Derivation of equation used to obtain module temperature for CEC Rebate Rating

Current Standard Approach

Start with a typical steady-state power balance for a module:

$$P_{irradiance} = P_{dissipative} + P_{reflection} + P_{electricity} \tag{1}$$

where

$$P_{irradiance} = Irr \cdot A \tag{2}$$

$$P_{dissipative} = h_c \cdot A \cdot \left(T_{mod} - T_{amb}\right) \tag{3}$$

$$P_{reflection} = R \cdot Irr \cdot A \tag{4}$$

$$P_{electricity} = \eta \cdot Irr \cdot A \tag{5}$$

and Irr is irradiance, A is module area, h_c is thermal conductance, R is the fraction of the incident irradiance that is reflected, η is the gross module operating efficiency, T_{mod} is the average cell temperature in the module, and T_{amb} is the ambient air temperature.

Equation 1 can be simplified now:

$$Irr \cdot A = h_c \cdot A \cdot \left(T_{mod} - T_{amb}\right) + R \cdot Irr \cdot A + \eta \cdot Irr \cdot A \tag{6}$$

$$1 = \frac{h_c \cdot \left(T_{mod} - T_{amb}\right)}{Irr} + R + \eta \tag{7}$$

Leading to the following basic relation:

$$T_{mod} = T_{amb} + \frac{Irr \cdot \left(1 - R - \eta\right)}{h_c} \tag{8}$$

For the remainder of this discussion, the reflected fraction R will be assumed to be 10%.

The Nominal Operating Cell Temperature (NOCT) is obtained from measurements acquired in Nominal Terrestrial Environment (NTE)[1]. These conditions are 800 W/m^2 incident irradiance, 20 °C ambient temperature, 1 m/s average wind speed, with the module open-circuited and oriented normal to solar noon, back either open or closed.

Given these operating conditions, the composite heat transfer coefficient may be determined using Equation 8:

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[1] NTE conditions are currently described in ASTM E1036-96, Annex A1. They were previously described in LSSA Project Task Report 5101-31, "Thermal Performance Testing and Analysis of Photovoltaic Modules in Natural Sunlight", by Jet Propulsion Laboratory, 1977, Appendix A.

$$h_{c,NOCT} = \frac{800 \cdot (0.9 - 0)}{(NOCT - 20)} \qquad (\mathbf{9})$$

For the CEC rebate rating, PVUSA Test Conditions are assumed. These are 1000 W/m[2] incident irradiance (850 W/m[2] for concentrators), 20C ambient temperature, 1 m/s average wind speed, with the module operating at peak power. The mounting configuration is assumed to be the same as for NTE, except for modules that are not designed to operate in an open rack. For modules with special mounting considerations, the temperature adjustment must include those effects.

Given these operating conditions, Equation 8 gives the expected operating temperature of the module:

$$T_{mod,CEC} = 20 + \frac{1000 \cdot (0.9 - \eta)}{h_{c,CEC}} \qquad (\mathbf{10})$$

Note that the efficiency η under actual operating conditions varies with temperature, so this equation should be solved in an iterative fashion. However, the improvement in accuracy obtained by iterating is not significant, so simply using the efficiency under STC conditions is sufficient. In addition, the uncertainty in R is probably a few percent, which is more than the variation in efficiency due to temperature.

Having accounted for the effects of irradiance and conversion efficiency, we would now like to obtain $h_{c,CEC}$. Observing the thermal similarity between the CEC/PTC conditions and the NTE conditions (similar ambient temperature, similar mounting configuration, and similar wind speed conditions), we assume $h_{c,CEC}$=$h_{c,NTE}$.

If modules (such as concentrators) that should not be characterized using NTE are submitted to the list of approved modules, the manufacturer will bear the responsibility for predicting the cell operating temperature.

Therefore, the correct equation in practically all cases will be (combining Equations 9 and 10):

$$T_{mod,CEC} = 20 + 1.389 \cdot (NOCT - 20) \cdot (0.9 - \eta_{STC}) \qquad (\mathbf{11})$$

Ac Modules

We currently only have one module of this type on the list. A similar analysis may be applied to ac modules, and the temperature correction can be applied the ac power.

Original Approach

When PVUSA first drafted a request for data from module manufacturers in January 1998, there were two differences from the current approach. First, a value of "Installed NOCT" (INOCT) was deemed necessary, since some modules would not fit the "open-rack" environment specified by JPL's version of NTE (which PVUSA originally referred to when developing the original "suggested" equation). To be general, we assumed we would apply this requirement to all modules. Second, the efficiency was assumed to be 7% as an approximate number sufficiently accurate for estimating temperature.

The current version of NTE described by ASTM E1036-96 expands the defined mounting configurations to include both open- and closed-back mounting configurations. This supports the characterization of PV "shingles" and other integrated building materials using NOCT. Therefore, the rationale for involving an estimate of INOCT is less than originally thought.

A relation between NOCT and INOCT was outlined in Sandia Report SAND85-0330 (1987), by Martin K. Fuentes. The odd thing about the tabular relation presented in this report was that modules installed in "open-rack" configuration were found to have an INOCT that was 3 °C cooler than NOCT! This result implies that there were differences between the configuration of the tested modules between their NOCT testing and INOCT testing that are not described in the report. However, both the magnitude of the difference and anecdotal evidence by Chuck Whitaker (who was involved in the testing) suggest that the modules were actually operating when the temperature measurements were taken. Thus, we can either include this effect in our analysis (yielding a different relation between the Fuentes INOCT and the CEC temperature rating), or avoid using the Fuentes relation at all. We have chosen the latter option.

The use of 7% as a value for efficiency is liable to be in error by 2-4% in most cases. The effect of a 4% error in efficiency is less than 1% in the estimated power, which is much less than the 5-10% typical variation in output power for each module of a particular model of module. However, since the efficiency is so easy to compute, there is little to be gained by ignoring it.