SOLAR ELECTRIC GENERATOR SYSTEMS

Principles of Operation and Design Concepts

CONTENTS

I. Introduction

A. SOLAR ENERGY

The sun is a nuclear power plant which generates power in the form of radiant energy at the phenomenally high rate of 3.8 x 10^{23} kilowatts. An extremely small fraction of this (less than a billionth) is intercepted by the earth, but this small fraction amounts to a huge 1.8 x 10^{14} KW. On the average, about 60% of this amount penetrates the atmosphere to reach the earth's surface (1.1 x 10^{14} KW). Of course, this amount of power is distributed over the entire surface of the earth. To bring these numbers closer to home, consider that on a bright sunny day each square meter of surface facing the sun receives about one kilowatt.

To compare these numbers with our energy needs, consider that the present electrical generating capacity in the U.S. is in the neighborhood of 7 x 10^{8} KW (consumption is about half of this). This is equivalent to the average sunshine falling on only 1000 square miles. Even if we could only utilize 10% of the incident sunlight, a single square plot of land only 100 miles on a side would provide the same electrical power as the present U.S. generating capacity. Clearly, there is more than sufficient energy directly from the sun to meet present and future needs if we could learn to utilize it economically.

B. SOLAR CELLS - (Simple) -

Direct conversion of solar energy can occur in two ways. The sunlight can be converted directly into heat by photothermal conversion, using a device which selectively absorbs the suns rays. A black surface getting hot in the sun is an example of this conversion. The incident sunlight can also be converted directly into electricity by photovoltaic conversion, using a device called a solar cell which utilizes the photoelectronic properties of a semiconductor.

- (Technical) -

A solar cell is a large area semiconductor diode, so constructed that light can penetrate into the region of the diode p-n junction. Silicon is used almost exclusively today as the semiconductor in commercially available solar cells. Certain impurities deliberately introduced (doping) into the silicon give rise to excess negative or positive charges which can carry electric current in the silicon. For example, phosphorous atoms give up electrons to the silicon to form n-type silicon (excess negative charges), and boron atoms soak up electrons from the silicon, leaving holes (missing electrons) which behave like excess positive charges (p-type silicon). A p-n junction can be formed close to one surface by allowing boron to diffuse into the surface of an n-type single crystal wafer at high temperatures. The p-n junction formed between the n-type silicon wafer and the p-type surface layer provides the electric fields which give rise to the diode characteristics as well as the photovoltaic effect. Light is absorbed in the silicon by generating both excess holes and electrons (one hole-electron pair for each photon absorbed). If this occurs near the p-n junction, the electric fields present there will act to separate the holes from the electrons, causing the holes to build up in the p-type material and the electrons in the n-type material. By connecting wires to the n and p-type regions, these excess charges generated by the light and separated by the junction can be made to flow through an external circuit to provide power to an external load. The operation of a solar cell is illustrated schematically in Figure 1.

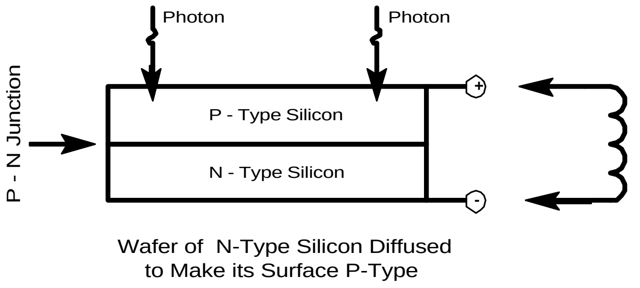

Figure 1. Schematic representation of a solar cell.

Each cell can supply current at voltages up to one-half volt. At lower voltages the current supplied is nearly independent of voltage, but varies with light intensity. The maximum power deliverable to an external load is typically 8% to 20% of the total solar energy incident on the cell. To obtain higher voltages, cells are connected in series; higher currents are obtained by connecting cells in parallel. Such connections are made when cells are packaged in modules. The modules then become the building blocks for arrays designed to meet specific needs of customers.

In order for the solar cell to work as described, the silicon surface must be accessible to the incident light. Therefore the exposed surface cannot be covered with a metal conductor. However, metal contact to the surface is needed to pick up the current, so at least part of the surface must be covered. The trick is to cover as little of the surface as possible while providing sufficient current-carrying capacity and widespread distribution of pickup points over the surface to avoid any significant power dissipation in the contacts. For this reason the contact is put down in the form of a grid. A typical solar cell with grid contact is pictured in Figure 2.

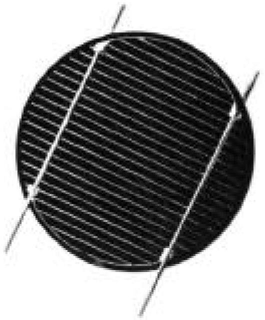

Figure 2.
Typical solar cell showing electrode grid pattern

C. ENERGY STORAGE

The total energy received from the sun in one year at any specific location on the earth is amazingly constant. The variation from year to year is less than 10%. However, within one year large variations occur both seasonally and daily, much of which is unpredictable. To avoid power outages at night and during inclement weather, some means of storing the energy generated on sunny days must be employed. Many photovoltaic generator systems in use today employ rechargeable electric storage batteries for this purpose. Therefore, standard solar cell modules are designed to provide the correct output voltage to efficiently charge these batteries. The solar generator array is designed to provide all the energy required by the load over the year. The storage battery acts as a buffer between the solar array and the load, supplying power to the load during periods of low sunlight (and no sun) and accepting charge from the array during periods of high sunlight. Therefore, its state of charge may vary seasonally as well as daily; the average sunshine during the winter may be insufficient to supply the load, but this insufficiency will be made up by an excess of sunshine during the summer. The capacity amp hours of the storage battery must be chosen to meet these demands.

Large solar systems are more cost effective if they combine other technologies such is wind micro hydro, or fuel powered DC generator. Using other technologies to generate power at night reduces both battery cost and maintenance. Also supplementing PV power during winter reduces PV array cost.

D. SOLAR GENERATOR SYSTEMS

In addition to a properly sized solar cell array and storage battery, a complete solar electric generator system will include a blocking diode and/or a voltage regulator to prevent battery current drain through the solar cell array at night. In complete darkness, the solar array is simply a string of diodes which would be forward biased by the storage battery. The blocking diode between the solar array and battery (Figure 3) allows current to flow from the array to the battery, but not from the battery to the array.

A voltage regulator should be included in a complete system to avoid overcharging the battery. This will occur when the battery is fully charged, and the solar array is still supplying more power than the load demands.

The following sections describe the concepts and methods used in designing or choosing the various components of the solar electric generator system. The concepts and methods used to determine the most economical complete system which meets the application needs (system sizing) are also described.

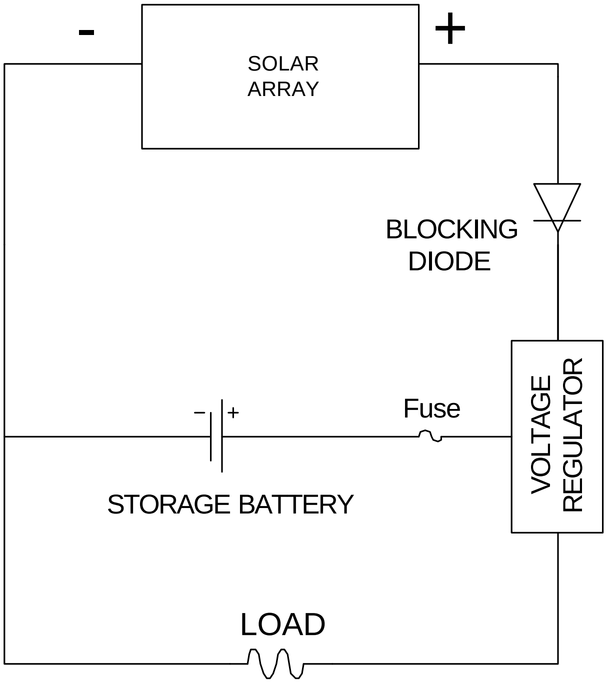

Figure 3. Electrical schematic of a complete solar electric generator system.

II. System Components

A. MODULE DESIGN

It is common to describe the size of solar photovoltaic arrays in terms of their peak power output; i. e., the maximum power that can be delivered to a matched load when the incident sunlight is 100 mW/cm^2. However, by itself, this is not a significant parameter in the design of a solar array battery charging system. Both the current and the voltage characteristics of the solar array must be considered in conjunction with the battery voltage characteristics to obtain a proper match between the two. This means that the power must be supplied to the battery at a high enough voltage to fully charge the battery. For a typical 12-volt lead-acid battery, this voltage can range up to slightly over 14.7 volts.

I-V curves for a typical solar cell module with 100mW / cm^2 incident sunlight are shown in Figure 4. Both curves were obtained from the same module, but the temperature of the solar cells in the module was different, as indicated. The maximum power point of each curve is indicated by the arrow. This module contains 35 cells of 100mm diameter, all connected in series, and was designed for charging a 12-volt lead-acid battery. Note that the solar module behaves essentially as a constant current source nearly independent of voltage below the maximum power point, but that current falls off rapidly with increasing voltage above the maximum power point. The voltage at which this falloff occurs depends on the number of cells connected in series (and on their temperature). By choosing 35 cells, the module can supply the fully rated current of 2.25 A to the battery even when it is almost fully charged (14 volts charging voltage) at cell temperatures up to 60ºC, and while accommodating voltage drops across a diode and 0.3 V across the cable leads. This allows the nominal current rating of this module to be used in sizing systems without temperature derating for most applications. Although an additional cell in series (36-cell module) would cause the current drop-off to occur at higher voltage, and increase the power rating of the module and its cost, no benefit would be derived for charging the standard 12-volt battery.

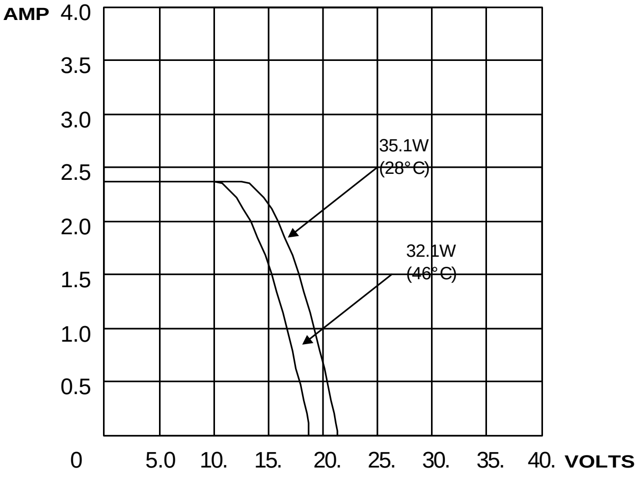

Figure 4. I-V Curves of a Solar Power Corporation Module

As shown in the figure, the voltage falloff occurs at lower voltage as the temperature of the solar cells increases. The amount of this shift in falloff voltage is given approximately by 0.5% per degree celcius. By this means, temperature derating of modules can be taken into account when sizing systems.

The constant charging current nature of a solar cell array properly matched to the storage battery allows system sizing to be computed in terms of ampere hours. This is very convenient because this quantity is very nearly conserved in a storage battery. Ampere hours out almost equals ampere hours in, even though power out is less than power in (amps come out at a lower voltage than they go in). In addition, the current supplied by the solar array is directly proportional to the incident sunlight. This does not affect the constant current nature of the solar array with respect to voltage; one should imagine the entire I-V Curve moving up and down along the current axis in direct proportion to the changes in sunlight intensity. This feature leads to a direct correspondence between integrated sunlight data and total ampere hours supplied by the array, independent of the sunlight intensity.

The current level obtained from a module of series-connected cells, as shown in Figure 4, is the same as that obtainable from a single cell in the module; this in turn, is determined by the exposed surface area of the cell. To obtain lower current levels than those shown, the module would have to be built with smaller diameter cells. However, the number of series-connected cells to match a given storage battery is independent of cell size. Higher current levels can be obtained either by using larger cells, if they are available, or by connecting modules in parallel. In the latter case, the total current obtained is the sum of the current from the individual modules. This does not change the voltages at which the current drops off, which is fixed by the number of cells in series in each module. For example, two identical modules connected in parallel would give the identical curve shown in Figure 4 if the current scale were doubled.

Different battery voltages are accommodated by connecting modules in series. If one module is properly sized in voltage for a 12-volt storage battery, then two such modules in series would be properly sized for a 24-volt battery. Thus, a specific application may require modules to be connected both in series and in parallel: series-connected to match the specific battery voltage, and additional modules connected in parallel to provide the required current generating capacity. The procedure for determining the required current generating capacity, called sizing the system, is described elsewhere.

The arguments on module design in this section were based specifically on the I-V Curve shape shown in Figure 4, which is typical of modules using solar cells manufactured by Solar Power Corporation. However, other solar cells may give rise to different curve shapes which could modify the arguments for the number of series-connected cells to charge a 12-volt battery. In Figure 5, Curve a. has the same shape as the solid line curve of Figure 4. If this module had been constructed of cells having excessive current leakage, the I-V Curve would look something like Curve b. in Figure 5. In this case, the nominal current rating of the module would have to be specified at a lower value, and conceivably it might be advantageous to put additional cells in series to minimize further derating at higher cell temperatures. If the module were constructed of cells having excessive series resistance, the I-V Curve would look something like Curve c. in Figure 5. In this case, it is clear that additional series-connected cells would be advantageous to reduce the very large derating which this module would exhibit at higher cell temperature. Also, the direct correspondence between integrated sunlight data and total ampere hours supplied by the module would no longer be independent of sunlight intensity, unless the number of series-connected cells were increased by about 25% for the case shown. This would seriously impact its cost. Thus, knowledge of the detailed shape of the I-V Curve is essential for proper module design.

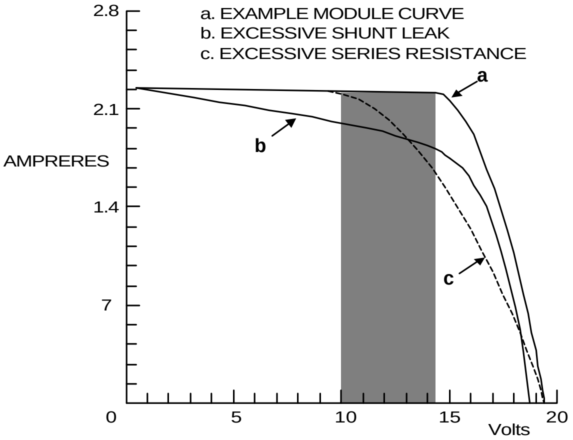

Figure 5. Effect of Shunt Leakage and Series Resistance on I-V Curves

B. BATTERY SYSTEM DESIGN

The major factors influencing the adaptation of storage batteries for use with solar panels are: the battery type required, the voltage, the ampere-hour capacity, and the environment in which it will be operating.

The two most common types of storage batteries used in solar electric generator systems are the various lead-acid types and nickel-cadmium (wet). It is important that batteries have low self-discharge and high cycle capacity. As the battery ages, self-discharge loss increases and the battery itself becomes a load to the solar electric system. Self-discharge is an important factor for determining when to replace the battery.

Battery capacity must be specified for the environmental conditions to which the battery will be exposed. Batteries are normally rated for operation at normal temperatures (between 0 and 30º C). When the battery cannot be insulated from abnormally cold temperatures (e. g., -20 to -40ºC) by burial or placement is an insulated enclosure, it is necessary to derate its capacity. It cannot be allowed to discharge to the point where the electrolyte will freeze. The derating factor can be obtained from the known variation of freezing temperature with the specific gravity of the electrolyte shown in the following chart.

Freezing Points of a typical Lead-Acid Battery Electrolyte:

Specific Gravity (at25°C)	**Freezing Point** (°C)	**Specific Gravity** (at25°C)	**Freezing Point** (°C)
1.300	-71	1.181	-22
1.283	-71	1.164	-18
1.266	-60	1.147	-15
1.249	-51	1.130	-12
1.232	-40	1.115	-10
1.215	-32	1.100	-8
1.198	-27		

One other factor influencing overall system design is the battery charging efficiency. Up until the battery reaches 90% of full capacity, the solar panel charges the battery essentially in a constant current fashion. Therefore, the system designer need only be concerned with ampere-hour charging efficiency of the battery. This efficiency is typically 95 % acceptance or greater at normal temperatures. The bulk of the charging inefficiency manifests itself in the form of voltage level. The battery requires a higher voltage to accept a certain number of ampere-hours than it provides when the same ampere hour capacity is drawn off. Also, as the battery cools down, the charging voltage increases. However, this is offset by the fact that the silicon solar cell I-V Curve extends farther out on the voltage scale as temperature decreases.

As the battery reaches and exceeds 90% of capacity the solar array current decreases rapidly with increasing voltage. If the solar panel voltage (i.e., number of cells in series) and current outputs have been carefully matched to the load, this will provide a self regulating mechanism. However, when the solar array outputs exceed the load requirements by more than 20%, an external voltage regulator is required to avoid excessive overcharging of the battery. This situation can arise because the sum of the various calculations for the load, PV array output, battery charge efficiency, and insolation will yield an inprecise result.

Batteries used with solar electric generator systems frequently operate under conditions which favor electrolyte stratification: the battery bank is stationary, and charging and discharging currents are low (typically less than 1% of battery capacity per hour). Under such conditions, it may be desirable to allow occasional mild gassing of the electrolyte to provide for mixing.

Nickel-cadmium batteries exhibit low self-discharge losses, and are more tolerant of accidents than are lead-acid batteries. For example, they will fully recover from freezing (the electrolyte becomes slushy). Complete discharge to zero volts however can lead to cell reversal. Excessive overcharging will not damage the battery, but of course, the water lost from the electrolyte must be replaced. These advantages are often offset by high cost, voltage inefficiency (charging voltage 15% higher than discharging voltage, compared to a 5% change for lead acid batteries), and lower voltage per cell resulting in more cells to obtain a given battery voltage than lead-acid systems.

C. BLOCKING DIODE

If the voltage regulator does not prevent reverse bias at night then a blocking diode should be incorporated into the system.

To prevent current drain through the solar array at night, a blocking diode is connected between the battery and the solar array (Figure 3). Two types of diodes are used in Solar Power Corporation's systems: the p-n junction silicon diode and the Schottky barrier diode. Both are available with a wide range of current ratings. The Schottky barrier diode, while considerably more costly than the p-n device, has a low forward voltage drop of 0.4 volt as opposed to the p-n diode's 0.7 volt to 0.9 volt. This lower voltage drop allows a savings of one solar cell in each series string of the solar array. Therefore, the array is more efficient since not as much power is dissipated in the blocking diode.

For system voltages greater than 100 volts, however, a p-n junction diode should be used because the p-n diode can withstand higher reverse voltages than the Schottky diode. At night, the battery reverse biases the blocking diode. For maximum reliability, Schottky diodes are replaced by the higher reverse bias rated p-n junction diodes in systems of greater than 100 volts.

In addition to the concern shown for diode losses, all cable conductors and interconnecting wires for each array are of a sufficiently large wire gauge to insure that at 100mW/cm^2 incident intensity all resistance-caused voltage drops are less than 0.3 volt.

D. VOLTAGE REGULATOR

A voltage regulator is recommended for those systems that might otherwise experience excessive overcharging of the battery.

III. System Sizing

A. INSOLATION DATA

The amount of solar radiation received and the daily energy demand are the two controlling factors in the design of photovoltaic power systems. The selection of raw insolation data to be used in the design of a solar array system is dependent on the location and meteorological conditions prevailing between the data station and system location. Other contributing factors are the units in which the sunlight data is expressed, the source of the data (i.e., the recording agency), the various types of detecting instruments used, and the period over which the data was accumulated. Ground cover such as snow can effect array output through reflection. Ambient temperatures also effect output. Increasing temperatures lowers output voltage (current is not effected).

In most cases, a proposed solar array installation is located away from populated areas. Most of the solar radiation recording stations are centered around major cities or in populated locations. Therefore, selection of a suitable sunshine data station requires a careful match between both the climatic and geographical conditions. Since a few hundred miles separation between recording stations and installation location may have profound effects on prevailing sunlight conditions, factors such as terrain differences (mountain range, arid or heavily vegetated regions, proximity to large bodies of water), elevation differences, and physical distance must be weighted for each location. The aim in selecting a data station location is to find one with a similar climate, a close match in latitude (since tilted gain figures are a function of latitude) and longitude, and at least three years of accumulated data readings. Since the sunlight data is expressed as monthly average, day-to-day variations will be smoothed out over the month. Long term weather conditions resulting in abnormally heavy snow falls, rainy or overcast periods, and excessively dry, clear weather may occur during a given year, affecting monthly and yearly averages of the solar radiation data recorded. However, over several years, such occurrences will tend to average out.

Sunlight data is available in many different forms. Weather services generally report the percentage of possible sunshine actually received day to day and the number of hours of sunshine received. This data is useful for determining the climatic conditions of an area, but is not normally used in the design of a solar electric generator, which requires a knowledge of the total energy received. Approximate energy figures could be obtained by making some assumptions about weather and sky conditions, but the results would be much less reliable than even short duration data recorded in energy units, and therefore is rarely used. Since the sunlight is a day-to-day variable, monthly and yearly averages are most adaptable to use in systems design.

Some of the commonly used energy units are watts per sq. meter, BTU's per sq. ft. and calories per sq. cm (Langleys). BTU's per sq ft are most commonly used by people designing solar thermal collectors, while the Langley is extensively used in the design of solar electric generators. However, other energy units are useful after the correct conversions have been made to more convenient forms.

Two final factors involved in the selection of a solar data station are the recording agency and the instrument used in obtaining the data. A publication by the University of Wisconsin has compiled solar energy data for many areas of the world entitled "World Distribution of Solar Radiation." For the most part, solar energy is recorded by the national meteorological and weather service. For the United States, the data is compiled by the Department of Commerce, Weather Bureau Climatological Center. For other areas of the world local weather services, the World Meteorological Organization (WMO), various university and private field installations, and in some cases, private individuals are the sources for insolation data.

The majority of instruments used in recording solar radiation are either thermo-electric or bi-metallic expansion types. Other instruments include devices that record solar radiation by means of discoloration of a wax coated chart. In the United States, Europe and Africa, the thermo-electric type recording instruments (pyranometers) are widely used. With a well maintained instrument, accuracies of 3% to 5% are obtainable. In South America and Asia, the bi-metallic expansion type instrument is more widely used. However, a well maintained bi-metallic expansion instrument will have a lower accuracy than the thermo-electric type. Deviations of at least ten percent (10%) or greater can be expected. The wax coated strip chart recorder and other similar instruments provide meaningful data only when the incident solar energy is at relatively high levels. They are unable to record lower level diffuse radiation which in some areas comprises a considerable portion of the insolation received. Generally, these types of data stations are not used in solar electric generator design.

B. WEATHER AND CLIMATIC DATA

In the design of solar electric generator systems, other climatic conditions apart from sunlight must be considered. Since the voltage of silicon solar cells is a temperature related parameter, the designer must be aware of the prevailing daily temperatures, both extremes (high and low) and seasonal variations. In addition, rain and snowfall must be considered in the design of the mounting structure. Wind loading is especially important in mountain top installations. Infrequent weather phenomena such as hail storms, electrical storms, and incidence of fog should also be investigated as to their effects on systems operation. For the United States, the Environmental Science Services Administration has compiled a "Climatic Atlas of the United States" listing much of the above data. Also, from the National Climate Center, the Weather Service publishes monthly summaries of the weather conditions at their stations located throughout the country. For other areas of the world, the data is not as extensive and is usually found in university studies or through the WMO records.

As in the case of sunlight stations, weather information must also be adapted to the specific installation area. Temperature is most commonly adjusted. Differences in elevation result in large temperature changes. Thorough design takes this into account and adjusted temperature data is substituted for the raw data.

C. COMPUTER AIDED SYSTEMS DESIGN

There are programs to aid in the design of solar electric generator systems. The programs can be operated in a totally automatic mode or they can be operated in a conversational mode where the operator (the solar electric generator designer) can ask for different systems to be visually displayed to satisfy special requirements. However, the purpose of the programs is to facilitate the selection of the optimum combination of solar cells, a battery bank, and generator for a particular power requirement.

Only in the vicinity of the equator is a horizontal panel fully utilizing the available solar energy. As you move either north or south in latitude, the optimum angle of tilt moves with you. For year round average, the best tilt angle is the same as the latitude of the installation location. However, generally during the summer months there is an excess of sunlight, while during the winter months the solar energy is at a low level due to the shift in the sun's position. By increasing the tilt angle of the solar panel (with respect to the horizontal) 5º to 15º more than the latitude, significant gains can be obtained during the winter months while sacrificing some of the excess energy received in the summer months. This procedure is not useful in every system, but in some cases it can reduce the size of the solar panel/battery system as illustrated in the example at the end of this section. For solar refrigeration, air conditioning, and some water pumping applications array optimization for summer months is desired. Most program use flat Langleys (cal/sq cm) averaged over a month's time. This information along with the location name, its latitude, longitude, and elevation are also fed into the computer at the start of the design procedure. At this time, temperature values reflecting the adjustment for elevation or other geographical differences between recording station and use area are also entered. The program then automatically returns a printout of equivalent daily Langleys for each month of the year and a yearly average for a user's specific tilt range or the programs selects the tilt angle.

The equivalent tilted Langley data is the combination of a derived gain factor and the flat Langley data. In calculating the gain factors, the computer goes through routines that develop numbers relating time of year and sun position to length of day. Two numbers are generated under length of day; the day length on a horizontal surface and the equivalent day length on a tilted panel. Combining the proper length of day for a specific tilt angle and the percentage of total daily energy received for each hour of the day with day length, a gain factor is generated.

The gain factor, if directly applied to the flat Langley data, would give very large gains during the winter months while showing only modest decreases in the summer months. This is due mainly to the type of energy received in these periods of the year. The two types of radiation, direct and diffuse, play a large part in determining the magnitude of the gain factor. Direct radiation can be improved significantly by alignment with the sun, but diffuse radiation is not very sensitive to orientation. The computer programs should have correction factors for this diffuse light with the variation of diffuse light with both time of the year and latitude.

Most programs are concerned with the combination of customer power requirements, available solar energy for his installation area, climatic factors, available solar energy devices, and battery voltage, type, and capacity. In addition, programs generates a detailed Systems Design Report for the optimum system. Included in this report is information on the data location used, the tilt angle of the array and the expected solar radiation for that tilt angle as it varies month to month, the expected solar electric generator output in ampere-hours per day, the average daily high temperature for the installation, and the average state of charge of the battery as it varies from month to month. In addition, the location of installation and the data stations, the model number of the solar array, and the suggested battery type and capacity are also provided. All of the above are generated automatically by the computer. In selecting the optimum system, the computer may run through many different combinations of tilt angle, solar cells, and batteries before the optimum system is found.

Most programs go through a temperature derating routine in order to use current and voltage values in the various calculations that reflect the expected currents and voltages from the solar array at the installation site. At the same time, the effect of variation in the battery state of charge on its charging voltage is taken into account. The resulting currents and voltages are combined with the various corrected tilt angles to find the output of test arrays. The computer then offers the system to the designer for inspection.

In practice, the computer calculates the smallest possible solar panel for each tilt and power requirement. At the same time, the computer compares the solar array output against the load requirements and generates the battery capacity necessary to operate the system during periods of low sunshine. Typical programs include a specific number of no sun days" of battery storage. A "no sun day" is one in which it is assumed the solar array provides no power to either the battery or the load. (In reality, the solar panel will provide some power even during heavy overcast days.) The number of "no sun days" is selected by the designer. In determining this number, a quick check of extended periods of overcast weather and a check of the climate in general is taken. For example, in desert or semi-arid regions, 5-days storage is generally added, while in areas of heavy fog with much coastal cloudiness, such as found in the North Sea or the Gulf of Mexico, 20 to 30 days are required. (U.S. Coast Guard regulations require the use of 30-days storage in offshore solar energy power systems.)

In calculating a "minimum" system, the solar panel must provide, on a yearly average, the customer's load plus an extra 10%. This added 10% allows for a bad year in sunshine, the self-discharge of the battery system (only when low loss batteries, 1% per month, are used), and other minor variations that may occur.

The computer program can handle systems of many different voltage and ampere-hour drains. It also has separate routines for derating depending on the type of
storage battery specified (lead-acid, low and high self-discharge types, or nickel-cadmium type batteries). In addition, the computer can select a minimum battery capacity required when the battery is subjected to extremely low or high temperatures. Automatic oversizing can be selected to allow sufficient reserve capacity for when the battery is at its lowest state of charge and operating in temperatures from -20ºC to -40ºC.

All of the above procedures can be performed automatically when a system consisting of a constant daily load and no special environmental factors is designed. When a system with special conditions presents itself, the operator can take advantage of the computer's calculating speed while maintaining control over the important parameters.

An example of system sizing is shown in the computer printout reproduced in Figure 7. This is for a 12 V system located in Boston, MA. The load is a constant 15 amp-hours per day. The first row of data (FLT LNGLYS) shows the average daily number of Langleys incident on a flat surface each month. The second row (TEMP) is the average daily high temperature (°C) for each month, which is used for temperature derating of modules when required. From this input data, the computer picks the optimum system of solar modules, battery capacity, and array tilt angle which provides at least 10% in excess of the load requirement over the year, and prints the output data shown in the columns.

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                 TYPICAL SYSTEMS DESIGN REPORT

        DATE:                           7/31/95
        LOCATION:                       BOSTON MASS
        DATA LOCATION:                  BOSTONNA
        DATA LATITUDE:                  42.33 N
        DATA LONGITUDE:                 71 W


MONTH       JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
FLT LNGLYS  139   198   293   364   472   499   496   425   341   238   145   119
TEMP        0     5     5     10    20    25    25    25    20    15    10    5

        TILT 65
        LOAD   15.0     SERIES  = 1      PARA    = 2

        MONTH      TEMP   LNGLYS   LOAD    OUTPUT   DFCTS     SURPL
        JAN          0     291    15.00     15.2     0.0        6.2
        FAB          5     323    15.00     16.8     0.0       50.8
        MAR          5     376    15.00     19.6     0.0      142.6
        APR         10     350    15.00     18.2     0.0       96.0
        MAY         20     370    15.00     19.3     0.0      133.3
        JUN         25     354    15.00     18.5     0.0      105.0
        JUL         25     364    15.00     19.0     0.0      124.0
        AUG         25     371    15.00     19.3     0.0      133.3
        SEP         20     390    15.00     20.3     0.0      159.0
        OCT         15     366    15.00     19.1     0.0      127.1
        NOV         10     305    15.00     15.9     0.0       27.0
        DEC          5     275    15.00     14.3    21.7        0.0
        AVE/TOT      0     344    15.00     17.9    21.7     1104.3

        LOW SUN STORAGE                  21 AHRS
        15 DAYS STORAGE                 225 AMRS
        TOTAL <@ 100 HR RATE>           246  AHRS

              LEAD ACID BATTERY SYSTEM
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Figure 7. Computer printout of system sizing data

In the example shown, the computer has chosen a solar array consisting of two modules, wired 1 in series, 2 in parallel, and has chosen to tilt the array 650 from the horizontal, facing due south. The first column (TEMP) repeats the temperature data in the second row. The second column (LNGLYS) gives the average daily number of Langleys incident each month on a surface tilted at 65º.

The third column (LOAD) is the constant 15 amp-hours/day load of this example. The fourth column (OUTPUT) is the average daily output of the solar array each month, in amp hours. Depending on whether the output is greater or less than the load, there will be a surplus or a deficit each month. These are recorded in the last two columns, headed DFCTS and SURPL, as the total amp hours for the month. For example, in December the average output is 14.3 amp hours/day, which is 0.7 amp hour/day less than the load requires. The total deficit for December is therefore, 0.7 amp hour/day x 31 days = 21.7 amp hours. The last entry in these two columns is the sum of the monthly deficits and surpluses for the whole year. The total deficit for the year becomes the "low sun" storage component of battery capacity. To this is added 15 days of "no sun" storage (15 amp hours/day x 15 days = 225 amp hours) to give the total required battery capacity of 247 amp hours. The net surplus (total surplus minus total deficit) is 19.7% more than the load requires which just exceeds the design requirement of at least 10% oversize.

Based on the monthly deficit and surplus, the expected variation in state of charge of the battery can be deducted. The result is plotted in Figure 8. The accumulation of deficits during the winter months leads to the partial discharge of the battery during that period as shown. The provision for 15 days "no sun" storage is also indicated.

The maximum output over the year from a solar array with a fixed tilt occurs when the tilt is approximately the same as the latitude of the location. Therefore, one may wonder why the computer didn't pick a tilt angle closer to 42 degrees in the example shown. The reason becomes clear if we examine the data for a tilt of 450 (Figure 9). In this case, the same solar array is required (two modules connected in parallel) and the net output over the year has increased from 19.7% oversize to 28.9% oversize. However, the total deficit accumulated over the winter months has also increased, almost quadrupling the low sun storage requirement on battery capacity (from 21 to 83 amp hours)~ Therefore, a larger and more expensive battery would be required. Since the additional output of the solar array tilted at 45° cannot be utilized in this application, it is clearly more economical to tilt the array at 65° and take advantage of the smaller storage battery this allows.

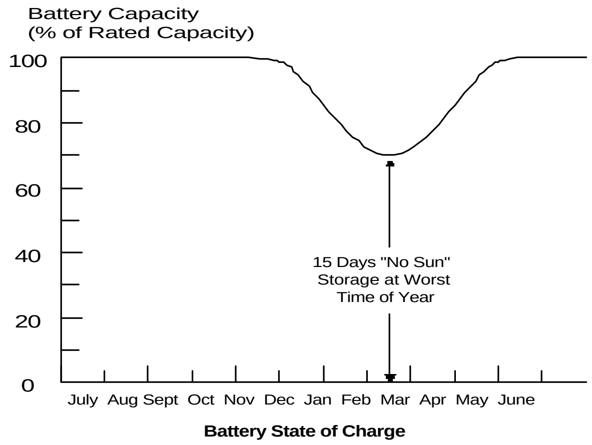

Figure 8. **Battery State of charge (monthly average)**

```
TILT 65
LOAD   15.0     SERIES= 1      PARA  = 2

MONTH       TEMP     LNGLYS    LOAD     OUTPUT    DFCTS      SURPL
JAN            0        291    15.00      15.2      0.0        6.2
FAB            5        323    15.00      16.8      0.0       50.8
MAR            5        376    15.00      19.6      0.0      142.6
APR           10        350    15.00      18.2      0.0       96.0
MAY           20        370    15.00      19.3      0.0      133.3
JUN           25        354    15.00      18.5      0.0      105.0
JUL           25        364    15.00      19.0      0.0      124.0
AUG           25        371    15.00      19.3      0.0      133.3
SEP           20        390    15.00      20.3      0.0      159.0
OCT           15        366    15.00      19.1      0.0      127.1
NOV           10        305    15.00      15.9      0.0       27.0
DEC            5        275    15.00      14.3     21.7        0.0
AVE/TOT        0        344    15.00      17.9     21.7     1104.3

LOW SUN STORAGE                          21 AHRS
15 DAYS STORAGE                         225 AMRS
TOTAL <@ 100 HR RATE>                   246  AHRS

          LEAD ACID BATTERY SYSTEM
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```
TILT 65
LOAD   15.0     SERIES= 1      PARA  = 2

MONTH     TEMP       LNGLYS    LOAD     OUTPUT  DFCTS        SURPL
JAN         0           273    15.00      14.2   24.8          0.0
FAB         5           315    15.00      16.4    0.0         39.5
MAR         5           393    15.00      20.5    0.0        170.5
APR        10           395    15.00      20.6    0.0        168.0
MAY        20           446    15.00      23.3    0.0        257.3
JUN        25           434    15.00      22.6    0.0        228.0
JUL        25           441    15.00      23.0    0.0        248.0
AUG        25           431    15.00      22.5    0.0        232.5
SEP        20           419    15.00      21.8    0.0        204.0
OCT        15           367    15.00      19.1    0.0        127.1
NOV        10           284    15.00      14.8    6.0          0.0
DEC         5           255    15.00      13.3   52.7          0.0
AVE/TOT     0           371    15.00      19.3   83.5       1674.9

LOW SUN STORAGE                          83 AHRS
15 DAYS STORAGE                         225 AMRS
TOTAL <@ 100 HR RATE>                   308  AHRS

          LEAD ACID BATTERY SYSTEM
```

Figure 9.

D. FIELD SIZING TECHNIQUES

Sometimes it is desirable to obtain a quick field estimate of the solar array size required for a specific application. In many cases a reasonably good estimate can be obtained from a few simple calculations. The daily load (amp hr/day) must be obtained along with the yearly average of the daily sunlight incident at the proposed installation site. The incident sunlight (Langleys/day) can usually be obtained from a publication by the University of Wisconsin entitled "World Distribution of Solar Radiation". It is convenient to multiply the average number of Langleys/day by the factor 0.0116 to convert the total sunlight energy received during the day to an equivalent number of hours of peak sunlight (defined as 100 mW/cm^2). This is because module output specifications are quoted for incident peak sunlight of 100 mW/cm^2. Therefore, module output (amp hr/day) is simply its rated charging current output multiplied by the equivalent number of peak sunlight hours/day.

The total number of modules in the array is given by the number connected in series multiplied by the number connected in parallel. The number in series is known when the battery voltage of the application is specified. Most modules are made to match a pre-specified nominal system voltage such as a 12V lead-acid battery. A 12V system, therefore, requires one module in series, a 24V system requires two in series, and so on. The number of modules connected in parallel is obtained simply by dividing the daily load (amp hr/day) by the average daily module output (amp hr/day) as determined above. The following example illustrates this procedure.

EXAMPLE

A 24v mountain top radio repeater located near Grand Junction, Colorado draws 6 amps when transmitting (20% of the time), but only draws 0.5 amp during standby and receiving (80% of the time). The daily load is 38.4 amps hrs/day.

Load = 6 amps x 4.8 hrs) + (0.5 amp x 19.2 hrs)
= 28.8 + 9.6
= 38.4 amp hrs/day

At Grand Junction, the annual average Langley reading is 454 Langleys/day. Multiplying by 0.0116 gives 5.27 equivalent hours of peak sunlight per day. The specifications for the module chosen indicate an output current of 2.25 amps at the battery charging point under peak sunlight conditions. Therefore, the average daily output of each module is 2.25 amps multiplied by 5.27 peak sunlight hours which gives 11.86 amp hrs/day.

Peak Sun Hr = 454 Langleys/day x 0.0116
= 5.27hrs.

Module Output = 2.25 amps x 5.27 hrs.
= 11.86 amp hrs/day

The number of modules connected in parallel is obtained by dividing the load (38.4 amp hrs/day) by the module output (11.86 amp hrs/day), which gives 3.2 modules. Because fractional modules are not available, the next whole number of modules must be used (4 modules).

No. Parallel Modules = Load/Module Output
= 38.4/11.86
= 3.2
= 4 whole modules

Since this a 24 V system, there are 2 modules connected in series. The complete array will, therefore, contain eight (8) modules.

Total Number = No. Series x No. Parallel
= 2x4
= 8 modules

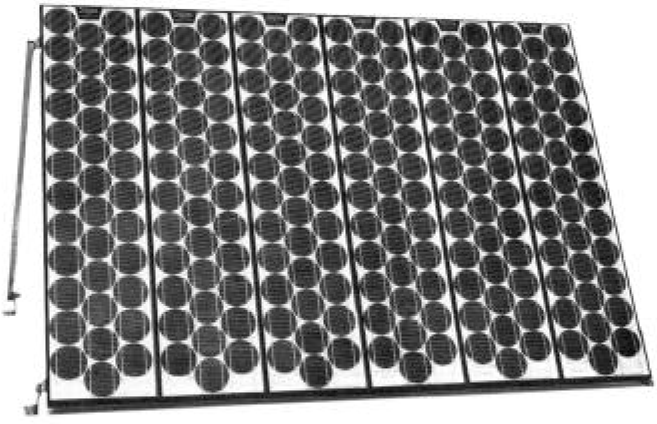

Figure 10. Typical six module array

BATTERY CAPACITY

Only very rough estimates of required battery capacity can be made in the field. The system sizing procedure used in the field gives no indication of the seasonal deficits which will accumulate. A rough rule of thumb is given in the following table, which gives battery capacity in terms of the number of days of storage required for different latitudes. The table applies only to locations having normal weather conditions. The estimator must use his own judgment about local weather conditions.

Latitude	Days storage
0º - 30º	5-10
30º - 40º	10-15
40º - 50º	15-20
50º+	20 +

Battery capacity estimates obtained this way are likely to be conservative.

The actual battery capacity required is the number of days storage multiplied by the daily load of the system.

In the EXAMPLE, the latitude of Grand Junction is 39ºN. This gives 15 days x 38.4 amp hrs/day = 576 amp hrs battery capacity.