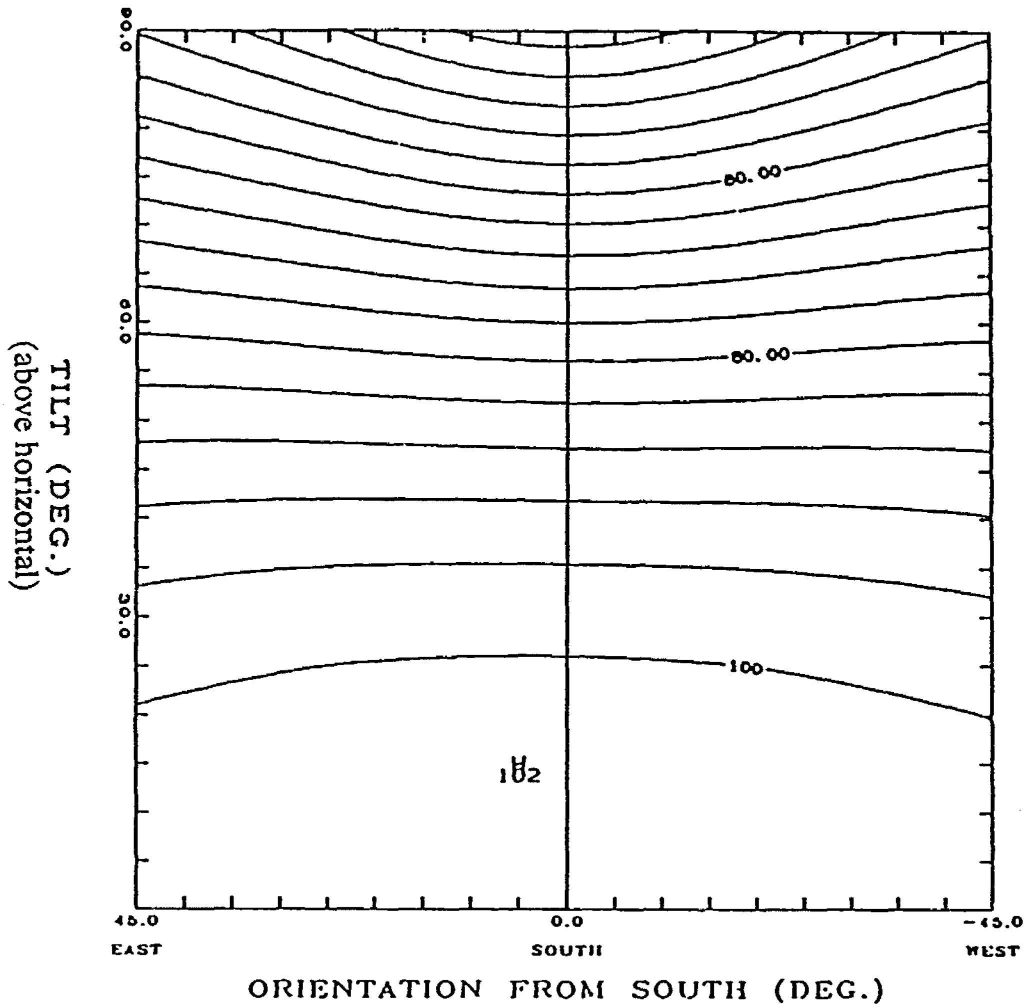
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 692961. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ AUGUST

ISOENERGY LINES FOR FIXED ARRAY



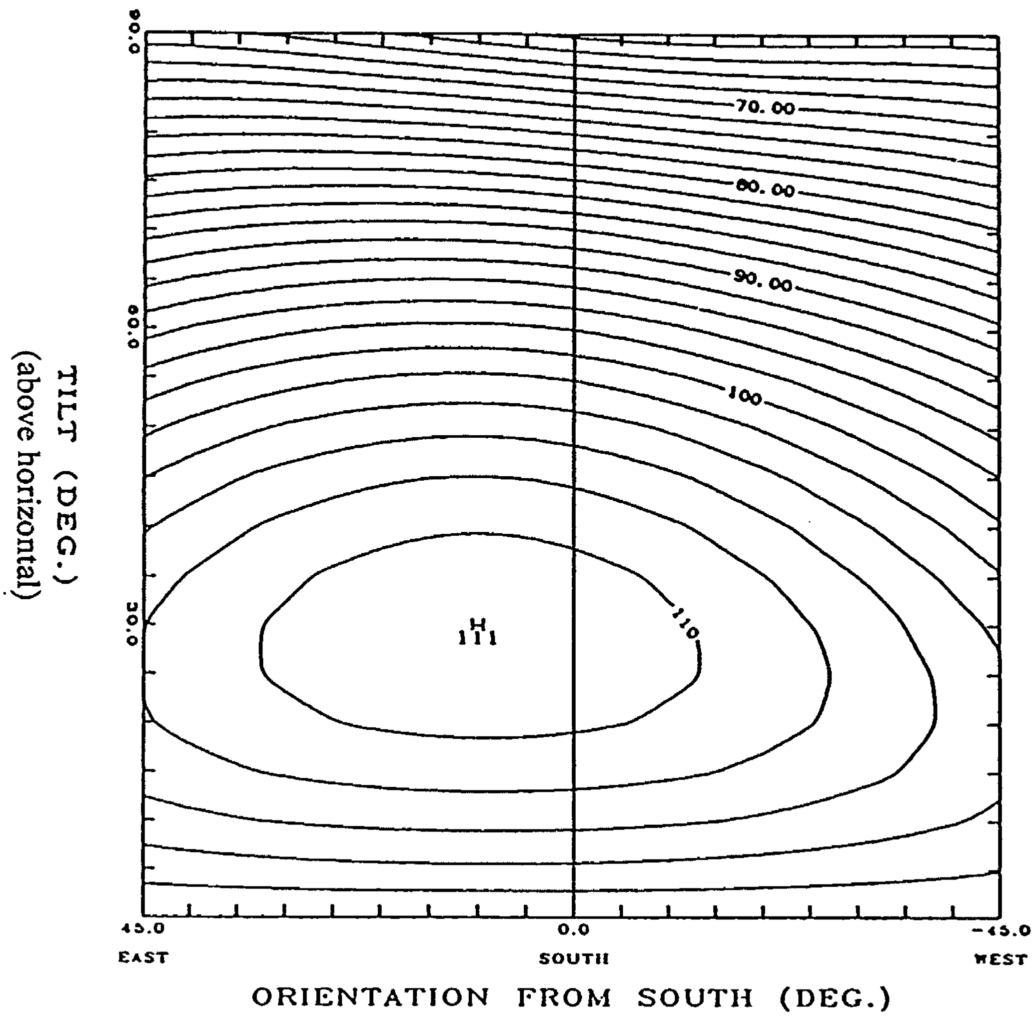
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 657448. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX–AZ SEPTEMBER

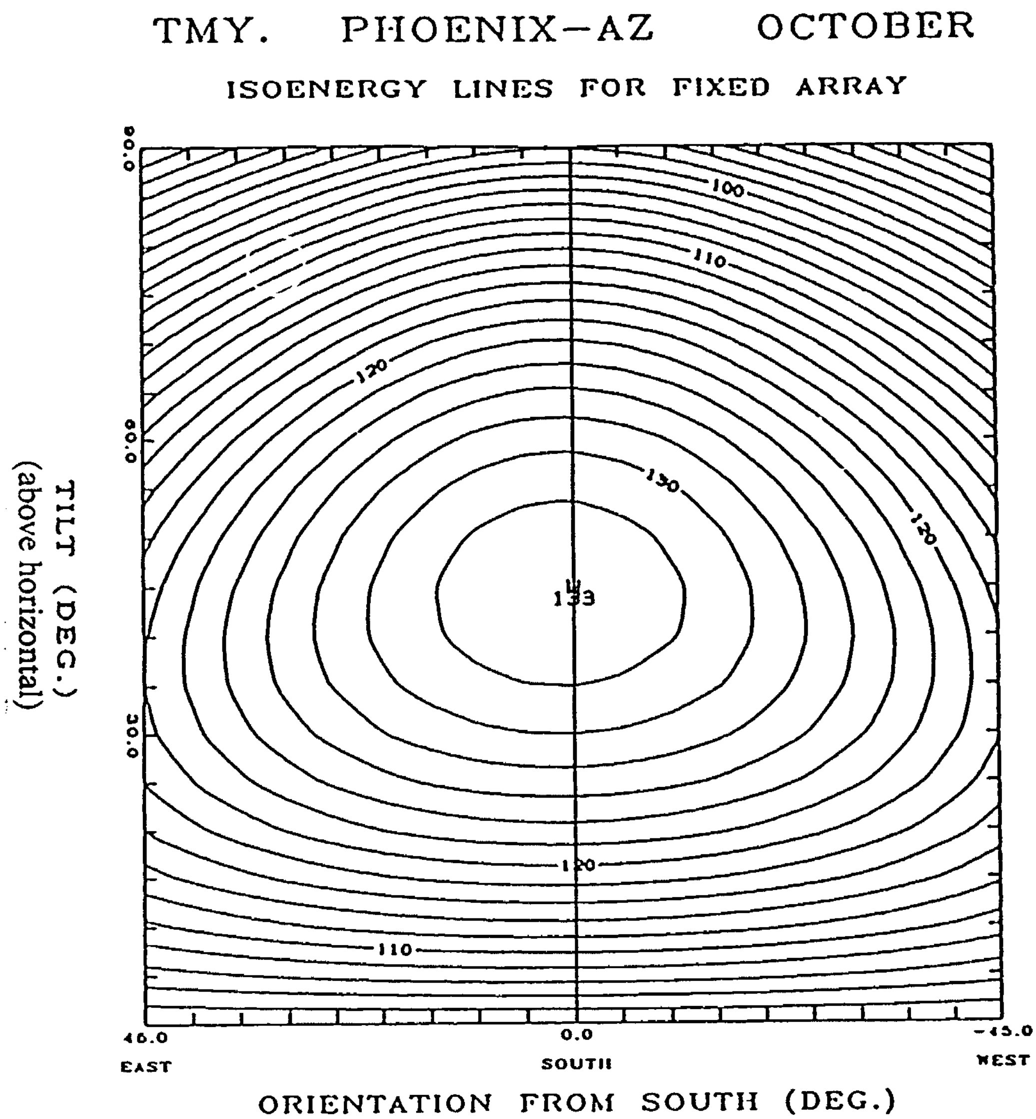
ISOENERGY LINES FOR FIXED ARRAY



TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 670702. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared



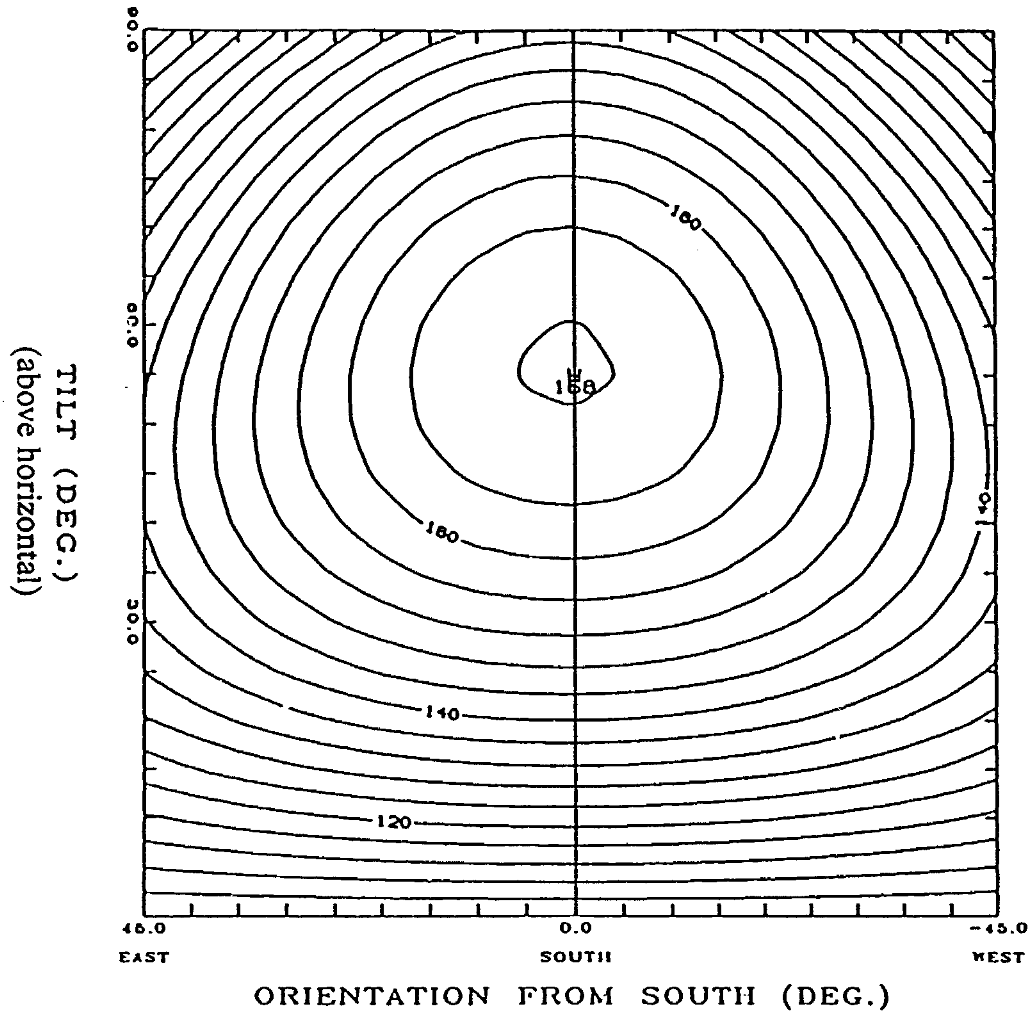
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 467039. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ NOVEMBER

ISOENERGY LINES FOR FIXED ARRAY



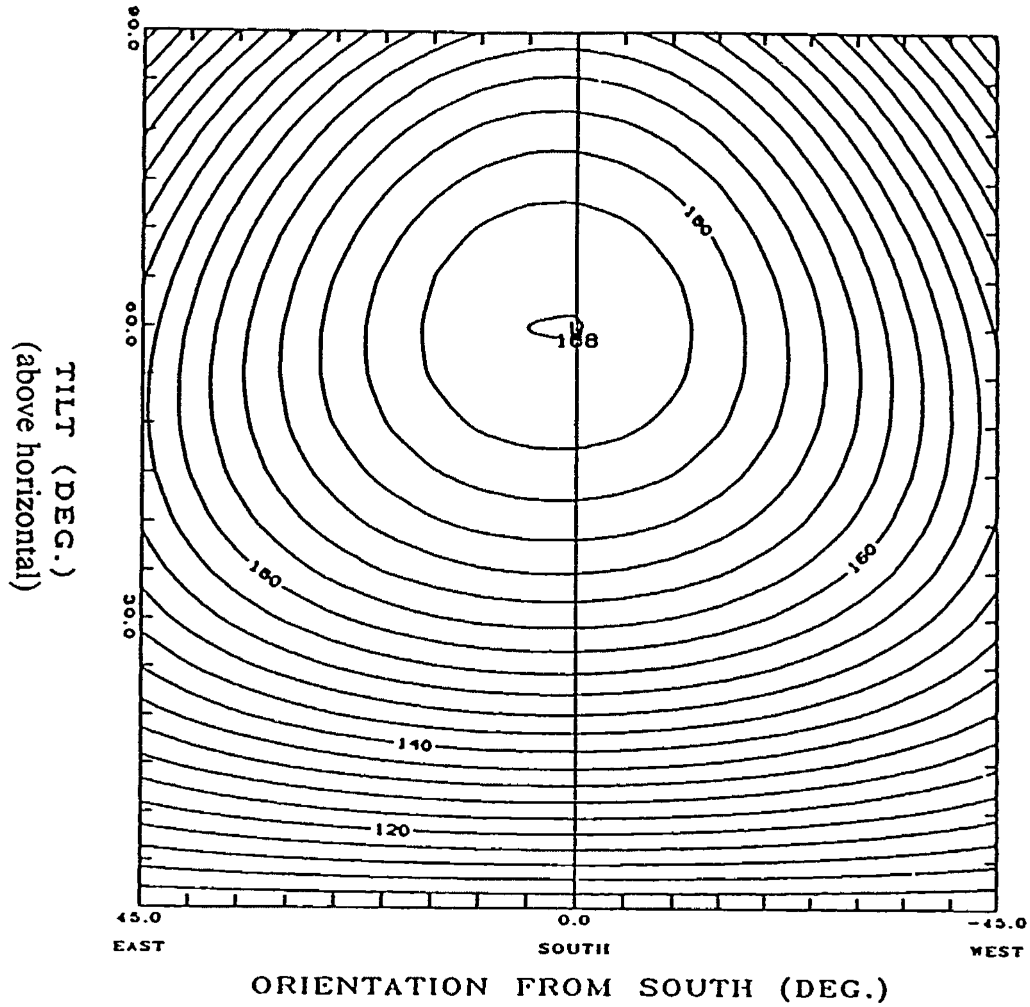
TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 356490. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

TMY. PHOENIX-AZ DECEMBER

ISOENERGY LINES FOR FIXED ARRAY



TOTAL ENERGY FOR HORIZONTAL ARRAY (IN KJ) = 284876. (per month)
THE ARRAY PRODUCES 1 KJ FOR EACH KJ/M^2 OF INCIDENT
SOLAR ENERGY , IF ITS TEMPERATURE IS 25 DEG. CELSIUS.
GROUND REFLECTION COEFF.=0.2

The values on the isoenergy lines represent the amount of energy received at that tilt and orientation as compared to a horizontal array.

KJ = kilojoule
M^2 = meter squared

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