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COMPUTATION OF PHOTOVOLTAIC PARAMETERS UNDER LUNAR TEMPERATURE VARIATION[1]

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Photovoltaic (PV) arrays with regenerative-fuel-cell energy storage is a prime, power-system, candidate for lunar photo-power. The PV module performance decreases at higher temperatures. Surface temperature variations of the moon are extreme, the maximum (noon) temperature being 384 K. The present work utilizes detailed computations of photovoltaic parameters with computer program developed earlier for the computation of optimum bandgaps of single- and two-junction solar cells at different temperatures; and calculates the power output of single- and two-junction solar modules under different configurations which constitutes an improvement over the assumption of a linear variation of efficiency with temperature. The program also calculates the necessary PV-array size to satisfy stipulated levels of day- and night-time power consumption.

INTRODUCTION

Photovoltaic (PV) arrays with regenerative-fuel-cell energy storage is a prime, power-system, candidate in a lunar base development plan that does not require high power levels initially (ref. 1). The advantages of PV arrays are modularity, lightweight, and a long record of reliable power production in space with a reduced technical risk. They have the disadvantage of necessitating a storage system for the long (~354.36 hours) lunar night and possibly for the early morning and late afternoon when the incident energy on an horizontal array is small. Lunar surface temperatures are extreme in comparison to the surface temperatures on earth because of the slow synodic rotation period, lack of atmosphere, and low conductivity of lunar soil (ref. 1,2). The PV module performance decreases at higher temperatures. The earlier calculations of lunar photopower arrays did not take into account the continuous variation of cell parameters during the lunar day (ref. 1). Moreover the temperature dependence of the characteristics of solar cells cannot be described adequately by a linear approximation (ref. 5). Osterwald et al (ref. 3) have given a linear fit for the variation of the measured basic parameters for Si, GaAs, InP, and $CuInSe_2$ solar cells with the temperature and calculated the temperature coefficients over a limited temperature range of 15-60 °C. In most cases, the measured parameters showed a non-linear behavior at temperatures above 50 ° C (ref. 3). When studying the efficiency of a solar cell on the moon, the temperature variation on the lunar surface and its effects on the solar cell conversion efficiency must be taken into consideration (ref. 4). The short circuit current mainly depends on the intensity of light, and therefore will have little temperature dependence except for minor corrections due to bandgap variation and diffusion-length changes. The main temperature effect is due to the change in open-circuit voltage. The fill factor FF and the photovoltaic conversion efficiency vary with temperature in a complex manner. The present paper carries out detailed computations of photovoltaic parameters; and calculates the power output and PV-array size of single- and two-junction solar modules necessary to satisfy stipulated levels of day- and night-time power consumption, under different configurations.

LUNAR TEMPERATURE CONDITIONS

Surface temperature variations of the moon are extreme, the maximum (noon) temperature at the lunar

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equator being ~384 K and the temperature at sunrise being ~220 K (ref. 2,6,7). The surface-temperature variation of the moon depends on the exact position of the earth-moon system from the sun (ref. 6). The temperature equation can be written in a simple form as follows:

$$T = T_d + T_0 \cos^{1/6}(\theta) \quad (1)$$

where $T_0 = T_n - T_d$, T_n is the temperature at noon and T_d the temperature at sunrise of the latitude under consideration. θ, is the angular position of the sun with respect to zenith.

The variation of temperature at a given latitude can be determined using the equation (1) described above, along with the information of the maximum and minimum temperature at that particular latitude.

THEORY

Single Junction Solar Cell

The bandgap of a material at any given temperature is calculated using the following equation (ref. 5):

$$E_g(T) = E_{g0} - \alpha T^2 / (T + \beta) \quad (2)$$

where E_{g0} is the bandgap of the material in electron volts at 0 K, α and β are empirical constants specific to the material, and T is the absolute temperature in Kelvin. For most materials α is positive, hence the bandgap usually decreases with temperature.

The dark reverse saturation current of a solar cell, $J_0(T)$ at any given temperature is calculated using the following equation (ref. 5):

$$J_0(T) = K' T^3 \exp[-E_g(T) / kT] \quad (3)$$

where k is the Boltzmann's constant, K' is an empirical factor dependent on the quality of the material used for the solar cell. K' has a lower value for highly crystalline materials and a higher value for polycrystalline or amorphous materials. For the calculations which were not material specific, a value of 0.005 was chosen. Calculations that were specific to a particular material have used values that are appropriate to that material.

The short-circuit current density, $J_{sc}(T)$ is calculated using the following equation (ref. 8):

$$J_{sc}(T) = q N_{ph}(T) \quad (4)$$

where q is the electronic charge, $N_{ph}(T)$ is the effective photon flux incident on the solar cell that is used in the generation of current at temperature T. N_{ph} at temperature T was calculated as follows. The wavelength, $\lambda(T)$ equivalent to the bandgap $E_g(T)$ at a given temperature T is calculated by using $\lambda(T) = hc / E_g(T)$, where h is the Planck's constant, c is the speed of light in free space. The theoretical photovoltaic parameters viz. short circuit current, J_{sc}, open circuit voltage, V_{oc}, fill factor, FF, efficiency, η, and their normalized temperature coefficients in the absence of atmosphere (air mass zero AM 0) were calculated using AM0 spectral data (ref. 9) and standard equations and procedures (ref. 5).

The open-circuit voltage, V_{oc} is calculated using the following equation (ref. 5):

$$V_{oc}(T) = (kT / q)\ Ln[J_{sc}(T) / J_0(T) + 1] \quad (5)$$

Because of the exponential increase in the dark-reverse-saturation current $J_0(T)$ with temperature, $V_{oc}(T)$ decreases significantly with temperature.

The optimum voltage, V_m is calculated using the following equation (ref. 5):

$$\exp[qV_m(T)/kT] [1 + qV_m(T)/kT] = J_{sc}(T) / J_0(T) + 1 \tag{6}$$

The fill factor, FF is calculated using the following equation (ref. 5):

$$FF(T) = \{ V_m(T)/V_{oc}(T) \} \{1 - [(\exp(qV_m(T) / kT) - 1) / (\exp(qV_{oc}(T) / kT) - 1)] \} \tag{7}$$

The efficiency, $\eta(T)$ is calculated using the following equation (ref. 5):

$$\eta(T) = [V_{oc}(T) J_{sc}(T) FF(T)] / P_{in} \tag{8}$$

where P_{in} is the solar constant = 1.353 kW m^{-2} (AM0 value) (ref. 9).

Two-Junction Cell

Various combinations of materials can be employed in the fabrication of a two-junction cell from two different materials having different bandgaps. The bandgap of the top cell E_{g1} in a two-junction cell must be larger than the bandgap of the bottom cell E_{g2} (ref. 8). Incident light with energy larger than the bandgap of the top cell will generate a current and the corresponding voltage. The bottom cell generates electricity using photons having wavelengths within the window of energies falling between the bandgaps of the top- and the bottom-cells. The efficiencies for top cell, the bottom cell, and the two-junction cell are calculated as a function of three parameters: the temperature, and the bandgap of the top- and of the bottom-material. This calculation is useful in finding the optimum combination of materials (or bandgaps) that would give the best efficiency of the cell.

The values for the top cell (J_{01}, J_{sc1}, V_{oc1}, V_{m1}) and the corresponding values for the bottom cell (J_{02}, J_{sc2}, V_{oc2}, V_{m2}) are calculated. The equations and the procedures followed in the calculation of J_{sc1}, J_{01}, J_{02}, V_{oc1} and V_{oc2} are the same as those outlined above. The current, J_m corresponding to the optimum voltage for both the top and bottom cell is calculated using the following equations:

$$J_{m1}(T) = J_{01}(T) [\exp(qV_{m1}(T) / (kT)) - 1] - J_{sc1}(T) \tag{9}$$

$$J_{m2}(T) = J_{02}(T) [\exp(qV_{m2}(T) / (kT)) - 1] - J_{sc2}(T) \tag{10}$$

In making the calculation for the two-junction cell, it may be noted that the current passing through both top and bottom cells must be of the same magnitude (ref. 8). This magnitude is determined in the following way. The smaller of the values of J_{m1} and J_{m2} is assigned to J_{min} and the larger is assigned to J_{max}. The value of J_{min} is successively incremented till the value of J_{max} is reached. In each case the voltage corresponding to the current is evaluated for both the top and bottom cell so as to obtain the maximum value for the sum of the individual voltages V_{opt1} and V_{opt2} generated by the top and bottom cells respectively corresponding to the current J_{opt} where J_{opt} is the optimum value of current passing through both the cells. Care must be taken to assign $V_{opt} = 0$ whenever the corresponding J_{sc} is exceeded. The optimum power, P_{opt} is obtained by the following equation:

$$P_{opt} = J_{opt} (V_{opt1} + V_{opt2}) \tag{11}$$

Various Solar Array Configurations and Equations

Of the various designs for array configurations proposed in the literature, the most common configurations are flat-plate, 60-degree-triangular, constant-tracking, and incremental-tracking. The flat-plate and the 60-degree-triangular configurations are the simplest ones requiring no moving parts. Hence maintenance is negligible and the configurations are very cost effective. The tracking array would be gimballed and synchronized with the relative movement of the sun ~1.97 hrs/degree (ref. 1). At sunset the panels could be reset to sunrise. The incremental tracking array would be either manually or automatically adjusted in a certain incremental angular steps. If the angular step is 30 degree, then the automatic adjustment would be done 6 times per lunar day. Thus the incident angle of the sunlight would continuously vary over ±15°. Both the continuous tracking and incremental tracking require mounting and tracking mechanisms, increasing the cost. The array configurations are mounted on structures and hence positioned a few feet above the surface of the Moon. The efficiency of PV arrays will be affected by the lunar dust suspended and transported by the movement of astronauts, rovers, and the rocket launch and landing activities (ref. 10). Lunar base activities like rocket launching can be especially troublesome if the dust settles on moving parts. The particles have 5 times larger parabolic trajectories because of the lower gravity. Small dust particles, charged by the solar wind can adhere to the panels by electrostatic attraction (ref. 10). The adhesion can be reduced by grounding the electrostatic charge with a transparent conductive coating.

The temperature of the solar cell will be different, for different configurations and it will be different from that on the surface of the moon. The solar-array temperature is calculated based on the amount of incident solar energy and irradiation from the lunar surface, and the energy lost by photovoltaic conversion and irradiation neglecting the difference between the absorptivity and emissivity, using the following equation (ref. 11):

$$A_p \sigma T^4_{sun} 6.85 \times 10^{-5} (1-\eta) \cos(\theta)/\pi + A_p \sigma T^4_{moon} 2\pi/4\pi = 2 A_p \sigma T^4_{cell} \quad (12)$$

where $\sigma = 2\pi^5 k^4 / 15 h^3 c^2$, A_p is the area of the solar cell inclined to solar rays at an angle θ, and T_{sun} is the temperature of the sun. The temperature of the solar array in the horizontal configuration is calculated by using the following equation (ref. 11):

$$T_{cellhor} = \{0.5 [6.85 \times 10^{-5} T^4_{sun} (1 - \eta) \cos(\theta) / \pi + T^4_{moon} /2] \}^{1/4} \quad (13)$$

To begin with the efficiency η is assumed to be equal to 0.3. The temperature obtained above will be an approximate value (i.e., T_{cx} = Tcellhor(η = 0.3)). Using this approximate value, the efficiency of the solar cell is calculated. This calculated value of efficiency is substituted for the value of 'η' in the equation for $T_{cellhor}$, and the refined value for the temperature (T_{ct}) of the cell is determined (i.e., $T_{ct} = T_{cellhor}(\eta = \eta(T_{cx}))$). The temperature of the solar array in the tracking configuration is calculated by using the following equation:

$$T_{celltrk} = \{0.5 [6.85 \times 10^{-5} T^4_{sun} (1 - \eta)/\pi + T^4_{moon} /2] \}^{1/4} \quad (14)$$

The refined value of the cell temperature is obtained by the same procedure mentioned under horizontal configuration. The temperature of the solar array in the triangular configuration is calculated by using following equation:

$$T_{celltrg} = \{0.5 [6.85 \times 10^{-5} T^4_{sun} (1 - \eta) (Side1 + Side2)/\pi + T^4_{moon} /2] \}^{1/4} \quad (15)$$

where Side1 = $\cos(\phi_1)/2$, $\phi_1 = \theta + \pi/3$; and Side2 = $\cos(\phi_2)/2$, $\phi_2 = \theta - \pi/3$.

Only one side of the solar cell array arranged in a triangular configuration produces electrical energy during the first and the last 60° relative movement of the sun. Both the sides of the solar cell array produce electrical energy during the middle 60° movement of the sun. This is taken into consideration by the factors Side1 and Side2. The refined value of the cell temperature is obtained using the procedure mentioned above.

The electrical energy obtained from the solar array in horizontal configuration, during an interval of 1.968 hours, corresponding to 0.5 degree increase in θ, is calculated using the following equation:

$$dEn_{hor} = (0.5 P_{in} H_{pd} \eta(T)) \cos(\theta) \quad (16)$$

where H_{pd} (= 1.968 hours/degree) is the rate of relative solar movement at the lunar equator. This incremental energy is summed through the whole lunar day comprising of approximately 14 earth days (~ 354.36 hours), to obtain the total energy, E_{hor}.

The electrical energy obtained from the solar array in tracking configuration, during an interval of 1.968 hours is calculated using the following equation:

$$dEn_{trk} = 0.5\, P_{in}\, H_{pd}\, \eta(T) \quad (17)$$

This incremental energy is summed through one whole lunar day, to obtain the total energy, E_{trk}. The electrical energy obtained from the solar array in triangular configuration, during an interval of 1.968 hours is calculated using the following equation:

$$dEn_{trg} = (0.5\, P_{in}\, H_{pd}\, \eta(T))\,(\mathrm{Side1} + \mathrm{Side2}) \quad (18)$$

This incremental energy is summed through one whole lunar day, to obtain the total energy, E_{trg}.

Computer Program

Computer programs were developed for the calculation of parameters required for the design of a lunar photopower system. The development started with a program for single-junction, solar-cell design. Using that another program was written for the two-junction solar cell. The lunar photopower program combines the calculations at different temperatures for both the single-junction and the two-junction cell performance with the calculation of temperatures of different solar array configurations. The programs were also customized for system design, by adding queries for the user and default parameters. Default values for the bandgap of the material used in the solar cell were chosen based on the highest efficiency obtained in the calculations and analysis that were carried out using the computer program. The following default values were used for the other parameters: day-time power consumption = 100 kW, nignt-time power consumtion = 50 kW, regenerative-fuel-storage-cell efficiency = 60%.

RESULTS

The flat plate, tracking array, and 60° triangular configurations which have been proposed for lunar photopower were utilized for the analysis (ref. 1). The single-junction and two-junction programs developed above were utilized to compute the solar-cell-performance parameters during a lunar day for single-junction arrays of specific materials and two-junction arrays having the optimum bandgaps mounted at lunar equator in the three configurations.

The solar cell parameters such as α and β, etc. were calculated using specific material parameters for single-junction solar cells of known materials. The empirical value of K' were calculated on the basis of the best reported AM0 solar-cell parameters for single-crystal GaAs, InP, and Si solar cells; and AM1.5 parameters for polycrystalline-thin-film $CuInSe_2$ solar cells. The chosen K' values utilized for calculations of dark-reverse-saturation current J_0 were 0.005 for GaAs and InP single-crystal solar cells, 0.05 for Si single-crystal cells; and 0.5 for $CuInSe_2$ thin-film solar cells. These were approximately equal to those obtained from the reported parameters. The K' value of 0.5 was also utilized for polycrystalline-thin-film CdTe solar cells even though the calculated value was significantly higher for the best CdTe cell. It is expected that with improvements in the quality of CdTe thin-film solar cells, cell parameters and hence K' values will approach the chosen values.

As expected, the small decrease in the bandgap with temperature $E_g(T)$ was found to result in a gradual increase in the short-circuit current, J_{sc} values. The open circuit voltage, V_{oc} dropped considerably with an increase in temperature mainly due to a significantly increased dark-reverse-saturation current. The behavior of fill factor and efficiency reflected these changes. The drop in the conversion efficiencies of the lower bandgap $CuInSe_2$ and Si cells was much larger than that in higher bandgap InP, GaAs, and CdTe cells.

Figure 1 a and b show the variation of temperatures, short circuit current density J_{sc}, open circuit voltage V_{oc}, fill factor, FF, and efficiency, Eff from lunar sunrise to noon for CdTe solar arrays in the horizontal configuration and $CuInSe_2$ solar arrays in the triangular configuration respectively. Table I shows the sizes of solar array of Si, GaAs, InP, $CuInSe_2$, and CdTe single-junction solar cells mounted in the three configurations required for providing 100 kW of power during 354.36 hour lunar day and 50 kW of power during the 354.36 hour lunar night using 60%-efficient regenerative-fuel-cell storage.

In the calculations of two-junction solar cell parameters, the default values chosen for α and β were 4.01×10^{-4} and 0 respectively and E_{g0} was varied continuously. The chosen value for the empirical parameter K' was 0.05 for these calculations. Figure 2 a and b show the variation of temperatures and photovoltaic parameters for a two-junction array having optimum bandgaps E_{g1} = 1.81 eV, E_{g2} = 1.18 eV and E_{g1} = 1.83 eV, E_{g2} = 1.2 eV for the maximum power output in the horizontal and tracking configurations respectively. The behavior was found to be similar for each of the configurations for the different types of cells. Table I also provides the sizes of solar array of two-junction solar cells having the optimum bandgaps mounted in the three configurations required for providing the above power levels.

Practical efficiencies are expected to be lower than the calculated efficiencies because of the effects of series and parallel resistance losses which have not been considered in this analysis. However, variation of the efficiencies is expected to show a similar trend. The calculated theoretical parameters show a slightly non-linear behavior similar to the calculations of Fan (ref. 5).

TABLE I

Sizes of single-junction-solar cell arrays of Si, GaAs, InP, $CuInSe_2$, and CdTe, and two-junction solar cell arrays having optimum bandgaps mounted in the horizontal, tracking, and triangular configurations, required for providing 100 kW of power during 354.36 hour lunar day and 50 kW of power during the 354.36 hour lunar night using 60%-efficient regenerative-fuel-cell storage.

Material		Area of Solar Cell Arrays in square meters		
		Horizontal	Tracking	Triangular
Si		1084.8	725.7	1269.8
GaAs		885.7	579.1	1076.3
InP		901.4	592.2	1086.2
$CuInSe_2$		1438.0	988.4	1616.0
CdTe		1034.5	682.4	1239.0
Two-Junction Cells	E_{g1} = 1.83 eV, E_{g2} = 1.20 eV	676.6	443.3	855.1
	E_{g1} = 1.81 eV, E_{g2} = 1.18 eV	676.2	443.5	853.0
	E_{g1} = 1.77 eV, E_{g2} = 1.14 eV	677.1	444.8	851.2

The lunar surface temperatures increase considerably immediately after the sunrise. The calculated photovoltaic module temperatures increased continuously for horizontal arrays (Figures 1a and 2a). The tracking array temperatures were found to rise sharply at sunrise following a gradual increase to the same maximum value as in the horizontal case (Figure 2 b). The increase of temperatures for triangular array was intermediate following a similar pattern as the tracking array (Figure 1b). The optimum values of bandgaps E_{g1} and E_{g2} for obtaining the maximum power output during the lunar day were found to be higher for the tracking and horizontal configurations than for the triangular configuration. This has been attributed to the higher overall operating temperatures in the tracking and horizontal configurations. The calculations can be refined further by choosing actual material parameters of semiconductors having bandgap values in the vicinity of the optimum values.

Even though the tracking array would be the most effective, it requires a complex structure and tracking mechanism. Horizontal array is the simplest configuration. In this geometry, the power output would increase slowly reaching a maximum at local noon and decreasing slowly afterwards. The energy output from the triangular array would be the lowest. However, it has the advantage of a constant power supply. The average effectivities normalized with respect to the tracking arrays were found to be in the ranges of 0.654-0.687 and 0.518-0.612 for the horizontal and triangular arrays respectively, compared to the respective estimated values of 0.635 and 0.46 (ref. 1).

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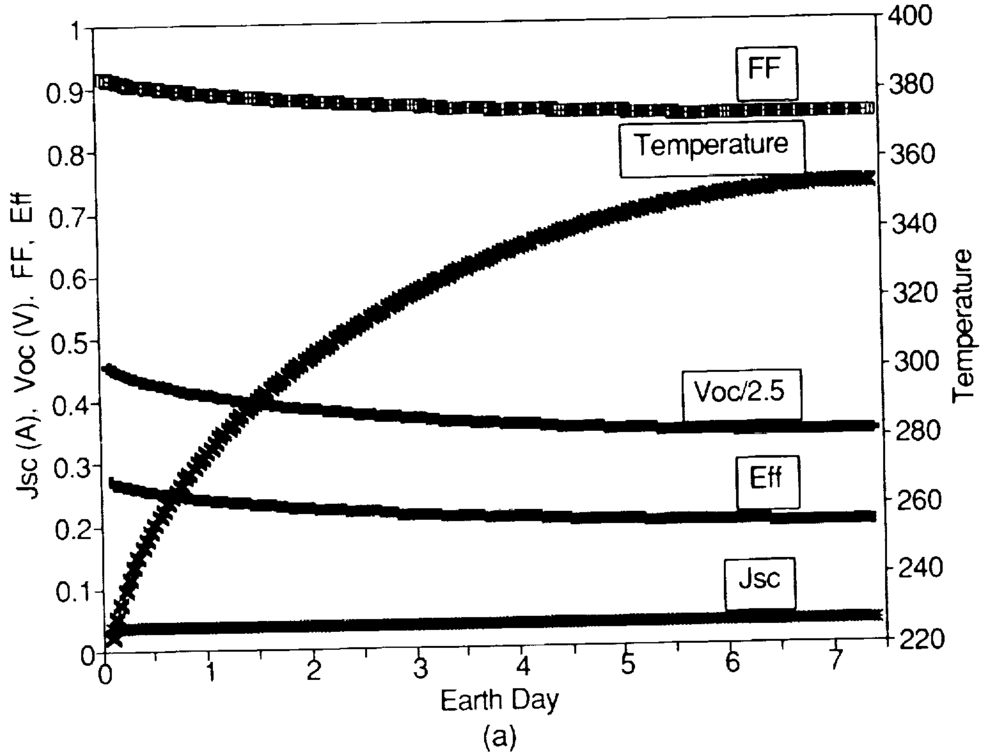

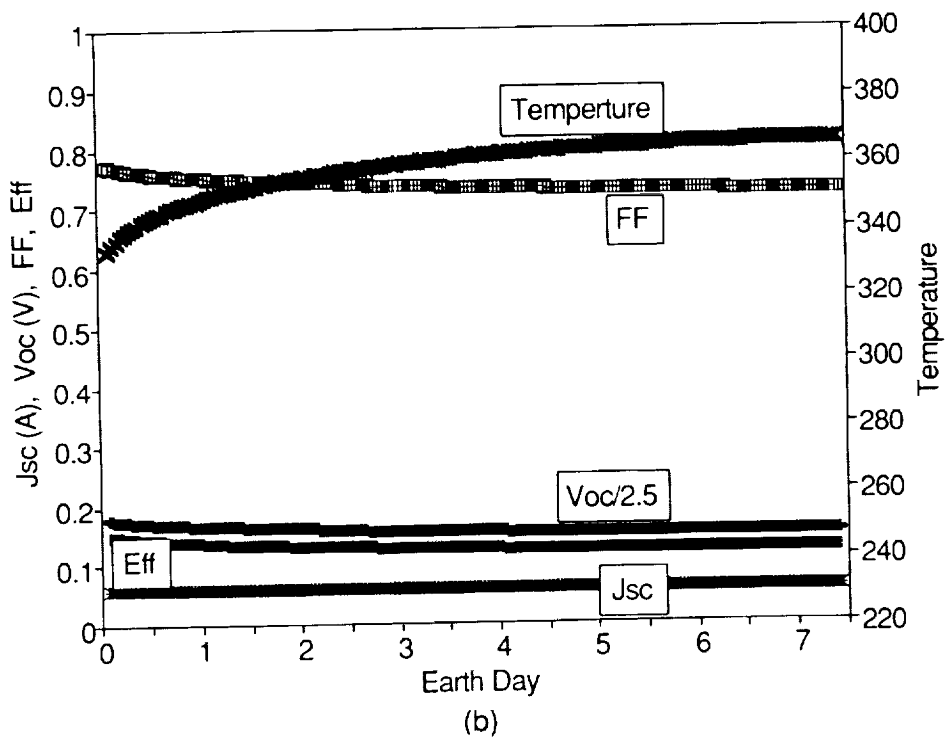

Fig. 1. Variation of the module temperature and the photovoltaic parameters short curcuit current, J_{sc}, open circuit voltage, V_{oc}, fill factor, FF, and efficiency, η, from the lunar sunrise to noon of single-junction solar-cell arrays of: a) CdTe mounted in the horizontal flat plate configuration, and b) $CuInSe_2$ mounted in 60° triangular configuration.

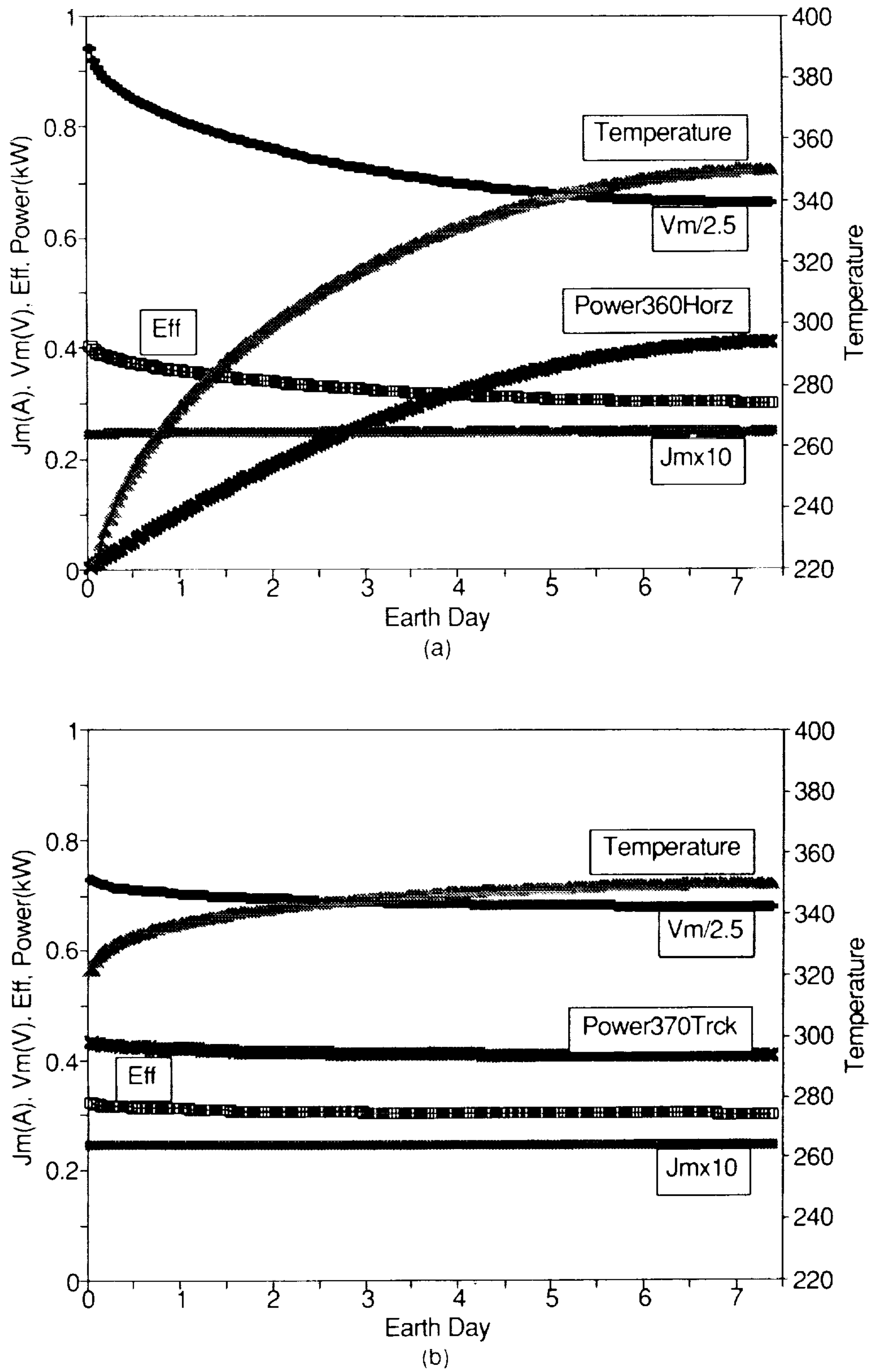

Fig. 2. Variation of the module temperature and the photovoltaic parameters optimum current, J_m, optimum voltage, V_m, efficiency, η, and power, P, from the lunar sunrise to noon, for two-junction solar-cell arrays having the optimum bandgaps mounted in: a) horizontal flat plate configuration with E_{g1} = 1.81 eV, E_{g2} = 1.18 eV, and b) tracking configuration with E_{g1} = 1.83 eV, E_{g2} = 1.20 eV.