A Simplified Solar Cell Array Modelling Program

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As part of the energy conservation/self-sufficiency efforts of DSN Engineering, it was necessary to have a simplified computer model of a solar photovoltaic (PV) system. This article describes the analysis and simplifications employed in the development of a PV cell array computer model. The analysis of the incident solar radiation, steady-state cell temperature, and the current-voltage characteristics of a cell array are discussed. A sample cell array was modelled and the results are presented.

I. Introduction

As part of the Deep Space Network (DSN) effort in energy conservation and energy self-sufficiency at DSN tracking stations, the use of photovoltaic (PV) systems is being considered as a means of supplying cost-effective electrical power to these facilities. Flat-plate PV systems offer the advantages of relatively high efficiency, compactness, mechanical simplicity, high reliability, and adaptability to a variety of installation locations such as roof-top, ground, etc.

In order to have an analysis tool which could be used in conjunction with present computer models that quantify facility energy consumption, it was necessary to have a PV system computer model which operates with a minimum of computer storage space, is inexpensive to execute, and which can be easily interfaced with this existing software.

Several existing computer programs which model PV systems were investigated and were found to contain far more computational details and associated nonessential features than are required for the DSN engineering applications. For instance, the SOLCEL program developed by Sandia Laboratories is capable of performing a complex financial analysis which takes into account the ratio of preferred stock to total capitalization, the annual rate of return on common stock, investment tax credits, etc. Other PV computer models were surveyed, among which was a program developed by the Low-Cost Solar Array (LSA) Project at JPL. This model, which addresses the cell reliability and failure modes, provides a basic cell array operation and maintenance analysis capability.

The requirement by DSN engineering to have design-oriented analysis procedures emphasized the need to develop, using a minimum effort, a simplified PV system computer model to support ongoing predesign studies. This article describes the first phase of this effort, which involved developing a computer model of only the PV cell array. The development of the entire system model, which will include such components as batteries, dc – ac inverters, and voltage regulators, which enable the system to generate maximum power and perform load-following, will be described in a subsequent article.

The emphasis in this work has been on using existing analysis tools, such as the ASHRAE solar radiation model (Ref. 1), and on developing a simplified solar cell model. The result was a compact, low cost, and relatively accurate computer program.

II. Technical Approach

The program analyzes flat-plate solar cells with a varied selection of tracking types, from stationary to double-axis (direct pointing) tracking. Hourly values for solar radiation and solar angles may either be input from data or calculated by an internal model. An approximate heat transfer analysis is performed to calculate the solar cell temperature, which determines cell efficiency. An iterative scheme is used, since cell temperature and efficiency are interdependent. Tables of current-voltage (I-V) performance curves as a function of temperature must be supplied to the program for the cell efficiency calculations.

The electrical circuit calculations are straightforward, since the main purpose is to analyze a PV array that is used to charge electrical batteries. A system voltage must be specified, and the power calculations are performed at this voltage.

In this fashion, relatively few PV cell properties are required from the user. The program is easy to operate and the results are quite accurate when compared to other photovoltaic programs which are much larger and more complicated to use.

A typical PV system, ARCO Model No. 104106, was selected to be analyzed, since cell array property data were available for this device from the LSA Project documentation (Ref. 4).

III. Technical Analysis

The analysis is performed on a monthly basis using "typical" values of ambient and solar conditions for each month. Any single month or succession of months may be analyzed. A complete cell array performance summary which consists of 24 hourly conditions may be printed out. At the user's option, a short printout may be selected which prints only the total dc power for the "typical day" of each month and the total of all these "typical days" for the study period.

All calculations are performed in SI metric units. The computations are divided into the following segments:

A. Solar Radiation Calculations

The solar radiation intensity I_t incident on the flat surface of a PV panel consists in general of three components: direct solar radiation I_D, diffuse sky radiation I_d, and the solar radiation reflected from surroundings I_r. The direct component is expressed as:

$$I_D = I_{dN} > \cos\theta \qquad (1)$$

where I_{dN} is the direct normal insolation in W/m^2, and θ is the angle of incidence between incoming solar rays and a line normal to the surface, as shown in Fig. 1. For a planar, tilted surface, the angle θ is determined (Ref. 1) from the relation

$$\cos\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma \qquad (2)$$

where β is the solar altitude angle, the angle between the sun's ray and the projection of the ray on a horizontal surface; γ is the surface-solar azimuth angle, the angle between the projection of the normal to the surface on the horizontal plane and the projection of the sun's ray on the horizontal plane; and Σ is the angle the surface makes with the horizontal plane; Σ can be either fixed or changing each hour according to the tracking mechanism (single-axis, double-axis).

The surface-solar azimuth angle can be written as:

$$\gamma = \phi + \psi \qquad (3)$$

where ψ is the surface azimuth angle, the angle between the projection of the normal to the surface on the horizontal plane and the direction south (ψ is taken positive for an angle west of south); ϕ is the solar azimuth angle, the angle between the south direction and the projection of the sun's ray on the horizontal surface.

Furthermore, the solar angles β and ϕ are obtained from

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta \qquad (4)$$

$$\sin\phi = \cos\delta \sin H / \cos\beta \qquad (5)$$

where L is the site latitude angle, δ is the solar declination angle, and H is the hour angle of the sun. Since this model assumes that the local solar time equals the local civil time, and the longitude correction and equation of time (about +14 minutes) can be neglected, then the hour angle H is expressed by

$$H = 0.25 \times \text{(number of minutes from solar noon)} \qquad (6)$$

The declination angle δ is expressed by a Fourier series that is obtained by curvefitting data contained in Ref. 1.

$$\delta = (\pi/180)\left[0.2833\text{-}23.188\cos\left(\frac{M\pi}{6}\right) - 0.15\cos\left(\frac{M\pi}{3}\right)\right.$$

$$\left. -0.211\sin\left(\frac{M\pi}{6}\right) + 0.1155\sin\left(\frac{M\pi}{3}\right)\right] \quad (7)$$

where M is the month index (1, 2, 3 . . . 12).

The diffuse sky radiation is expressed as (Ref. 1):

$$I_d = I_{Hd}(1 + \cos\Sigma)/2 \quad (8)$$

where I_{Hd} is the diffuse sky radiation falling on a horizontal surface.

The reflected solar radiation is expressed as:

$$I_r = \rho I_H (1 - \cos\Sigma)/2 \quad (9)$$

where I_H is the total radiation falling on a horizontal surface and ρ is the average reflectivity of the ground and surrounding surfaces. I_H is given by:

$$I_H = I_{Hd} + I_{dN}\sin\beta \quad (10)$$

Therefore, the total radiation I_t is given by

$$I_t = I_{dN}\cos\theta + I_{Hd}(1 + \cos\Sigma)/2 + \rho I_H (1 - \cos\Sigma)/2 \quad (11)$$

If measured solar data are supplied, I_{dN} and I_H are given and the expression for total insolation becomes:

$$I_t = I_{dN}\cos\theta + (I_H - I_{dN}\sin\beta)(1 + \cos\Sigma)/2$$

$$+ \rho I_H (1 - \cos\Sigma)/2 \quad (12)$$

If the model described in Ref. 1 is used, I_{dN} for clear sky conditions is expressed as

$$I_{dN} = A/e^{B\sin\beta}$$

and I_{Hd} is expressed as

$$I_{Hd} = CI_{dN}$$

where A, B and C are coefficients that vary throughout the year in a periodical shape. The coefficients A, B, and C are curve-fitted with Fourier series using the data of Ref. 1:

$$A = 3.1538\left[3.685 + 23.98\cos\left(\frac{M\pi}{6}\right) - 1.083\cos\left(\frac{M\pi}{3}\right)\right.$$

$$\left. + 4.893\sin\left(\frac{M\pi}{6}\right) - 0.722\sin\left(\frac{M\pi}{3}\right)\right] \quad (13)$$

$$B = \left[1.7158 - 33.08\cos\left(\frac{M\pi}{6}\right) + 3.08\cos\left(\frac{M\pi}{3}\right)\right.$$

$$\left. -10.34\sin\left(\frac{M\pi}{6}\right) + 1.3\sin\left(\frac{M\pi}{3}\right)\right](.001) \quad (14)$$

$$C = \left[90.333 - 39.63\cos\left(\frac{M\pi}{6}\right) + 6.83\cos\left(\frac{M\pi}{3}\right)\right.$$

$$\left. -10.651\sin\left(\frac{M\pi}{6}\right) + 3.17\sin\left(\frac{M\pi}{3}\right)\right](.001) \quad (15)$$

The coefficient A is expressed in W/m^2; the coefficients B and C are dimensionless. For non-clear sky conditions (clouds, fog, etc.), a cloud cover factor must be used. This cloud cover factor represents the fraction of clear sky insolation which occurs at ground level by multiplying the total insolation I_t. Five solar-tracking options are available to the user and are selected through an input parameter:

(1) The PV panels are stationary with surface tilt angle specified. Panels are facing south (north for southern hemisphere); in this case:

$$\psi = 0$$

(2) The PV panels are single-axis tracking about a horizontal east-west axis (ie., panels pivoting on a horizontal rod oriented east-west); in this case:

$$\gamma = \phi$$

$$\Sigma = \tan^{-1}(\cos\phi/\tan\beta)$$

$$\psi = 0$$

(3) The PV panels are single-axis tracking about a horizontal north-south axis; here:

$$\psi = \frac{\pi}{2}$$

$$\Sigma = \tan^{-1} (\sin |\phi| / \tan \beta)$$

(4) The PV panels are single-axis tracking about a vertical axis (i.e., tilted at a constant angle to the ground and mounted on a vertical rod which rotates); here:

$$\psi = \tan^{-1} \{\cos \beta \sin \phi / [\sin |L| \cos (x - |L|)]\}$$

where $x = \tan^{-1} (\cos \phi / \tan \beta)$, and $\Sigma = \tan^{-1} (\tan |L| / \cos \psi)$

(5) Double-axis tracking, PV panels normal to sun vector ($\theta = 0$).

B. Cell Temperature Analysis

For all tracking options the cell array is assumed to be passively cooled by ambient air on the front surface only, with the rear surface insulated. The heat flux which is deposited in the cell is expressed as:

$$Q = I_t (\alpha - \eta) \tag{16}$$

where α is the product of cell visible light absorbtance and cell encapsulation transmittance (the fraction of incident energy which enters the cells), and η is the cell efficiency, fraction of incident insolation which is converted into dc electricity.

Figure 2 shows the equilibrium heat flux condition for the approximate heat transfer model used in this analysis. At equilibrium, the heat flux Q will be equal to the sum of heat lost from the cell outer surface by both convection and radiation; i.e.,

$$Q = (h_c + h_r)(T_c - T_a) \tag{17}$$

where h_c and h_r are the convective and radiative heat transfer coefficients, respectively. Equations (16) and (17) give the temperature T_c as:

$$T_c = T_a + \frac{Q}{(h_c + h_r)} \tag{18}$$

The following empirical relationships for the heat transfer coefficients h_c and h_r are taken from Ref. 2. The convective heat transfer coefficient h_c consists of two parts: a free convection coefficient h_1 and a forced convection coefficient h_2, for a flat plate in a moving airstream:

$$h_c = h_1 + h_2$$

The free convection heat transfer coefficient, h_1, is expressed in W/m^2 K as

$$h_1 = (k/x)(0.13)(\mathrm{GrPr})^{.333} \tag{19}$$

where k, the thermal conductivity of air, is expressed in W/m - K as

$$k = 3.623 \times 10^{-4} \, T_m^{.7488} \tag{20}$$

T_m is the average of the air and cell temperatures (K); x is the characteristic panel length (m); and Gr is the Grashof number:

$$Gr = 9.8 \beta_T (\Delta T) x^3 / \nu^2$$

where β_T is the thermal expansion coefficient of air in (K^{-1}):

$$\beta_T = 1/T$$

$$\Delta T = |T_{air} - T_{plate}|$$

ν is the kinematic viscosity of air in m^2/s:

$$\nu = 9.253 \times 10^{-10} (T^{1.709})$$

$$Pr = \text{Prandtl number (0.72 for air)}$$

The forced convection heat transfer coefficient h_2 is given in W/m^2 - K as

$$h_2 = \frac{0.664 \, kPr^{.333} \sqrt{Re}}{x} \quad [Re \leqslant 5 \times 10^5]_{\text{Laminar}}$$

or (21)

$$h_2 = \frac{0.036 \, kPr \, (Re^{.8} - 23000)}{x} \quad [Re > 5 \times 10^5]_{\text{Turbulent}}$$

where Re = Reynold's number = Vx/ν, and V is wind speed in m/s.

The radiation heat transfer coefficient h_r is linearized and given as

$$h_r = 5.688 \times 10^{-8}\, \epsilon\, (T_c^{\ 4} - T_r^{\ 4})/T_c - T_a) \qquad (22)$$

where ϵ is the infrared emittance of the cell encapsulent; T_c is the cell temperature, taken as the plate surface temperature (K); T_a is the ambient air temperature (K); T_r is the "effective" radiative temperature, which is taken as the average of apparent sky temperature and ambient air temperature:

$$T_r = (T_{sky} + T_a)/2$$

$$T_{sky} = 0.0552\, T_a^{\ 1.5} \qquad (23)$$

The cell temperature calculation procedure is started by assuming an initial guess for both T_c and η. Then calculate Q from Eq. (16) and calculate h_1, h_2, h_r from Eqs. (19), (21), and (22). The cell temperature T_c is calculated from Eq. (18) to check on $\eta = \eta\ (T_c)$. If η is inconsistent, repeat starting with Eq. (16). This iteration is found to converge within two to three steps, and therefore it is performed only four times in the program.

C. Cell Efficiency Analysis

The method for calculating cell efficiency is based on the assumption that the efficiency is a strong function of cell temperature and a weak function of insolation within normal operating conditions. Consequently, η may be derived by interpolating among a family of reference I-V curves, as shown in Fig. 3, in which each curve represents a particular cell temperature. Once the voltage is given by the user, the current will be determined for a given cell temperature and cell efficiency. Hence,

$$\eta = IV/Cr \qquad (24)$$

where Cr is a reference insolation. Note that this current is a representative value corresponding to a reference insolation and is used only for calculating efficiency. A justification for the above assumption may be made according to the circuit analysis (Ref. 3) as follows.

An equivalent circuit for a solar cell is shown in Fig. 4, where R_s = series resistance of the cell, I_L = light-generated current, I_D = dark current, V_D = diode voltage, I = net output current, and V = cell voltage. By writing

$$I = I_L + I_D\ (I_L >> I_D) \qquad (25)$$

$$V_D = IR_s + V \qquad (26)$$

I_D may be expressed as (Ref. 3)

$$I_D = I_0\ (1 - e^{(q/kT)V_D}) \qquad (27)$$

where I_0 is the reverse saturation current.

Thus, by combining Eqs. (25), (26), and (27), we obtain

$$I = I_L + I_0^{\ [1 - e\ (q/kT)\ (V + IR_s)]} \qquad (28)$$

Since cell efficiency is the ratio of dc power output to total incident insolation, $\eta = IV/AI_t$, then

$$\eta = I_L V/AI_t + (I_0 V/AI_t)\ [1 - e^{(q/kT)\ (V + IR_s)}] \qquad (29)$$

where A is the cell area.

For normal operating conditions (i.e., when voltage does not approach the cell's open-circuit voltage) the light-generated current is known to be proportional to insolation (Ref. 3). Thus, it can be seen that the first term is independent of I_t and the second term is linearly dependent on I_t and exponentially dependent on T^{-1} since R_s is usually small. This reasoning then supports the assumption that efficiency is primarily a function of temperature for a given voltage, and may be interpolated from a family of I-V curves.

D. PV Array Power Output

The net dc power output, in kW, for any hour of the analysis is:

$$P_{net} = \frac{I_t\, \eta\, \bar{A} f N}{1000} \qquad (30)$$

where $\bar{A}$ is the area of each module of cells in m^2, f is the packing factor of cells (ratio of cell area to module area), and N is the number of modules in the system. The sum of the hourly values of P_{net} represents the total dc power obtained for the typical day of each month under study.

IV. Program Description

The cell array program is written in FORTRAN and consists of three routines.

(1) The MAIN routine reads input data, performs initializations, and controls the overall simulation.

(2) The PWR subroutine performs the insolation calculations, the thermal analysis, and the power analysis; PWR is called by MAIN.

(3) The EFF subroutine is called by PWR to calculate the cell efficiency for a given voltage and temperature.

Program input consists of three parts:

(1) The namelist "CDAT", which contains current-voltage (I-V) curve data.

(2) The namelist "PVIN," which contains various system parameters and program operation flags.

(3) A formatted input file which contains data about ambient and insolation conditions.

Note that the last input is not needed if the internal insolation model is used. The output is described for the sample case in the following section.

V. Sample Case Analysis

The sample solar photovoltaic module chosen to be analyzed was the ARCO Solar Module, Model Type 10699-C, Module Serial No. 104108. A drawing of the module which illustrates pertinent physical features and electrical connections is shown in Fig. 5 (Ref. 4).

For this case, the program's internal solar model was used, since complete hourly data for direct normal insolation was not available for the Los Angeles site. Hourly data are now being recorded for the Los Angeles site by the National Oceanic and Atmospheric Administration (NOAA) and computer tapes should be available in late 1982.

A listing of both the long and short versions of output for this case are shown in the Appendix. The primary input parameters which describe the ARCO solar module are listed under the headings "SYSTEM PARAMETERS" and "SITE DESCRIPTION." The voltage was selected to be regulated at 15 volts dc since the cell efficiency is relatively high at this voltage and also excess charging voltage is allowed for charging a 12-volt battery system.

The tilt angle of the panels was fixed at 24 degrees from horizontal, the ground reflectivity was 0.2, the product of cell absorbtance and encapsulent transmittance was 0.9, the infrared emittance of the cell encapsulent was 0.526, the surface area of each PV panel module was 0.2701 m^2, the cell packing factor was 0.692, there were 100 modules, the site was Los Angeles, California, and the latitude was 33.56° north. Also, the I-V curve data were taken from Fig. 3. The cloud cover factors for the 12 months of the year were 0.82, 0.75, 0.78, 0.78, 0.80, 0.82, 0.87, 0.9, 0.91, 0.92, 0.88, 0.86.

The first page of the Appendix is a summary of the input. The analysis results are shown in the following pages of the Appendix for both a long print version and a short print version of the output. An interpretation of the output is as follows: Under the column heading "HOUR," the integer number indicates the hourly period starting from midnight; subsequent columns are hourly averages. "AMBIENT TEMPERATURE" and "WIND SPEED" are as taken from input; "TOTAL INSOLATION" is the mount of insolation incident on the cells (not on the entire module area) during the hourly period; "CELL TEMPERATURE" is the calculated cell temperature; and "POWER OUTPUT" is the calculated power output for the hourly period. At the bottom, "TOTAL POWER FOR A TYPICAL DAY IN JAN" is the total of all hourly power outputs in the last column above. Note that this power is rated at the specified voltage, and the corresponding current may be calculated accordingly.

A parametric study was performed in which the panel tilt angle was varied over the range 10-70 degrees to determine the optimum angle for each month. Table 1 shows the results of this study in terms of power as a function of month and tilt angle. Table 2 shows the optimum tilt angles for each month and the resulting power for each typical day. The single tilt angle which gave the maximum total power for the entire year was approximately 35 degrees, which is equal to the site latitude, as expected. The trend in Table 2, which shows peak optimum power in the summer months is a result of the cloud cover factor.

The benefit of changing tilt angle to the monthly optimums instead of keeping a fixed angle of 35 degrees results in an increase of only about 5% in net power output over a one-year period (14443.83 kWh compared to 137.7 kWh) for 12 "typical days." Thus it would not seem reasonable to implement this feature in such a system unless a very simple and inexpensive way to do so was devised. The average daily power output for the entire year for the system of 100 panels is about 11.9 kWh.

VI. Summary

The analysis result was compared to the photovoltaic computer program SOLCEL and found to predict very similar results. SOLCEL has more capabilities than SCAMP, but it is very large and somewhat difficult to use. In the sample case, which consisted of a system of panels mounted at a selected angle, the results showed that a fixed tilt angle of 35 degrees, approximately the site latitude, was the optimum single angle for an entire year. The performance improvement realized by selecting an optimum angle for each month was only about a 5% gain in net power. Also, the system of 100 panels will have an annual average power output of 11.9 kWh per day.

The simplified model has been developed to fill a specific need. It is applicable to the design decision-making process and will be incorporated into a PV system model. A subsequent article will describe the overall PV system model that is currently being developed and will have the ability to interface with existing energy conservation analysis tools.

References

1. *American Society of Heating, Refrigeration and Air Conditioning Engineer (ASHRAE) Handbook of Fundamentals*, ASHRAE Inc., New York, 1977.
2. Kreith, F., *Principles of Heat Transfer*, 2nd edn., International Textbook Co., Scranton, Pa., 1965.
3. Angrist, S. W., *Direct Energy Conversion*, 3rd edn., Allyn and Bacon Inc., Boston, Ma., 1977.
4. Smokler, M. I., "User Handbook for Block III Silicon Solar Cell Modules," Low Cost Solar Array Project Document 5101-82, Jet Propulsion Laboratory, Pasadena, Calif. 1979.

Table 1. PV array power output (kWh) as a function of month and tilt angle for sample analysis case

Month	Angle, deg						
	10	20	30	40	50	60	70
Jan	7.63	8.77	9.67	10.28	10.64	10.75	10.61
Feb	8.53	9.43	10.09	10.47	10.60	10.48	10.08
Mar	10.63	11.18	11.45	11.49	11.15	10.58	9.74
Apr	11.80	11.92	11.75	11.31	10.59	9.61	8.39
May	12.84	12.77	12.39	11.72	10.77	9.55	8.09
Jun	13.23	13.12	12.70	11.98	10.97	9.70	8.18
Jul	13.47	13.39	13.03	12.38	10.38	10.11	8.59
Aug	12.90	12.98	12.79	12.33	11.60	10.58	9.25
Sep	11.70	12.19	12.42	12.38	12.08	11.52	10.66
Oct	10.03	10.98	11.64	12.03	12.16	12.02	11.61
Nov	7.95	9.11	9.97	10.53	10.93	11.04	10.90
Dec	7.27	8.51	9.52	10.23	10.67	10.87	10.81
Total	127.98	134.36	137.43	137.14	133.55	126.79	116.91

Table 2. Optimum tilt angles for sample analysis case

Month	Angle, deg	Power, kWh
Jan	60	10.75
Feb	50	10.60
Mar	35	11.48
Apr	20	11.94
May	13	12.85
Jun	11	13.23
Jul	12	13.48
Aug	18	12.99
Sep	34	12.44
Oct	50	12.16
Nov	59	11.04
Dec	62	10.87
Total		143.83

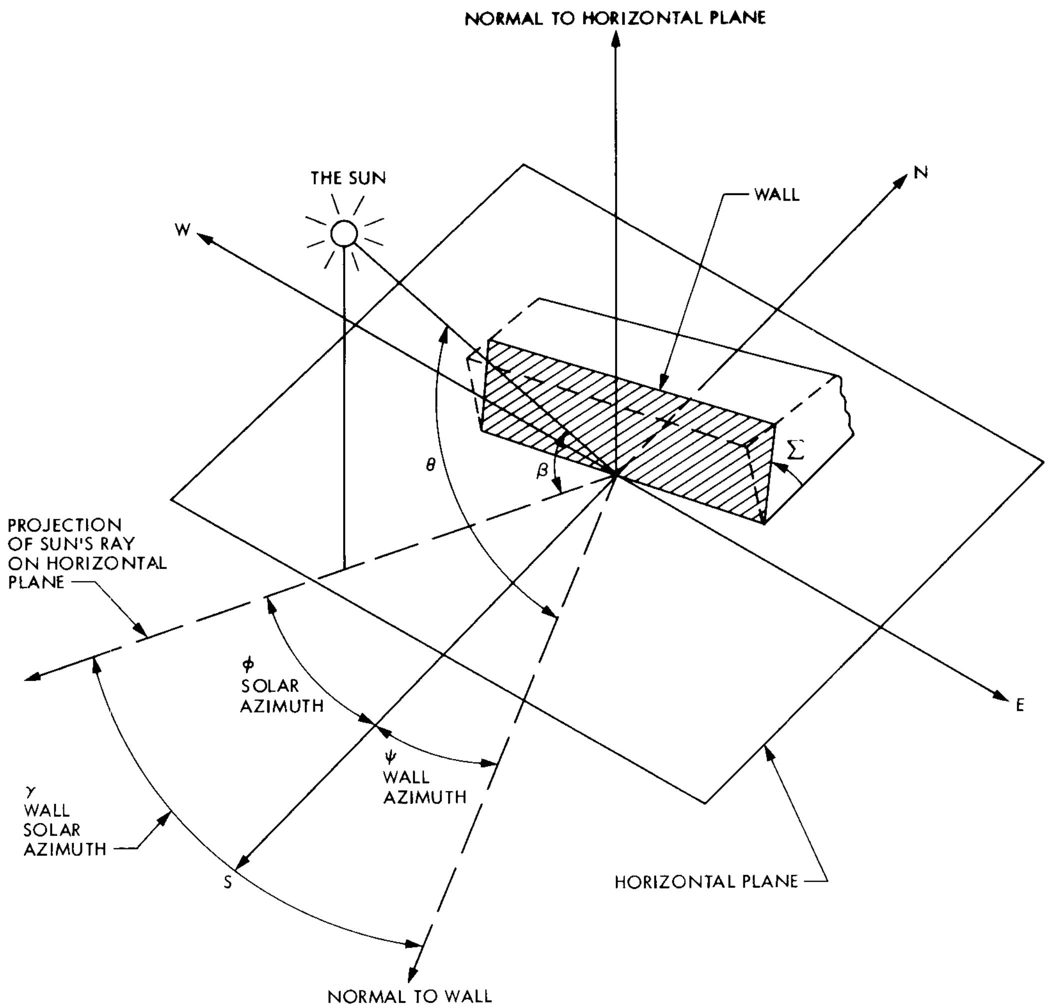


Fig. 1. Solar angles on a tilted plane

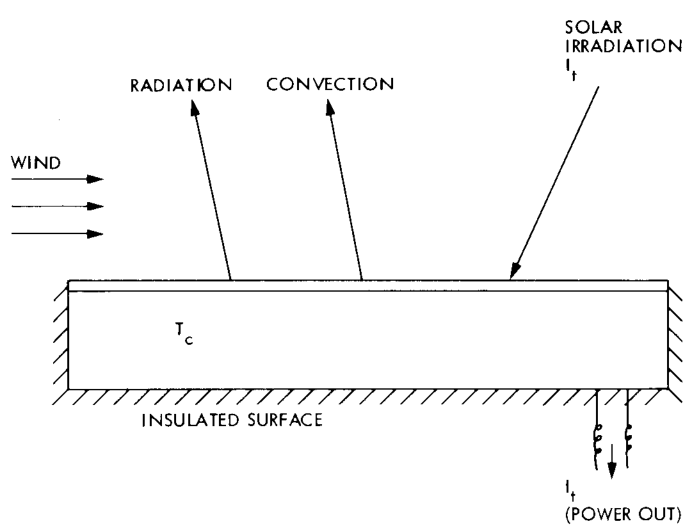


Fig. 2. Equilibrium heat transfer in TV panel

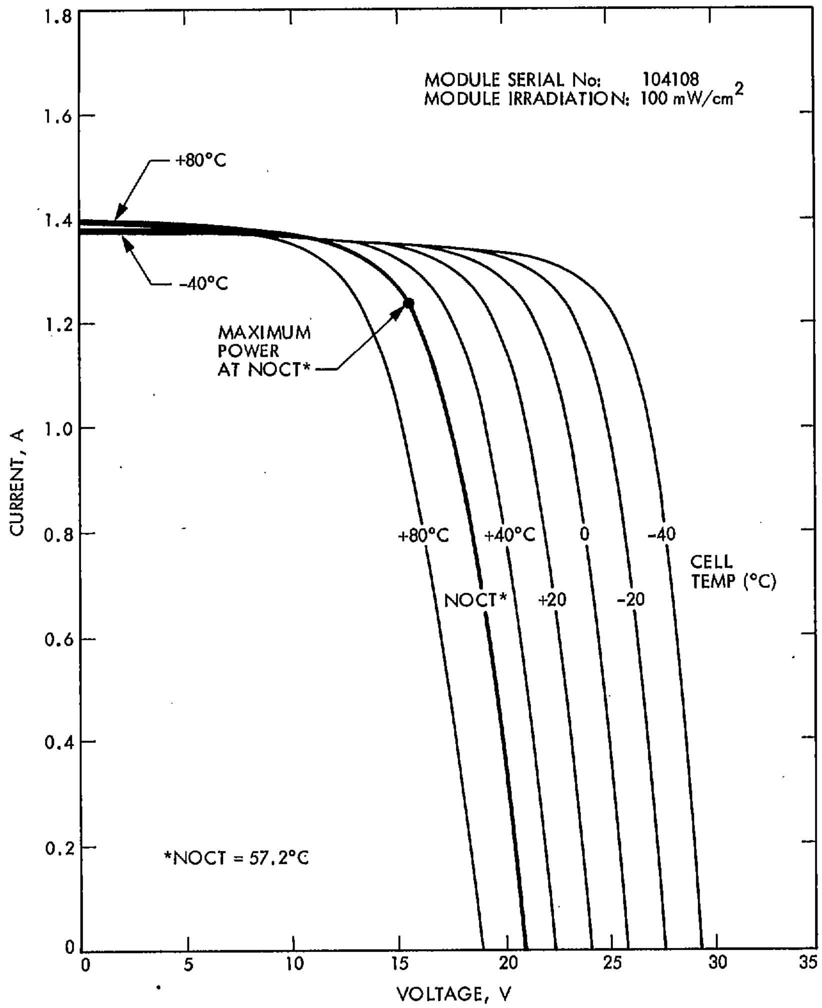


Fig. 3. I-V curves of a sample solar module (manufactured by ARCO)

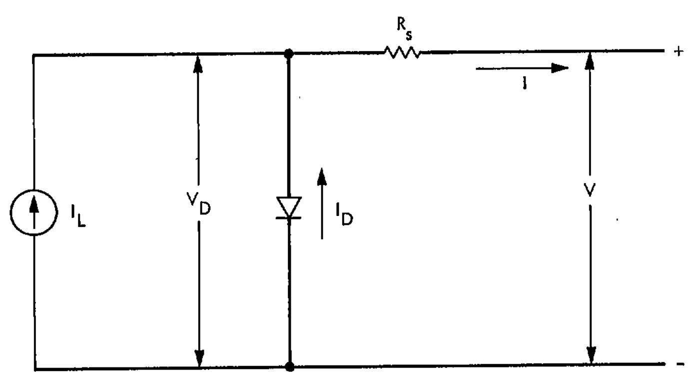
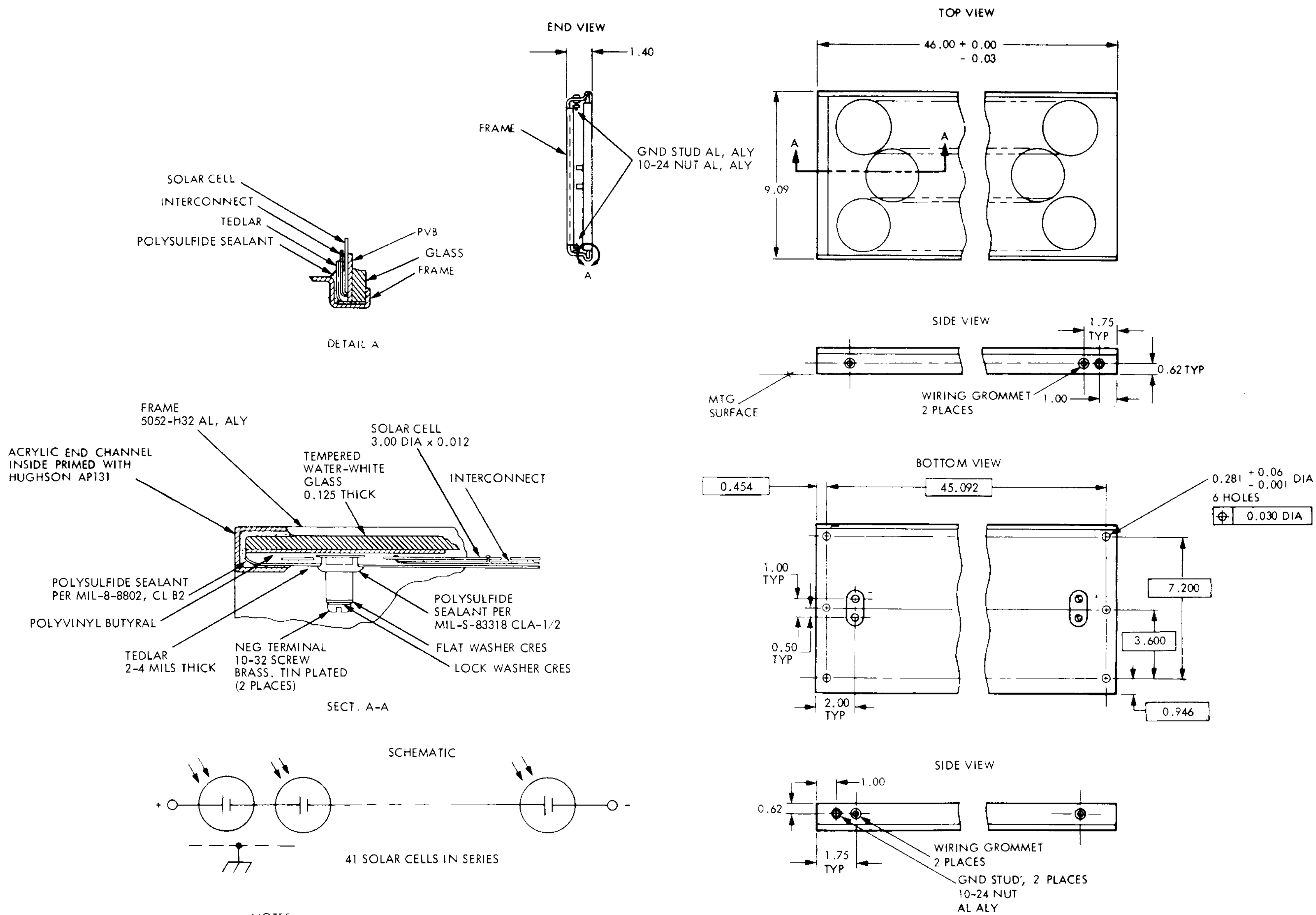


Fig. 4. An equivalent circuit for a solar cell



NOTES:

1. DO NOT SCALE
2. DIMENSIONS ARE IN INCHES
3. TOLERANCES ARE ±0.03 UNLESS OTHERWISE SPECIFIED
4. MOUNTING PLANE OF SUBARRAY MUST NOT EXCEED ONE QUARTER INCH PER FOOT DEVIATION FROM PLANARITY

Fig. 5. ARCO solar module (from Ref. 4)

Appendix
Sample Case Output

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******** PHOTOVOLTAIC CELL ARRAY MODEL ********
ARCO SOLAR MODULE NO. 104108


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SYSTEM PARAMETERS:

     REGULATED VOLTAGE=15.00 VOLTS DC
     TILT ANGLE FROM HORIZONTAL=24.00 DEGREES
     GROUND REFLECTIVITY=.200
     CELL ABSORBTANCE * ENCAPSULENT TRANSMITTANCE=.900
     IR EMITTANCE OF CELL ENCAPSULENT=.526
     INDIVIDUAL MODULE AREA=.2701 M**2
     CELL PACKING FACTOR=.692
     NUMBER OF  MODULES=100

SITE DESCRIPTION:

    LOCATION--LOS ANGELES, CA.
    LATITUDE = 33.560 DEG NORTH

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SYSTEM ANALYSIS FOR THE MONTH OF JAN

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HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	12.0	1.9	.0000	12.0	.0000
2	11.4	1.9	.0000	11.4	.0000
3	10.9	1.6	.0000	10.9	.0000
4	10.5	1.6	.0000	10.5	.0000
5	10.3	1.9	.0000	10.3	.0000
6	10.1	1.8	.0000	10.1	.0000
7	10.3	1.7	.3769+00	10.3	.4020-01
8	10.9	2.0	.4399+04	24.2	.4673+03
9	12.7	2.3	.8458+04	37.4	.8931+03
10	14.5	2.3	.1143+05	47.4	.1182+04
11	16.2	1.4	.1326+05	57.1	.1335+04
12	17.3	2.5	.1388+05	56.0	.1402+04
13	18.0	3.1	.1326+05	53.6	.1349+04
14	18.0	3.6	.1143+05	48.0	.1180+04
15	17.5	4.5	.8458+04	38.9	.8925+03
16	16.7	4.1	.4399+04	28.0	.4665+03
17	15.7	3.6	.3769+00	15.7	.4015-01
18	14.6	3.5	.0000	14.6	.0000
19	14.3	3.5	.0000	14.3	.0000
20	14.1	2.8	.0000	14.1	.0000
21	13.9	2.3	.0000	13.9	.0000
22	13.3	2.4	.0000	13.3	.0000
23	12.9	2.6	.0000	12.9	.0000
24	12.5	2.1	.0000	12.5	.0000

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TOTAL POWER FOR A TYPICAL DAY IN JAN = 9.17 KWH

SYSTEM ANALYSIS FOR THE MONTH OF FEB

****

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	12.6	1.5	.0000	12.6	.0000
2	12.2	1.8	.0000	12.2	.0000
3	11.6	1.5	.0000	11.6	.0000
4	11.3	1.8	.0000	11.3	.0000
5	11.3	1.6	.0000	11.3	.0000
6	10.8	1.4	.0000	10.8	.0000
7	10.6	1.8	.1147+04	12.9	.1222+03
8	12.3	2.1	.5359+04	28.4	.5682+03
9	15.1	2.0	.8899+04	41.7	.9343+03
10	17.6	2.5	.1158+05	50.3	.1188+04
11	19.3	3.0	.1326+05	55.1	.1343+04
12	20.0	3.5	.1383+05	56.1	.1397+04
13	19.6	4.3	.1326+05	52.8	.1351+04
14	19.3	4.5	.1158+05	48.2	.1195+04
15	18.6	5.0	.8899+04	40.5	.9374+03
16	17.8	5.0	.5359+04	31.0	.5675+03
17	16.6	4.3	.1147+04	18.7	.1220+03
18	15.3	3.5	.0000	15.3	.0000
19	14.8	3.3	.0000	14.8	.0000
20	14.8	3.0	.0000	14.8	.0000
21	14.5	2.2	.0000	14.5	.0000
22	14.0	1.7	.0000	14.0	.0000
23	13.6	1.9	.0000	13.6	.0000
24	13.3	1.9	.0000	13.3	.0000

****

TOTAL POWER FOR A TYPICAL DAY IN FEB = 9.73 KWH

SYSTEM ANALYSIS FOR THE MONTH OF MARCH

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	10.9	2.6	.0000	10.9	.0000
2	10.6	2.3	.0000	10.6	.0000
3	9.9	2.5	.0000	9.9	.0000
4	9.7	2.2	.0000	9.7	.0000
5	9.3	2.5	.0000	9.3	.0000
6	9.1	2.4	.1165-28	9.1	.1165-29
7	9.6	3.1	.2733+04	16.7	.2911+03
8	11.9	3.4	.6700+04	30.1	.7098+03
9	14.0	3.3	.1019+05	41.5	.1071+04
10	15.5	3.6	.1289+05	49.1	.1326+04
11	16.7	4.1	.1459+05	53.4	.1484+04
12	17.2	5.2	.1517+05	53.3	.1543+04
13	17.3	5.6	.1459+05	51.5	.1492+04
14	17.0	5.9	.1289+05	47.0	.1334+04
15	16.8	6.4	.1019+05	40.3	.1074+04
16	16.3	5.8	.6700+04	32.2	.7091+03
17	15.6	5.3	.2733+04	21.8	.2906+03
18	14.0	5.3	.1165-28	14.0	.1238-29
19	13.1	4.3	.0000	13.1	.0000
20	12.8	3.7	.0000	12.8	.0000
21	12.4	2.9	.0000	12.4	.0000
22	12.0	2.9	.0000	12.0	.0000
23	11.6	2.7	.0000	11.6	.0000
24	11.2	2.6	.0000	11.2	.0000

TOTAL POWER FOR A TYPICAL DAY IN MARCH= 11.32 KWH

SYSTEM ANALYSIS FOR THE MONTH OF APRIL

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	13.3	1.7	.0000	13.3	.0000
2	13.0	1.5	.0000	13.0	.0000
3	12.8	1.4	.0000	12.8	.0000
4	12.6	1.6	.0000	12.6	.0000
5	12.5	1.4	.0000	12.5	.0000
6	12.5	1.5	.9026+03	14.0	.9619+02
7	13.3	1.8	.3864+04	25.1	.4102+03
8	15.0	1.9	.7257+04	37.1	.7664+03
9	16.8	2.5	.1048+05	46.6	.1086+04
10	18.0	2.9	.1299+05	53.4	.1322+04
11	18.6	4.5	.1458+05	54.6	.1478+04
12	18.9	5.1	.1512+05	55.1	.1531+04
13	18.9	5.7	.1458+05	52.9	.1485+04
14	18.7	5.9	.1299+05	49.0	.1338+04
15	18.1	6.1	.1048+05	42.5	.1098+04
16	17.5	6.0	.7257+04	34.6	.7673+03
17	16.7	5.5	.3864+04	25.8	.4101+03
18	15.7	4.8	.9026+03	16.9	.9612+02
19	14.8	4.2	.0000	14.8	.0000
20	14.4	3.6	.0000	14.4	.0000
21	14.0	2.8	.0000	14.0	.0000
22	13.8	2.6	.0000	13.8	.0000
23	13.7	1.9	.0000	13.7	.0000
24	13.5	1.8	.0000	13.5	.0000

TOTAL POWER FOR A TYPICAL DAY IN APRIL= 11.88 KWH

SYSTEM ANALYSIS FOR THE MONTH OF MAY

****

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	13.7	2.3	.0000	13.7	.0000
2	13.5	2.1	.0000	13.5	.0000
3	13.3	2.4	.0000	13.3	.0000
4	13.0	2.4	.0000	13.0	.0000
5	12.9	2.1	.0000	12.9	.0000
6	13.2	2.4	.2401+04	19.7	.2555+03
7	14.6	2.6	.5414+04	30.2	.5736+03
8	16.0	3.1	.7819+04	37.6	.8256+03
9	16.8	3.3	.1059+05	45.3	.1102+04
10	17.6	4.1	.1295+05	50.5	.1329+04
11	18.0	4.6	.1445+05	53.5	.1470+04
12	18.3	5.4	.1496+05	53.7	.1521+04
13	18.5	6.0	.1445+05	51.9	.1476+04
14	18.5	6.4	.1295+05	48.1	.1337+04
15	18.0	6.4	.1059+05	42.4	.1110+04
16	17.6	5.9	.7819+04	36.1	.8262+03
17	17.1	5.6	.5414+04	30.0	.5736+03
18	16.3	5.0	.2401+04	21.7	.2553+03
19	15.4	4.8	.0000	15.4	.0000
20	15.0	4.2	.0000	15.0	.0000
21	14.6	3.6	.0000	14.6	.0000
22	14.4	3.2	.0000	14.4	.0000
23	14.2	2.8	.0000	14.2	.0000
24	13.9	2.4	.0000	13.9	.0000

****

TOTAL POWER FOR A TYPICAL DAY IN MAY = 12.65 KWH

SYSTEM ANALYSIS FOR THE MONTH OF JUNE

****

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	15.7	2.0	.0000	15.7	.0000
2	15.6	1.9	.0000	15.6	.0000
3	15.7	1.7	.0000	15.7	.0000
4	15.6	2.2	.0000	15.6	.0000
5	15.6	2.3	.2440+00	15.6	.2440-01
6	15.8	2.1	.3006+04	24.5	.3192+03
7	16.6	2.5	.6024+04	34.1	.6370+03
8	17.7	2.4	.8435+04	42.1	.8847+03
9	18.8	3.0	.1067+05	48.0	.1101+04
10	19.6	3.8	.1298+05	53.0	.1322+04
11	20.2	4.7	.1444+05	55.5	.1461+04
12	20.5	5.2	.1494+05	56.1	.1509+04
13	20.6	5.9	.1444+05	54.1	.1467+04
14	20.6	5.9	.1298+05	50.8	.1330+04
15	20.3	6.2	.1067+05	45.0	.1110+04
16	19.8	6.0	.8435+04	39.6	.8898+03
17	18.9	5.7	.6024+04	33.3	.6372+03
18	18.0	5.1	.3006+04	25.0	.3191+03
19	16.9	4.6	.2440+00	16.9	.2591-01
20	16.4	4.2	.0000	16.4	.0000
21	16.2	3.6	.0000	16.2	.0000
22	16.0	3.1	.0000	16.0	.0000
23	16.0	2.5	.0000	16.0	.0000
24	15.8	2.1	.0000	15.8	.0000

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TOTAL POWER FOR A TYPICAL DAY IN JUNE = 12.99 KWH

SYSTEM ANALYSIS FOR THE MONTH OF JULY

****

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	17.4	2.2	.0000	17.4	.0000
2	17.3	1.7	.0000	17.3	.0000
3	17.1	1.5	.0000	17.1	.0000
4	17.0	1.7	.0000	17.0	.0000
5	16.9	1.3	.2440+00	16.9	.2440-01
6	17.1	1.5	.2580+04	25.0	.2740+03
7	18.4	2.1	.5844+04	35.9	.6175+03
8	20.3	2.3	.8444+04	44.9	.8789+03
9	21.5	3.1	.1134+05	52.2	.1157+04
10	22.5	4.2	.1385+05	57.3	.1394+04
11	22.8	4.7	.1544+05	60.4	.1518+04
12	22.9	5.3	.1599+05	60.7	.1568+04
13	23.1	5.6	.1544+05	59.2	.1532+04
14	23.0	6.0	.1385+05	55.0	.1403+04
15	22.6	5.7	.1134+05	49.4	.1166+04
16	22.1	5.7	.8444+04	42.2	.8853+03
17	21.3	5.5	.5844+04	35.4	.6177+03
18	20.2	4.7	.2580+04	26.2	.2738+03
19	19.1	4.4	.2440+00	19.1	.2590-01
20	18.6	3.8	.0000	18.6	.0000
21	18.2	3.0	.0000	18.2	.0000
22	18.0	2.6	.0000	18.0	.0000
23	17.8	2.3	.0000	17.8	.0000
24	17.6	1.9	.0000	17.6	.0000

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TOTAL POWER FOR A TYPICAL DAY IN JULY = 13.28 KWH

SYSTEM ANALYSIS FOR THE MONTH OF AUG

****

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	19.3	2.0	.0000	19.3	.0000
2	19.1	1.7	.0000	19.1	.0000
3	19.0	1.7	.0000	19.0	.0000
4	18.8	1.9	.0000	18.8	.0000
5	18.8	1.9	.2440+00	18.8	.2440-01
6	18.8	2.1	.1026+04	20.7	.1091+03
7	19.9	2.0	.4431+04	33.3	.4688+03
8	21.2	2.3	.8169+04	45.1	.8501+03
9	22.4	3.0	.1178+05	54.4	.1195+04
10	23.1	3.7	.1459+05	60.6	.1431+04
11	23.4	4.3	.1636+05	63.9	.1565+04
12	23.5	5.2	.1697+05	63.7	.1626+04
13	23.5	5.4	.1636+05	62.0	.1589+04
14	23.6	5.8	.1459+05	57.5	.1465+04
15	23.5	5.8	.1178+05	51.2	.1206+04
16	23.0	5.7	.8169+04	42.5	.8560+03
17	22.3	5.4	.4431+04	32.9	.4688+03
18	21.3	4.7	.1026+04	22.9	.1090+03
19	20.3	4.2	.2440+00	20.3	.2594-01
20	20.0	3.5	.0000	20.0	.0000
21	19.6	3.2	.0000	19.6	.0000
22	19.5	2.9	.0000	19.5	.0000
23	19.4	2.5	.0000	19.4	.0000
24	19.2	2.9	.0000	19.2	.0000

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TOTAL POWER FOR A TYPICAL DAY IN AUG = 12.94 KWH

SYSTEM ANALYSIS FOR THE MONTH OF SEPT

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	17.8	1.8	.0000	17.8	.0000
2	17.8	1.4	.0000	17.8	.0000
3	17.6	1.2	.0000	17.6	.0000
4	17.5	.7	.0000	17.5	.0000
5	17.4	1.3	.2440+00	17.4	.2440-01
6	17.5	1.5	.6227-09	17.5	.6227-10
7	18.1	2.0	.3058+04	27.1	.3243+03
8	19.1	2.0	.7555+04	41.8	.7930+03
9	20.6	2.3	.1152+05	53.6	.1171+04
10	21.7	3.2	.1458+05	60.4	.1434+04
11	22.4	3.8	.1651+05	64.4	.1574+04
12	22.9	4.8	.1717+05	64.3	.1637+04
13	22.9	5.4	.1651+05	61.7	.1606+04
14	22.8	5.8	.1458+05	56.7	.1470+04
15	22.5	6.1	.1152+05	49.3	.1185+04
16	22.1	5.9	.7555+04	40.0	.7969+03
17	21.3	5.6	.3058+04	28.3	.3242+03
18	19.8	4.9	.6227-09	19.8	.6602-10
19	19.3	4.5	.2440+00	19.3	.2587-01
20	19.0	3.8	.0000	19.0	.0000
21	18.8	3.4	.0000	18.8	.0000
22	18.7	2.8	.0000	18.7	.0000
23	18.5	2.0	.0000	18.5	.0000
24	18.2	2.0	.0000	18.2	.0000

TOTAL POWER FOR A TYPICAL DAY IN SEPT = 12.32 KWH

SYSTEM ANALYSIS FOR THE MONTH OF OCT

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	16.5	1.4	.0000	16.5	.0000
2	16.3	1.1	.0000	16.3	.0000
3	16.0	1.1	.0000	16.0	.0000
4	15.8	.7	.0000	15.8	.0000
5	15.8	1.0	.2440+00	15.8	.2440-01
6	15.8	1.5	.6227-09	15.8	.6227-10
7	16.1	1.7	.1273+04	19.0	.1355+03
8	17.5	1.9	.6301+04	36.8	.6656+03
9	19.3	1.9	.1057+05	50.9	.1083+04
10	20.7	2.9	.1380+05	58.1	.1380+04
11	21.5	3.8	.1583+05	61.8	.1539+04
12	21.7	4.7	.1652+05	61.8	.1606+04
13	21.7	5.1	.1583+05	59.5	.1567+04
14	21.4	5.6	.1380+05	53.9	.1403+04
15	20.9	5.7	.1057+05	45.9	.1097+04
16	20.1	5.7	.6301+04	35.1	.6661+03
17	19.1	4.9	.1273+04	21.4	.1354+03
18	18.3	4.0	.6227-09	18.3	.6623-10
19	17.9	3.5	.2440+00	17.9	.2595-01
20	17.7	2.8	.0000	17.7	.0000
21	17.5	2.0	.0000	17.5	.0000
22	17.3	1.7	.0000	17.3	.0000
23	17.2	1.6	.0000	17.2	.0000
24	16.8	1.4	.0000	16.8	.0000

TOTAL POWER FOR A TYPICAL DAY IN OCT = 11.28 KWH

SYSTEM ANALYSIS FOR THE MONTH OF NOV

****

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	15.1	2.0	.0000	15.1	.0000
2	14.3	1.9	.0000	14.3	.0000
3	13.9	1.7	.0000	13.9	.0000
4	13.6	2.0	.0000	13.6	.0000
5	13.4	1.9	.2440+00	13.4	.2440-01
6	13.2	2.3	.6227-09	13.2	.6227-10
7	13.2	2.1	.2567+00	13.2	.2567-01
8	15.5	2.6	.4546+04	28.5	.4820+03
9	18.2	2.7	.8865+04	43.2	.9270+03
10	20.5	2.7	.1203+05	53.9	.1222+04
11	22.5	2.9	.1398+05	60.4	.1374+04
12	22.8	3.6	.1464+05	60.7	.1436+04
13	22.4	4.5	.1398+05	56.9	.1409+04
14	21.9	4.6	.1203+05	51.7	.1229+04
15	21.2	4.8	.8865+04	43.2	.9270+03
16	20.5	4.9	.4546+04	31.7	.4813+03
17	18.9	4.1	.2567+00	18.9	.2718-01
18	18.0	3.2	.6227-09	18.0	.6592-10
19	17.8	2.6	.2440+00	17.8	.2584-01
20	17.8	2.7	.0000	17.8	.0000
21	17.2	1.9	.0000	17.2	.0000
22	17.2	2.1	.0000	17.2	.0000
23	16.7	2.1	.0000	16.7	.0000
24	16.2	2.3	.0000	16.2	.0000

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TOTAL POWER FOR A TYPICAL DAY IN NOV = 9.49 KWH

SYSTEM ANALYSIS FOR THE MONTH OF DEC

****

HOUR	AMBIENT AIR TEMP (DEG C)	WIND SPEED (M/S)	TOTAL INSOLATION (WATTS)	CELL TEMPERATURE (DEG C)	POWER OUTPUT (WATTS)
1	14.4	1.5	.0000	14.4	.0000
2	13.9	1.7	.0000	13.9	.0000
3	13.8	1.8	.0000	13.8	.0000
4	13.5	1.6	.0000	13.5	.0000
5	13.4	1.6	.2440+00	13.4	.2440-01
6	13.2	2.0	.6227-09	13.2	.6227-10
7	13.1	2.0	.2567+00	13.1	.2567-01
8	13.8	2.1	.3789+04	25.0	.4023+03
9	15.0	2.5	.8159+04	38.5	.8611+03
10	16.4	2.4	.1128+05	48.6	.1163+04
11	17.8	2.6	.1320+05	54.5	.1339+04
12	18.4	3.5	.1385+05	54.6	.1404+04
13	18.6	3.5	.1320+05	53.2	.1344+04
14	18.4	4.1	.1128+05	47.2	.1167+04
15	18.0	3.8	.8159+04	39.5	.8608+03
16	17.3	3.8	.3789+04	27.1	.4019+03
17	16.4	3.5	.2567+00	16.4	.2723-01
18	15.8	2.6	.6227-09	15.8	.6606-10
19	15.7	2.0	.2440+00	15.7	.2589-01
20	15.7	2.3	.0000	15.7	.0000
21	15.4	2.0	.0000	15.4	.0000
22	15.2	2.1	.0000	15.2	.0000
23	15.0	2.1	.0000	15.0	.0000
24	14.7	1.8	.0000	14.7	.0000

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TOTAL POWER FOR A TYPICAL DAY IN DEC = 8.94 KWH

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TOTAL POWER FOR SUM OF 12 TYPICAL DAYS IN THIS SIMULATION= 135.99 KWH

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 TOTAL POWER FOR A TYPICAL DAY IN JAN   =    9.17 KWH
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 TOTAL POWER FOR A TYPICAL DAY IN FEB   =    9.73 KWH
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 TOTAL POWER FOR A TYPICAL DAY IN MARCH=   11.32 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN APRIL=   11.88 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN MAY   =   12.65 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN JUNE =   12.99 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN JULY =   13.28 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN AUG   =   12.94 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN SEPT =   12.32 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN OCT   =   11.28 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN NOV   =    9.49 KWH
**********************************************************************
 TOTAL POWER FOR A TYPICAL DAY IN DEC   =    8.94 KWH
**********************************************************************
 TOTAL POWER FOR SUM OF 12 TYPICAL DAYS IN THIS SIMULATION=   135.99 KWH
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