INTRODUCTION

The development of an array electrical performance model is generally based on a model describing the output of the photovoltaic module being used. The latter will consist of an I-V curve defined for a given set of irradiance and environmental conditions and a set of irradiance and cell-temperature translation coefficients. After the modules are assembled into the array, loss mechanisms not accounted for when modeling the output of a module must be introduced into the array output model.

These loss mechanisms can be divided into two categories. The first category includes those loss mechanisms leading to a reduction in the average array electrical performance as defined by the I-V curve. These loss mechanisms manifest themselves as changes in the array I-V curve from that of the module, either as a simple translation in the two-dimensional I-V space, or a change in the curve shape. For example, a loss in irradiance transmission results in an I-V curve translation along the current axis. The net result is reduced power output when measured at the maximum-power point.

The second category of losses is associated with non-optimal extraction of power from the array. These mechanisms do not alter the array I-V curve, but result from an operating point different than the array maximum-power point.

* This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy, through an agreement with the National Aeronautics and Space Administration.

** Member of the Technical Staff, Reliability and Engineering Sciences Area, Flat-Plate Solar Array Project, System Integration Section.
ARRAY LOSS MECHANISMS

In the first category of loss mechanisms cited above are losses due to electrical mismatch, transmission losses due to soiling and steep-angle of reflectance, and electrical losses from field wiring resistance and the voltage drop across blocking diodes. Mismatch can arise either from module-to-module differences or from partial shadowing of the array.

In the second category are those losses resulting from operating-point considerations on the array I-V curve. These considerations include the issue of non-optimal load impedance and the constraining of the array operating point by the load to given ranges of current and voltage. The latter constraints may lead to operation off the I-V curve maximum-power point or to periods of time when the available array power is not used.

Module Mismatch

If the current and voltage of the modules in an array are not matched the array output will be limited by the low output modules. Current mismatch arises when low-current modules are included in a series string or when a portion of the array is shadowed. Voltage mismatch arises when cells are shorted or a bypass diode is turned on due to current limiting. Use of bypass diodes limits the effect of severe current mismatch. In general, increasing the number of cross ties in a configuration of series-parallel modules also decreases the effect of current mismatch, but may increase the effect of voltage mismatch. Similarly, increasing the number of parallel strings has the same effect.

Modeling mismatch power losses is a complex exercise dependent on a number of factors including the bypass diode frequency. Several techniques have been tried including a Monte Carlo approach using an analytical expression for the cell and module I-V curves (1). Bucciarelli (2) used a statistical technique based on variations in max-power current and max-power voltage from cell to cell. Mismatch due to shadowing has the additional complexity of time variance, as well as non-uniform, and difficult to determine, shadow densities.

Shadowing

Array shadowing, one of the causes of mismatch, is caused either by other arrays or by foreign objects. The modeling of the array shadowing from the direct component of solar irradiance is straightforward and is easily derived using solid geometry; for example, see the model developed by Budin and Budin (3). The degree of shadowing from other arrays is a function of array spacing, tilt angle, azimuth angle, and tracking mode.

To minimize the effect of array shadowing on the output of the shadowed array one can optimize the layout of the cell strings. It is desirable
to orient cell strings so that all of one or more series cell strings is shadowed as opposed to a part of many parallel strings. In the latter case the mismatch caused by the shadowing will cause the array power loss to be greater than that attributable to the area shadowed. In the former case the array power loss will be basically limited to that available from the shadowed area.

Shadowing of the diffuse component of solar irradiance is more subtle and easy to overlook; such shadows are not easily visible to the naked eye. Unlike modeling the direct-component shadows, the modeling of diffuse-component shadows must account for the anisotropic nature of diffuse lighting and make use of an appropriate sky model for the sky conditions being considered. Klucher (4) and Perez et al (5) discuss sky models in their studies of irradiance on tilted surfaces. The effect of the diffuse shadowing is similar to the mismatch caused by the shadowing of the direct component, except to a lesser degree. Figure 1 is a schematic representation of the concept of diffuse shadowing.

![Figure 1. Schematic representation of array shadowing from the diffuse radiation component.](image)

**Soiling**

Soiling reduces array output by reducing the transmission of irradiance to the cells and therefore can be modeled as an array I-V curve translation for reduced irradiance. Soiling tests on a number of samples of front cover materials have been performed by Hoffman and Maag (6) at several sites representative of different environments. Figure 2 presents some results of these tests. These tests indicate that the degree of soiling is strongly a function of module front surface material composition, the site soiling level, and the frequency of natural cleaning processes such as rain, unless regular cleaning is provided. Glass tends to retain dirt less than polymeric materials. Hoffman concluded that the rate of soil deposition is material-independent, but the effectiveness of removal by rain is material-dependent. For heavily soiled materials rain can cause improvements in transmission of 10 to 15% in hard cover materials such as glass. Long-term soiling loss can be approximated as a constant loss.
based on the above parameters. For urban sites the average losses in relative transmittance over a one year period were 7 to 8% for glass and higher for soft materials such as silicone rubbers. The average for a non-urban site for glass is about 3%. Figure 2 clearly shows the short-term variations in the amount of soiling due to the natural cleaning processes.

![Figure 2. Array loss of short-circuit current due to soiling as a function of front surface material and site.](image)

Additional studies reported upon by Maxwell et al (7) have been performed at JPL on the effects of field environments including soiling on modules. Studies were also performed by Cuddihy of JPL and Willis of Springborn Laboratories to determine the effectiveness of antisoiling surface coatings (8). After 28 months of outdoor exposure the antisoiling treatment resulted in performance gains in transmittance from about 1% for glass to 4% for Acrylar.

**Irradiance Losses at Steep Angles of Incidence**

Increased reflectance of module front surfaces at steep angles of incidence also causes transmission losses. These losses become significant at incidence angles greater than 60 degrees and are described by the classical Fresnel reflection formulas as shown below. Soiled modules suffer transmission losses at steep angles of incidence greater than those at normal incidence and above that of a clean module at the same angle. Measurements were made at JPL by Wilson and Ross (9) on transmission through glass surfaces at steep angles of incidence. A module with internal enhancement due to a reflective white surface surrounding the cells, was also characterized.
From Fresnel's law the optical reflection loss \( \rho(\theta) \), is given by:

\[
\rho(\theta) = \frac{I_R}{I_0} = \frac{1}{2} \left[ \frac{\tan^2(\theta - \theta')}{\tan^2(\theta - \theta')} + \frac{\sin^2(\theta - \theta')}{\sin^2(\theta - \theta')} \right]
\]

where \( \theta' = \arcsin \left( \frac{\sin \theta}{n} \right) \)

\( n \) = index of refraction of optical surface

Define

\[
FR = \frac{1 - \rho(\theta)}{1 - \rho(0)}
\]

where \( \rho(0) = \left( \frac{n - 1}{n + 1} \right)^2 \)

\( FR \) gives the fraction of transmitted irradiance at angle \( \theta \) compared to that transmitted at normal incidence.

A model was also developed by Wilson and Ross to determine angle-of-incidence dependence of soiling loss and is shown below.

Given fraction soiling loss at normal incidence = \( f \)

\[
f = \frac{l_0 - l_{so}}{l_0}
\]

where \( l_0 \) = current when \( \theta = 0^\circ \) for clean surface

\( l_{so} \) = current when \( \theta = 0^\circ \) for soiled surface

Define

\[
FS = \frac{1 - f \left( \frac{1}{2 \cos \theta} + \frac{1}{2} \right)}{1 - f}
\]

\( FS \) gives the light-transmission degradation that accounts for the increased soiling losses at steep angles of incidence. Figure 3 gives values of the correction factors, \( FR \) and \( FS \), as a function of angle of incidence. Figure 4 provides the results of applying the correction factors as well as the cosine correction.
In summary, the JPL measurements indicated the following:

- For modules with clean front surfaces the classical Fresnel reflection formulas accurately predict the transmission losses at steep angles of incidence.

- For modules with soiled front surfaces, an additional correction factor for soiling is required; the derived factor is good to about 70 deg.

![Figure 3](image.png)

Figure 3. Value of angle-of-incidence correction factors \((F_R, F_S)\), versus angle.

![Figure 4](image.png)

Figure 4. Measured angle-of-incidence-transmission dependence versus value of transmission with correction factors \((F_R, F_S)\)

To put the above results in perspective, one should note that, on the average, 2% of the annual array energy is produced at angles greater than 70 deg. and 8% at angles greater than 60 deg. This is for an array with a north-south azimuth and a tilt angle equal to the local latitude.
Array Circuit Losses

There are two primary loss mechanisms involved in array circuitry. One is the series resistance (I²R) losses resulting from the resistivity of the array wiring. This can be modeled as an additional series resistance term in the array I-V curve. The other loss mechanism is the drop in array voltage due to the blocking diodes used in the array source circuits to prevent reverse current flow. This loss can be modeled as a translation of the I-V curve along the voltage axis.

Stolte et al at the Bectel Group, Inc. (10) performed an extensive study on the tradeoffs involved in designing the array wiring system. They found that first costs and energy losses tend to decrease with increasing source-circuit dc voltage level and with increasing subfield peak power level. However, the rate of decrease due to voltage level becomes relatively small for voltage levels above 1000 to 2000 Vdc. The cost and losses are also a function of the array tracking mode, array spacing, and array efficiency.

The key tradeoff is between wire size (installed cost) and the value of the energy losses (lost revenue) at each voltage level. Wire size was considered in terms of the physical size of the conductor in relation to the current loading. Another tradeoff considered was the use of copper versus aluminum conductors. No difference between the two was found to the accuracy of the analysis.

Stolte found the optimal energy losses from the dc wiring to be about 1%, with the losses from the ac wiring being less than 0.5%. Peak dc power losses were somewhat higher, but still under 2%. Another result noted was the fact that for a specific yearly irradiance profile, the ratio between peak field power loss and yearly energy loss, is essentially constant.

I-V CURVE OPERATING-POINT CONSIDERATIONS

Next, loss mechanisms that do not change the array I-V curve, but are associated with operation off the array's maximum-power point, are considered. Here the concern is not with loss in the array electrical performance, but with lost power as delivered to the load.

Non-Optimal Load Impedence

The use of an array with a given load will result in additional power losses if the load impedance leads to operation away from the array's maximum-power point. For the array to operate near its maximum-power point the load impedance must be properly matched to the array I-V characteristic using an impedance matching device such as an AC power conditioner with a maximum-power tracker. The use of maximum-power tracking allows load-impedence matching under conditions of changing array temperature and irradiance level.

Studies performed by JPL, Branz et al and Rasmussen at the MIT Lincoln Laboratory (11, 12, 13, 14, 15) have considered the problem of
determining the appropriate operating point on an array I-V curve. These studies have shown that, next to a maximum-power tracker, a constant voltage operating point carefully selected to match the average site temperature is the most efficient array operating mode. The selection of the voltage for constant voltage operation is based on the average module operating temperature. In this mode the operating point may have to be adjusted periodically to account for those changes in array output that occur over a period of time due to both seasonal weather changes and array degradation.

When maximum-power tracking or constant voltage operation is not used, the array may operate off its maximum-power point much of the time. If the load is a fixed resistive load, and the array operates near its maximum-power point at high irradiance levels, it will operate far off its maximum-power point as the irradiance decreases. If the array operates near its max-power point at low irradiance levels, it will be far off at high irradiance levels. Therefore, operation of a fixed resistive load with an array results in a poor load impedance match. Other loads could result in even a worse match. To ensure optimal operation either maximum-power tracking or constant voltage operation should be used.

Array Operating Windows

Another mechanism causing array power loss is the existence of operating windows. This subject was also considered in the JPL and MIT studies (11, 12, 13, 14, 15). The load may impose minimum and maximum array current-voltage operating points and minimum (and maximum) start-up points. There will probably be a minimum start-up voltage for morning load turn-on that will prevent extraction of power from the array until the irradiance reaches a given level. Also, the existence of a maximum start-up voltage could prevent reconnection of the load if load shut-down has occurred at full irradiance, especially during periods of low temperature. This could also occur upon reappearance of the sun after an array is temporarily obscured by thick clouds causing load disconnect.

As in the case of minimum voltage start-up requirements a minimum current start-up requirement will limit the extraction of array energy until a minimum irradiance level is reached. Loads with maximum current and/or power limits can cause operation off the array's maximum-power point or cause load shut-down during periods of peak irradiance. If the load utilizes a maximum-power tracker it may simply move the array operating point to a current or power level below the maximum limit. On the other hand, if a maximum-power tracker is not used and the limits are exceeded, the load may simply disconnect from the array. Figure 5 is a schematic representation of the array operating window concept. A number of array I-V curves at different times are shown. Superimposed on the I-V curves, and shown by the dotted lines, are the load operating constraints. Note the maximum power limit represented by the power contour. If the array is operating on the second I-V curve from the top, there is room on the I-V curve for array operation, if a voltage tracker is used. However,
if the array is operating on the uppermost I-V curve, a limited voltage tracking range could result in load disconnect. Also shown in the figure is a maximum operating voltage. This is really an upper limit open-circuit voltage to which the load cannot be subjected, and usually is exceeded only during periods of extremely low temperature.

Figure 5. Schematic representation of array operating windows.

SUMMARY

A number of array loss mechanisms have been identified in this paper. The next point that normally would be addressed is the average array energy lost and/or the upper bound on the energy loss resulting from each of the mechanisms. The average energy loss resulting from soiling, irradiance losses at steep angles of incidence, and circuit losses is given in this paper. The energy losses resulting from the other mechanisms and from non-optimal operation can only be determined when the array parameters, circuit layouts, and the load parameters are defined. The references given in this paper provide results from studies involving the loss mechanisms in addition to the methodology developed to predict the impact on array performance.

REFERENCES


