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TECH DATA BULLETIN

PHOTOVOLTAIC CONCEPT, DESIGN, AND APPLICATION
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PHOTOVOLTAIC CONCEPT, DESIGN, AND APPLICATION

SYNOPSIS

This Tech Data Bullein provides a review of what makes up a photovoltaic system, where it can be used and an example of how to apply the technology.

INTRODUCTION

Traditional energy resources (natural gas, oil, and nuclear fission), formerly inexpensive and abundant, will become increasingly expensive or depleted in the future. Heightened awareness of energy and environmental issues has increased the search for alternative non-polluting energy resources. An alternative receiving closer scrutiny is the use of sunlight to produce electricity (photovoltaics).

BACKGROUND

Photovoltaics (PV) is the only technology that directly converts sunlight to electricity. Attractive advantages of PV technology include: a free and abundant fuel supply; little or no pollution or operation/maintenance costs (once installed), and unlimited system life.

Successful application of PV technology to energy problems in space programs, coupled with the 1973-74 oil embargo, prompted the Department of Energy (DOE) to initiate programs to commercialize PV systems. DOE funded the Federal Photovoltaic Utilization Program (FPUP) to demonstrate and test PV systems as an alternative to traditional energy sources. The results of this program and continuing improvement in efficiency and production costs have helped to prove the reliability and competitiveness of PV technology in numerous real-world applications.

THEORY AND CONCEPT

The heart of any PV system are the solar cells which are semiconductors. By definition, a semiconductor is a device made of material of intermediate conducting capability sandwiched between a good conductor (e.g., metal) and a good insulator (e.g., glass). Silicon is the semiconducting material most commonly used for PV cell production. Other materials, such as gramium, lead sulfide, cadmium sulfide, and gallium arsenide are being investigated as possible semiconductors for PV cell production. Silicon offers several advantages: high operating efficiency, relative low cost due to abundant supply; and non-toxicity.

The fabrication of solar cells using silicon consists of several steps. The silicon must first be purified to achieve high efficiency, via exposure to intense heat produced by an electrical charge. This procedure is known as the Siemens purification process. The purification silicon is then cut into wafers for use in integrated circuits, transistors, and solar cells. For solar cell production, silicon wafers must be treated with certain chemicals, such as boron, to alter the structure of electrons in the wafer. The addition of boron creates electron-free holes where electrons used to be. Electrons quickly fill these holes, creating new holes in other parts of the silicon crystal. Boron-treated silicon is called positive type (p-type). Another area of the crystal is treated with phosphorus, creating a region rich with electrons, called negative type (n-type) silicon. The p-type connects to the n-type to create a pn-junction, providing a built-in electric field.

As sunlight contacts a solar cell, it penetrates the n-type and the pn-junction, creating a pair of hole-electrons by forcing an electron from its place in the crystal structure. The built-in electric field prevents the hole-electron pairs from recombining This forces the free electrons to move to the upper part of the cell, where a metal contact grid transmits the negatively charged electricity to the load.

SYSTEM DESCRIPTION

In the most simple PV system, the array is directly connected to the load. This direct-drive type system is commonly found in toys and calculators. However, direct-drive systems are limited to small loads with a good correlation between power demand and solar intensity.

Typical stand-alone PV systems provide electricity to a wide range of loads (ac and dc applications) during the day as well as night, when sunlight is absent. In order to manage the various load demands, a PV system may employ many devices between the PV array and the load. These devices support various functions, from energy storage to system protection. A typical stand-alone PV system requiring at least 95 percent energy availability (e.g., a residential system) may involve many such devices. The designer must consider, in addition to the PV array, the need for batteries to store energy, dc-ac inverters (and/or dc-dc converters), blocking diodes, controllers, surge arresters, and monitoring and warning devices. Figure 1 illustrates the main system components. Other power handling equipment may be required, depending upon the application. A brief description of the main components follows.

Photovoltaic Array. A PV array consists of two or more 12-volt PV modules connected in a manner similar to regular batteries. Each PV module (Figure 6) contains an enclosed group of solar cells. This part of the PV system is responsible for electrical generation.

Batteries. Batteries are the most common energy storage devices. There are two classifications for batteries: primary and secondary. Primary batteries (e.g., flashlight batteries) are not rechargeable. Secondary batteries (e.g., car batteries) are rechargeable. However, car batteries are unsuitable for PV applications, as they are designed to provide high-current cold cranking amps for a short period of time. Afterwards, the battery is quickly recharged. PV batteries are designed to provide consistent quality energy for a long period of time.

DC-AC Inverters. These devices convert direct-current (dc) electricity to alternating-current electricity (ac). Since PV arrays produce dc electricity, stand-alone PV systems often require an inverter to produce ac electricity for a broad range of loads. The use of large inverters results in approximately 10 percent loss of generated electric energy. However, it is sometimes easier to use such devices rather than to convert all appliances to operate on dc electricity.

Blocking Diodes. These devices allow current flow in one direction only. In PV systems, blocking diodes allow current flow from the PV array to the batteries (or load) and prevent current feedback from the batteries to the array. When multiple PV modules are connected in parallel, blocking diodes should be used in each parallel connected string. String diodes prevent current flow from strong (well-exposed to sunlight) PV modules to weak (partially shaded) modules.

Controllers. Controllers regulate charge and discharge of batteries, thus increasing their lifetime. Most controllers incorporate a voltage-sensing device. Some controllers contain temperature compensation circuits to adjust to the effects of temperature on battery voltage and state of charge.

Surge Arresters. Surge arresters are designed to protect equipment from electrical surges created by lightning.

GENERAL CONSIDERATIONS

This section discusses general considerations that may be helpful when deciding whether a PV system is a feasible solution for a given application. Often, the most important factor in choosing a system is cost-effectiveness. However, many other factors play significant roles in the decision. The distinct advantages of PV systems (pollution-free operation; minimal maintenance; free and abundant fuel supply; and unlimited lifetime) make these systems the energy source of choice for remote sites.

Before designing a system for a particular application, the designer must decide whether a PV system is an appropriate choice. Logically, the first factor to consider is solar radiation. Solar radiation (measured in kilowatt hours per square meter) will determine the size of the photovoltaic system. Seasonal insulation maps for the United States are provided in Figures 7 and 8. The amount of electricity required by the load is a cornerstone for PV system sizing. Disregarding cost, PV systems can be designed to meet any given load.

Generally, choosing the right power system is not an easy task. The most significant factor is cost-effectiveness. In most cases, PV systems can compete with systems employing traditional energy resources if a life-cycle cost analysis is developed for a reasonably long period of time (20 years has been adopted by the government for life-cycle cost evaluations). PV systems require large initial investment, with minor maintenance over subsequent year; other energy sources require smaller initial expenses, with higher upkeep and fuel expenses over the same period of time. The return on initial investment made to install the PV system can be accounted for by using this longer time period.

PHOTOVOLTAIC SYSTEM DESIGN CONCEPTS

The main steps taken when designing a PV system are:

- Load calculation
- Determination of solar resources
- Battery sizing (if necessary)
- Sizing of PV system array
- Hybrid design (if necessary)

PV system design techniques differ in the approaches used to determine the size of the system and battery. Some techniques use probabilistic methods (loss of load probability [LOLP]) to derive an optimal size. Simulations of many design scenarios are employed to select a design for which capital investment and LOLP are minimum. A more simple design approach is presented herein, based on the technique presented in *Stand-Alone PV Systems: A Handbook of Recommended Design Practices*, published by Sandia Labs and available on the Construction Criteria Base CD-ROM disks from the National Institute of Building Systems. The design method follows the five steps outlined above.

Load Calculation. The first step in the design of a PV system is to determine the load size to be powered. Load size determines the size and cost of the PV system. Load calculations should be obtained separately for dc- and ac-powered loads. List and group loads according to their operating voltages; then, calculate the total load demand of each group. Identify the number of hours of use per day, and the operating voltages. The voltage of the group with the highest power demand is the system voltage.

If ac loads exist, inverters must be used. When ac loads dominate the system, system voltage should be compatible with the inverter input. Efficiency of ac inverters is increased with higher input voltage. However, as the voltage is increased, larger PV arrays and storage systems are necessary. On the other hand, higher system voltage corresponds to lower system current. High currents require large wire size, fuses, switches, and connectors. Therefore, keeping the current low will enhance cost-effectiveness.

For dc loads operating on voltages different from the system operating voltage, dc converters can be used to obtain adequate voltage to power such loads. Alternatively, the batteries can be tapped if the dc loads are small enough. If the batteries are supplying dc loads, battery charges equalizers must be used to overcome the problem of unequal current draw from series-connected batteries, eliminating possible battery failure. No more than 20 percent of the current of the full voltage load should be tapped. When dc loads dominate, select the operating voltage to maintain system current at acceptable levels. System current should be limited to 20 amps/source circuit for a total of 100 amps. If this is not possible, the PV array may be split as needed.

Determination of Solar Resources. Although solar behavior cannot be predicted for a specific day at a given location, daily average weather data are often locally available. Average weather data should be adequate for most PV applications. To derive values for solar insolation, the designer must consider the insolation on a tilted surface for a flat plate PV system. Tilted angle insolation data are available for some cities. In Table A-1, the average daily solar insolation availability is provided for Nashville, Tennessee. The data are presented for fixed array and one-axis tracking array with tilt angles fixed at Latitude -15° Latitude, and Latitude +15°, respectively. Table A-1 also provides data for two-axis tracking array. If such data is unavailable, tilted angle data may be estimated from horizontal data readings. Solar insolation data must be obtained for the worst month of the year and used to determine tilt angle and other related issues. Choosing the worst case month should be based upon review of the load behavior and solar availability for all 12 months. Figure 2 shows the seasonal trajectory of the sun for a location in the northern hemisphere with latitude of 40°. To minimize the effects of the sun's angle variation, the designer can set the tilt angle of the PV array at latitude. Figure 3 shows the effects of the tilting angle on the amount of solar energy received. Some applications may require a tilt angle at Latitude ±15° to skew energy production toward winter or summer, respectively (Figure 4).

Choosing the worst case month may be easier in some cases than others. If the load is constant, then the worst month is simply the month with the least insolation. The designer may consider a PV system with solar tracking capability to enhance the efficiency of the PV arrays. However, other factors may be addressed, such as solar conditions around the site; design complexity; and the cost of additional hardware compared with the cost savings from the extra solar energy gained. (See Table A-1 for sample data). For example, if a PV system is installed in a protected valley with mountains on the east and west, solar tracking may not be beneficial, as the mountains would limit morning and late afternoon sunlight.

It is important to note that local solar conditions may vary significantly from one area to another. Insolation data may be unavailable in remote locations. In these cases, insolation data from cities and areas surrounding the site of interest should be studied. Drawing insolation contours by developing a composite of all insolation data available from surrounding areas will help to derive estimates of insolation data for the proposed site.

Battery Sizing. Batteries in PV systems provide electricity when sunlight is unavailable. Since these periods are not limited to night, the longest period without sunlight for a given location is an important factor in sizing batteries. For example, if a communication tower must never be without electricity in an area where the longest period without sunlight is one week, storage batteries should be capable of operating the tower for at least one week without being recharged. In some applications, a designer may elect to design the PV system for 95 percent availability, rather than 100 percent, to achieve optimum cost-effectiveness.

Sizing of PV System Array. The PV system array is sized to meet the load demand and account for system losses. There are many factors that could affect system design. The designer must carefully study the proposed site for the PV system. Shading any part of the array may significantly reduce the output of the entire array. If modules are connected in series, the current will be the same in each module. If modules are partially shaded, they cannot produce the same amount of current. This will cause a reverse bias in the system, and may eventually lead to system failure. Under reverse biasing conditions, shaded modules will dissipate power as heat. The use of bypass diodes will prevent such problems. For modules connected in parallel, bypass diodes are not needed. For higher voltage arrays, however, bypass diodes around each module prevent dissipation of large amounts of power by providing an alternative current path. Blocking diodes should be used to prevent reverse current flow from the batteries to the array.

In the southern hemisphere, PV arrays should be mounted with the azimuths true south. To avoid significant decrease in overall power generation, the azimuths should not deviate more than ±20° from true south. However, if demand peaks around noon, the array may be positioned west of south to skew the electric production toward an afternoon peak.

Hybrid Design. A hybrid design system uses more than one source of electrical generation. A hybrid system is worth considering and may be optimal in many situations. In some cases, it may be more cost-effective to use a hybrid system to meet load demand than to design a PV system that meets 100 percent of the load. Also, where the load is critical, a backup system is necessary to meet load demand in case the PV system is out of order due to weather conditions or maintenance. Many hybrid designs, especially in remote areas, use diesel generators as a secondary energy source.

If a hybrid system is chosen, the designer must identify the type of load to be supplied by each energy source. The load may be split between the two generators if they will run the system simultaneously. If a secondary energy source will back up the PV system, the backup could be activated to recharge the batteries. Hybrid system design optimality will differ from one system to another. Thus, the designer must carefully study the options. Tests are available to assist in deciding the necessity of a hybrid system. Such tests are known as hybrid indicators.

APPLICATIONS

PV systems can be positioned on movable stations to provide electricity wherever needed. PV systems may be used to power military bases in remote areas, either as a backup to existing conventional electric generators, or as a primary energy source. Specific applications include remote site electrification, remote monitoring, warning signs, water pumping, restroom facilities, vehicle battery changing, cathodic protection, navigation aids, emergency call boxes along freeways, and facility power.

EXAMPLE PROBLEM

In this example, a PV water pumping system is designed, using typical data from an Air Force base. The designer must consider the five points mentioned earlier in the design concept section. The design specifications are for a water well located approximately 40 miles off base. The well is used for a period of five to six months per year; water demand is as high as 3000 gallons/day. Two weeks during the year, the water demand is as high as 15,000 gallons/day, when it is pumped and transported in a 5000-gallon tanker for road cleaning. During normal operations, water is pumped into a 10,000-gallon reservoir, and used for various daily activities. The key design specifications are:

Application: Remote area
Static Water Level: 34 feet
Use of Water: 5-6 mo/yr @ 3000/gal/day
1-2 wks/yr @ 15,000 gal/day
Average Annual Insolation: 6.5 kwh/m^2/day
Water Destination: 10,000 gal reservoir
Reservoir Elevation: 12 feet
Destination Distance: 20 feet
Water Type: Sandy

Following the five design steps, the designer must first calculate the load. The PV system is to be designed to supply a water demand of approximately 3000 gallons/day. PV systems are designed to operate unattended; most PV pumps are equipped with automatic float switches to activate the pump when water level in the reservoir is down. This eliminates the need for constant supervision experienced with conventional systems. Figure 5 shows a typical PV pumping system.

Step 1 - Load Calculation: In the design of water pumps, the capacity of the pump and motor are calculated using the described pumping capacity (gallons/day) and the vertical elevation from the static water level to the destination. The static water level is the level the water reaches, due to pressure, after the well is dug. It is important for the designer to distinguish between the water level and the total depth of the well (or water zone), since the water level indicates where the pumping will occur. Once the water level is determined, vertical elevation can be easily calculated. In this example, the water level is 34 feet below ground level, and the vertical elevation of the destination reservoir is 12 feet above ground; therefore, the total vertical elevation from the water level to the destination is 46 feet. Using this figure with the desired capacity of 3000 gallons/day, the designer can easily determine the smallest available system that meets the requirements. Manufacturers usually supply customers with detailed lists of different pumps and their capabilities.

Step 2 - Determining Solar Source: The lists (Table A-2) include the voltage and pumping capacity for different numbers of solar panels. Calculations provided by manufacturers are based upon a standard solar day of 6 kwh/m^2/day. For this particular application, the average seasonal insolation is 6.5 kwh/m^2/day.

Step 3 - Battery Sizing: Normally, three days of battery storage capability is recommended for water pumping systems. Once the pump is chosen, battery sizing will be an easy step. PV water pumping systems are normally sold in packages that include the pump, motor, well plate assembly cables, fiberglass battery enclosure, well controller, batteries, and battery hydrometer. Once the specifications have been determined. The manufacturer can recommend the appropriate system.

Step 4 - Sizing of a PV System Array: The size of the array is directly proportional to the pumping system capacity. Normally, the designer will choose the array that will provide the energy needed by the motor to meet the pumping requirements. This information can usually be obtained from the manufacturer.

Step 5 - Hybrid Design: The fifth step addresses the hybrid design. Since the second design approach is chosen for this application, a hybrid design is needed. The PV system will provide the normal load of 3000 gallons/day, and a conventional ac pump will be used to supply the 15,000 gallons/day demand for two weeks in a year.

It should be clear from this example and Table A-2 that, once pumping capacity and vertical lift are determined, the appropriate system can be chosen. For this example, the smallest water pumping system to meet the requirements has the following capabilities:

Total vertical lift capability: 46 feet
System voltage: 24 V dc
Solar panels: 4 panels

Batteries: 3-day storage capability

In this application, the PV array serves as a battery charger, so the motor actually runs using electricity provided by the batteries. This configuration provides the system with constant peak power. The use of batteries allows access to the water whenever necessary.

AIR FORCE CIVIL ENGINEER SUPPORT AGENCY

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AUTHOR/EDITOR

This Tech Data Bulletin was prepared by Ali Noureddine, under the direction of David Rhodes, Geo-Marine, Inc., and edited by the Air Force Civil Engineer Support Agency, Technical Support Directorate.

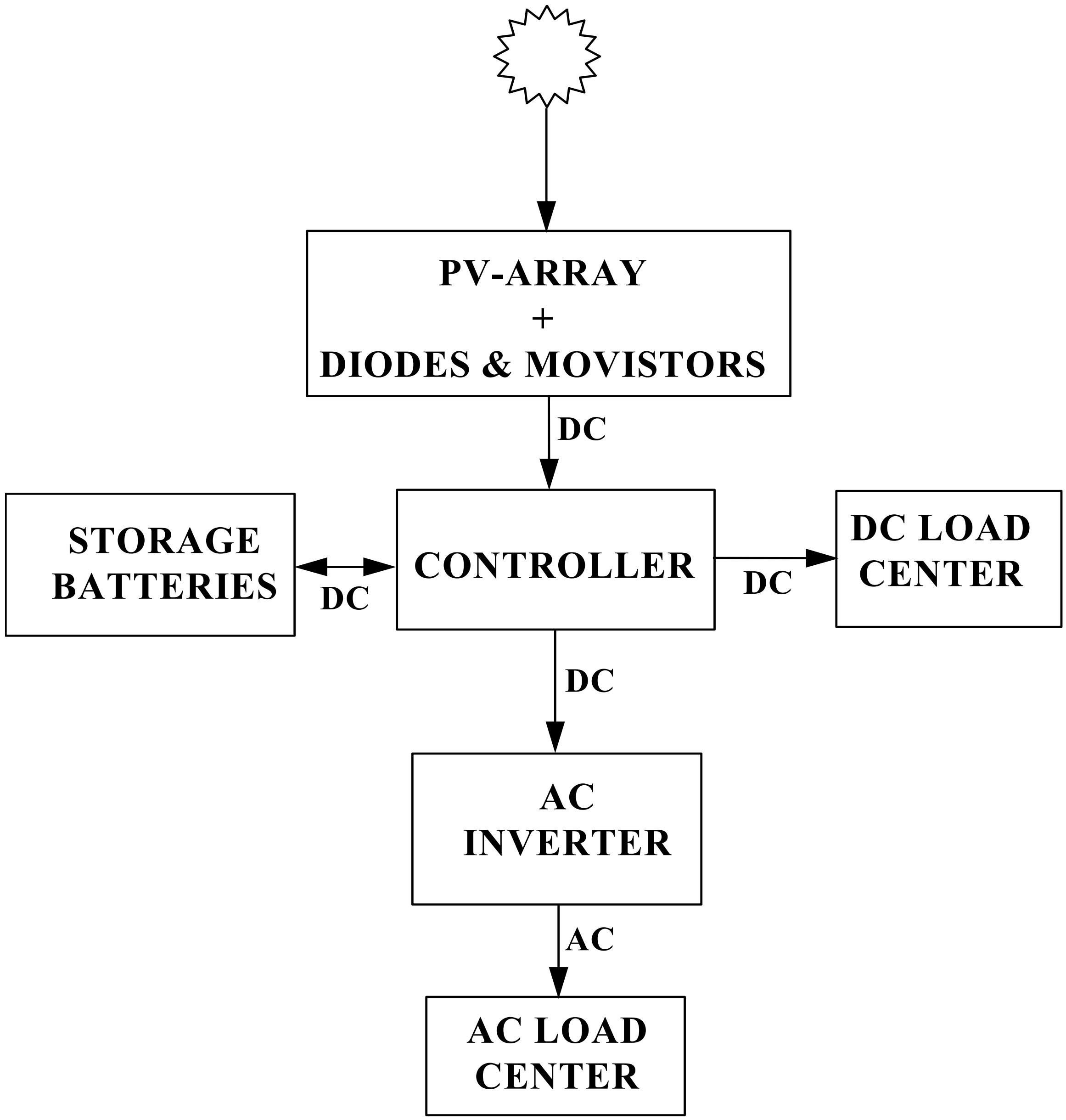


FIGURE 1. GENERALIZED SCHEMATIC OF PHOTOVOLTAIC SYSTEM

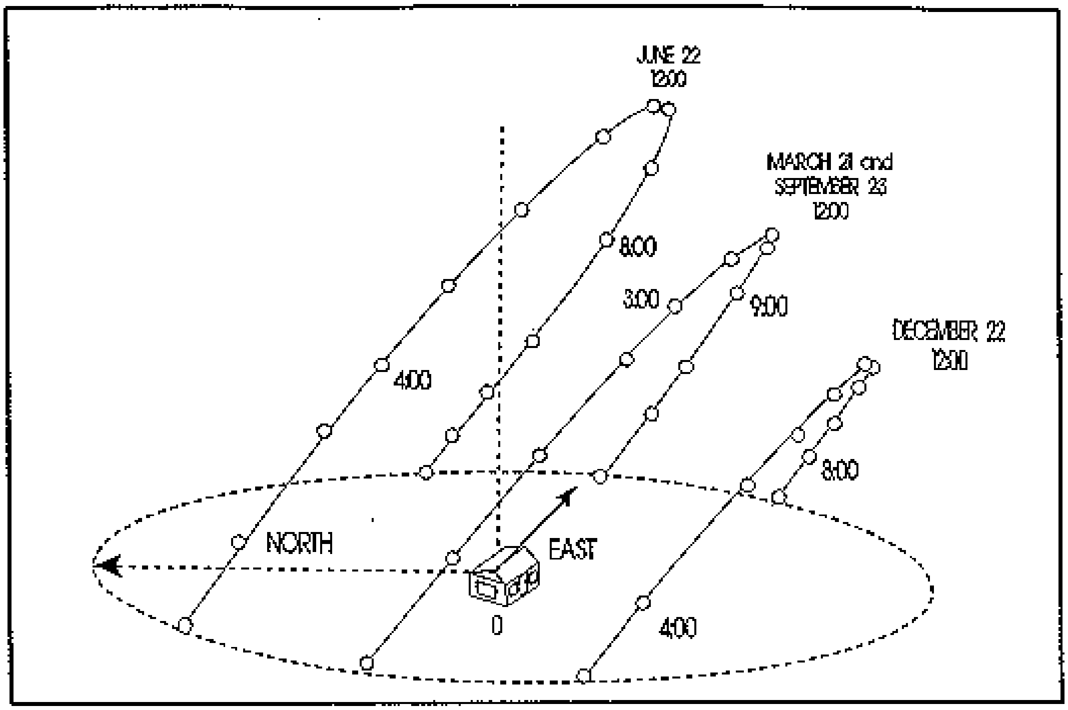


Figure 2. Seasonal Sun Trajectories at 40°N Latitude.

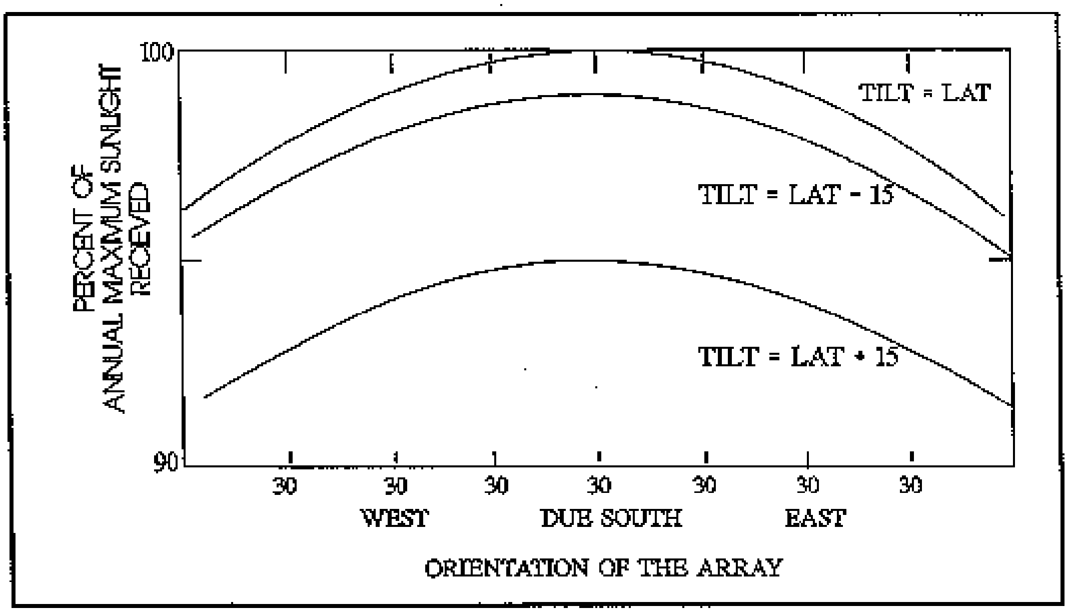


Figure 3. Effects of Array Tilt Angle on the Amount of Solar Energy Received. (Source: Reference 5)

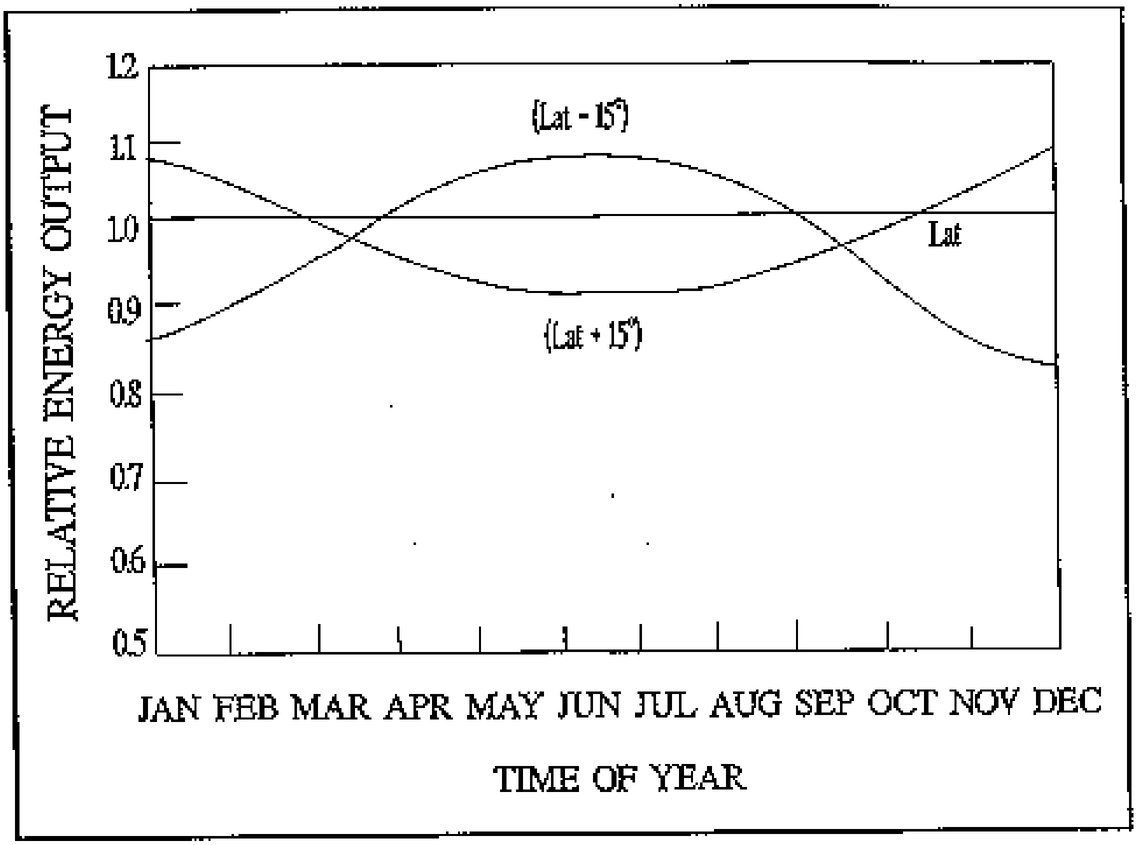


Figure 4. Effect of Array Tilt Angle on Annual Energy Production.

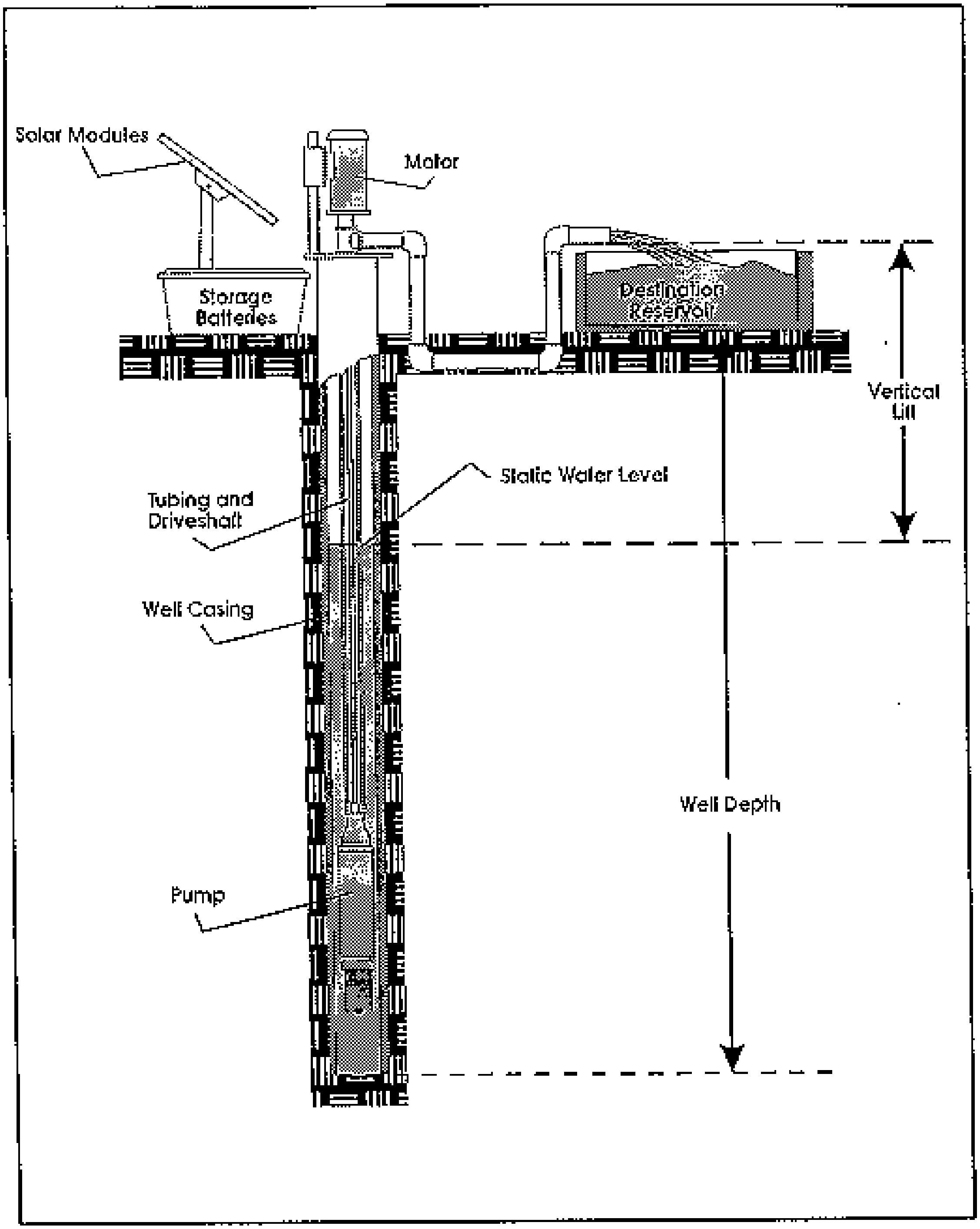


Figure 5. Typical PV Water Pumping System.

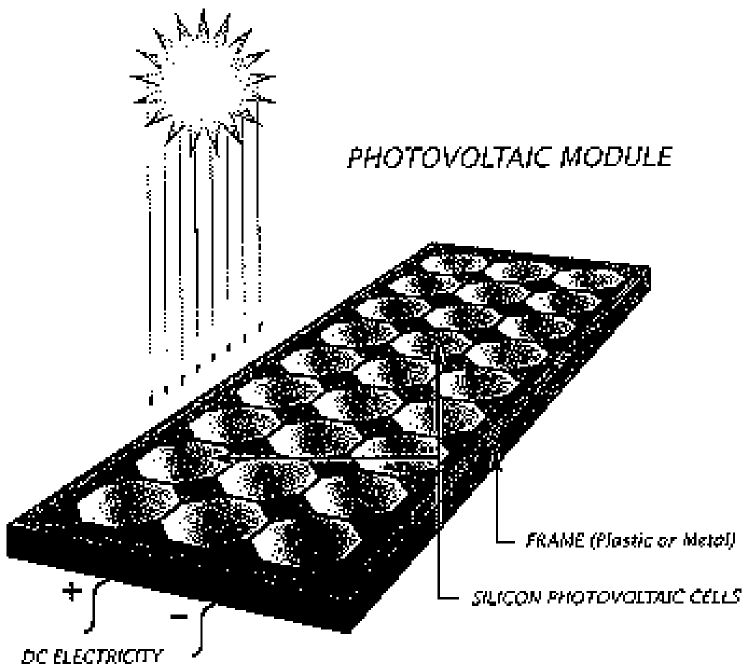
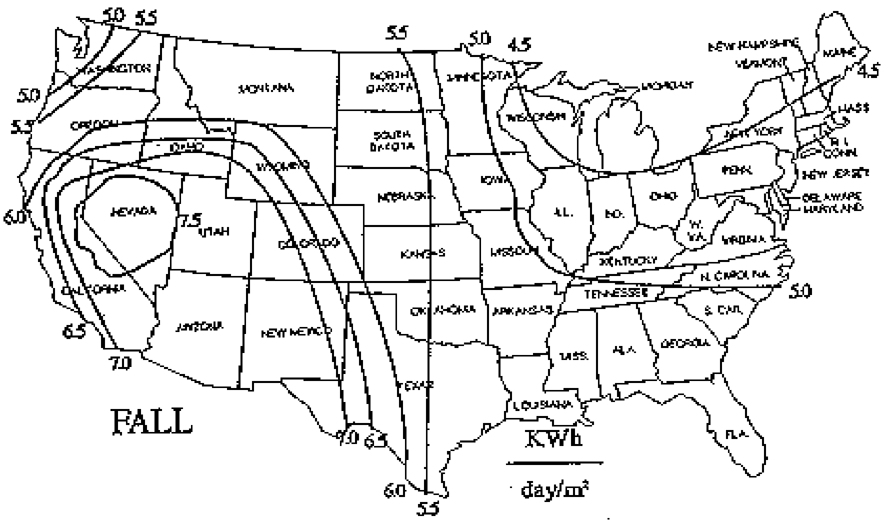
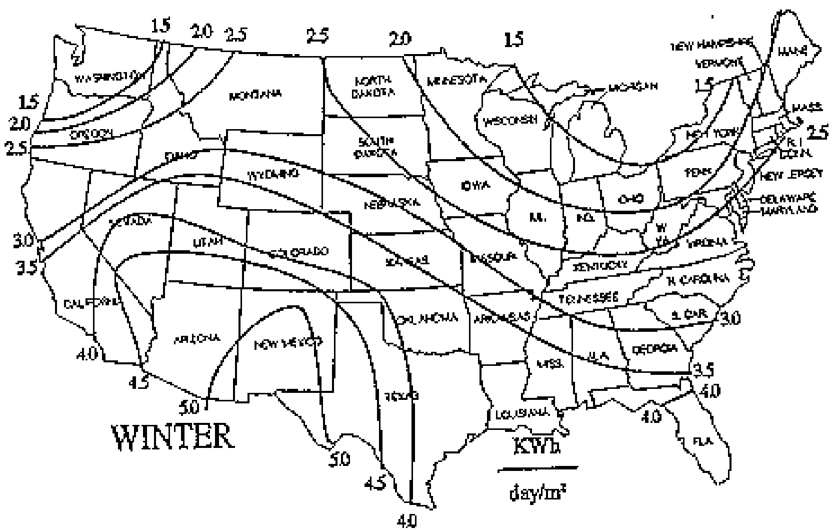

PHOTOVOLTAIC MODULE
FRAME (Plastic or Metal)
SILICON PHOTOVOLTAIC CELLS
+
–
DC ELECTRICITY

FIGURE 6

SOLAR ELECTRICITY



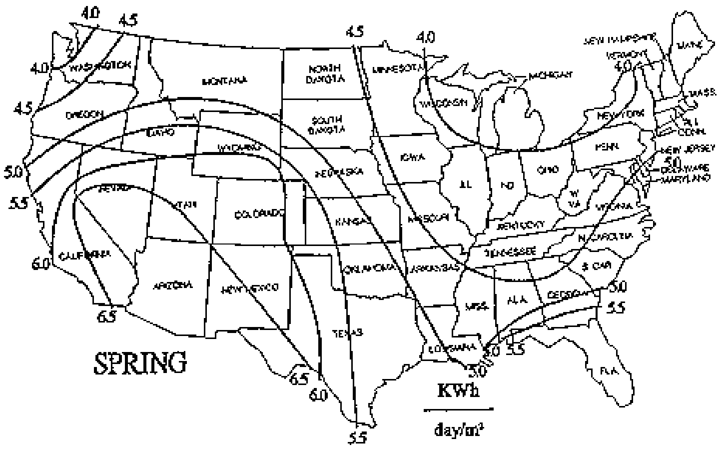
SOURCE: REFERENCE 5



SEASONAL INSOLATION DATA FOR THE UNITED STATES

FIGURE 7

SOLAR ELECTRICITY



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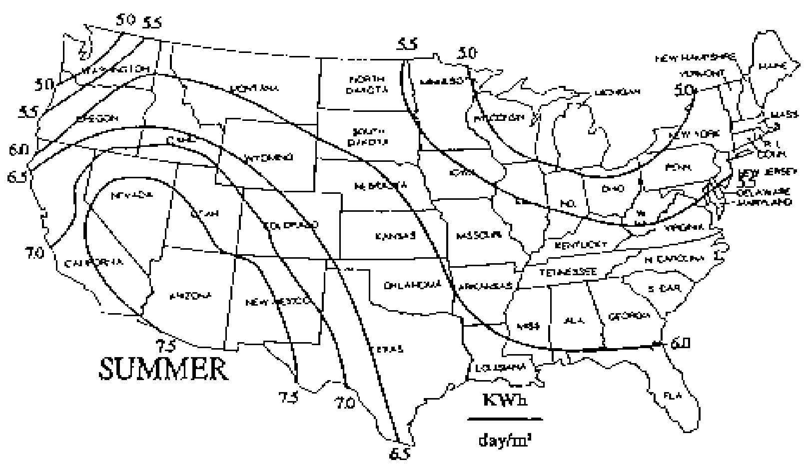

SEASONAL INSOLATION DATA FOR THE UNITED STATES

FIGURE 8

Table A-1

NASHVILLE, TENNESSEE AVERAGE DAILY INSOLATION AVAILABILITY KWH/M^2 LOCATION 36°, 07' N; 86°, 41' W, 180 Meters	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YR
LATITUDE TILT - 15 (°)													
Fixed Array	2.37	3.19	4.32	5.30	5.53	6.31	6.02	5.81	5.07	4.21	2.96	2.22	4.45
1-Axis North South Tracking Array	2.83	3.94	5.58	6.68	6.86	8.04	7.69	7.09	6.63	5.31	3.60	2.62	5.58
LATITUDE TILT (°)													
Fixed Array	2.69	3.48	4.50	5.26	5.29	5.89	5.66	5.68	5.18	4.57	3.34	2.56	4.51
1-Axis North South Tracking Array	3.09	4.16	5.72	6.66	6.68	7.74	7.44	6.99	6.72	5.59	3.91	2.89	5.64
LATITUDE TILT + 15 (°)													
Fixed Array	2.86	3.58	4.44	4.96	4.79	5.21	5.05	5.26	5.03	4.69	3.54	2.75	4.35
1-Axis North South Tracking Array	3.24	4.23	5.67	6.43	6.31	7.26	7.01	6.67	6.59	5.67	4.07	3.06	5.52
TWO AXIS TRACKING	3.27	4.24	5.72	6.71	6.9	8.18	7.79	7.11	6.72	5.67	4.1	3.1	5.8

Table A-2

TOTAL VERTICAL LIFT (TVL)	SYSTEM VOLTAGE	SYSTEM PRODUCTION (U.S. GALLONS/DAY)				
		2 PANELS	4 PANELS	6 PANELS	8 PANELS	10 PANELS
46 ft	24 VDC	1580	3160	4740	6320	7900
58 ft	24 VDC	1300	2600	3900	5200	6500
69 ft	24 VDC	1190	2380	3570	4760	5950
80 ft	24 VDC	930	1860	2790	3720	4650
92 ft	24 VDC	775	1550	2325	3100	3875
104 ft	24 VDC	646	1292	1938	2584	3230
115 ft	24 VDC	578	1156	1734	2312	2890

The pump performance shown above are based upon the usage of 60 watt photovoltaic modules with a peak output rating of 17.09 volts at 3.5 amperes. All figures shown above are based upon a solar day 6 KWHR/M^2. Source: Courtesy Energy Systems, Inc.