SAND2012-3781C

Improvement and Validation of a Transient Model to Predict Photovoltaic Module Temperature

Amanda Luketa-Hanlin(ajluket@sandia.gov), Joshua S. Stein (jsstein@sandia.gov)
Sandia National Laboratories, Albuquerque, NM

Abstract: Module temperature is modeled using a transient heat-flow model. Module temperature predicted in this fashion is important in the calculation of cell temperature, a vital input in performance modeling. Parameters important to the model are tested for sensitivity, and optimized to a single day of measured module temperature using simultaneous non-linear least squares regression. These optimized parameters are then tested for accuracy using a year's worth of data for one location. The results obtained from this analysis are compared with modeled data from a different site, as well as to results obtained using a steady-state model.

Models

The transient model [1] simulates module temperature as a balance between incoming heat and heat losses from electrical conversion, radiation, and convective heat transfer.

$$C_{module}\frac{dT_{module}}{dt} = q_{lw} + q_{sw} + q_{conv} - P_{out}$$

where:

$$C_{module} = \sum_m A \cdot \rho_m \cdot t_m \cdot C_m$$

$$q_{lw} = A \cdot \sigma \cdot \left[\left(\frac{1+\cos\beta_{surface}}{2} \cdot \varepsilon_{sky} \cdot T_{sky}^4\right) + \left(\frac{1-\cos\beta_{surface}}{2} \cdot \varepsilon_{ground} \cdot T_{ground}^4\right) - \left(\varepsilon_{module} \cdot T_{module}^4\right)\right]$$

$$q_{sw} = \alpha \cdot \Phi \cdot A$$

$$q_{conv} = -\left(h_{c,forced} + h_{c,free}\right) \cdot A \cdot \left(T_{module} - T_{ambient}\right)$$

$$P_{out} = C_{FF} \cdot \frac{E_e \ln(k_1 E_e)}{T_{module}}$$

The simpler steady-state model [2] uses the same weather data as does the transient model, and includes empirically-determined coefficients (*a* and *b*, both less than zero) to form a relationship between the weather inputs.

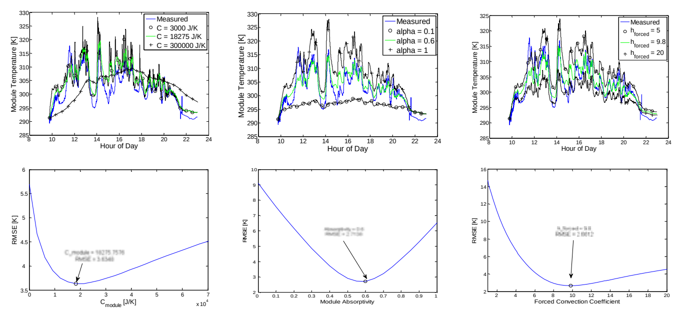
$$T_{module} = E \cdot \left\{e^{a+b \cdot WS}\right\} + T_{ambient}$$

Data

- One year's worth of data collected from tracking cSi modules in Lanai, HI, at 1-second intervals.
- Measured weather inputs include global horizontal and plane-of-array irradiance, wind speed, and ambient temperature.
- Measured module temperature data is used to quantify the accuracy of predicted module temperature.
- One month's worth of similar data collected in Albuquerque, NM at 1-minute intervals used to test for site-specific sensitivity.

Sensitivity and Optimization

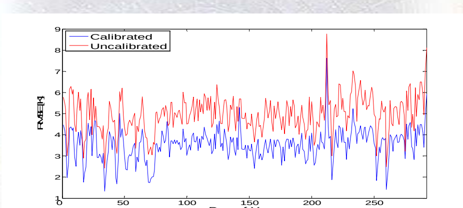
- Most important parameters to the model were found to be C_{module}, α, and $h_{c,forced}$.
- A relationship between $h_{c,forced}$ and wind speed was proposed, where h_{forced} = constant:
$$h_{c,forced} = h_{forced} \times WS$$
- Module temperature was simulated for a range of values for each parameter holding all else constant; to test $h_{c,forced}$, the coefficient h_{forced} took on different values.
- Data from a representative day in Lanai, HI was used for the simulation: March 25th, 2010.



- The 'best-fit' values (determined by lowest root mean square error) found from this simple study were used as initial conditions in the optimization analysis, which returned the following results using Matlab's built-in *lsqnonlin* function:

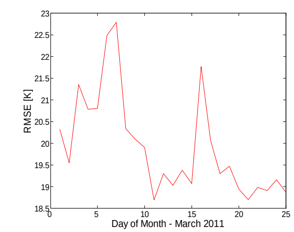
Parameter	Initial Value	Lower – Upper Bounds	Optimized Value
C_{module}	18,276 J/K	3,000 – 300,000	**22,280 J/K**
α	0.6	0 – 0.8	**0.8**
$h_{c,forced}$	9.8× WS	1 - 50	**10.65×** WS

- The model was tested using the optimized parameter values for most days in Lanai in 2010 for which there was data available; the RMSE between predicted and measured module temperature is shown below for each day of the year, using the initial values ('uncalibrated') and the optimized values ('calibrated').

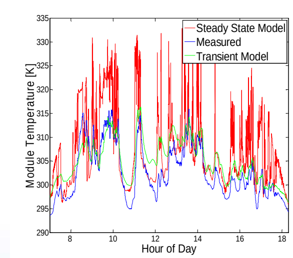


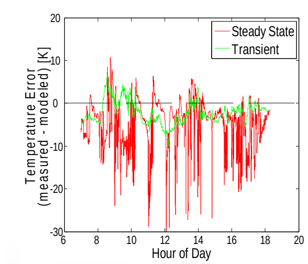
Results

- The transient model was used to simulate one month's (March 2011) worth of module temperature data in Albuquerque, NM using the parameter values optimized for Lanai.
- The error between measured and modeled module temperature as determined by the RMSE is significantly higher than for Lanai, indicating a site-specific model calibration may be necessary.



- Using the same weather and temperature data collected for March 25th, 2010, the steady-state model was used to predict module temperature. The results between the two models and measured temperature are shown below.





- The negative bias in the temperature errors seen for the steady-state model will result in generally higher module temperatures and consequently lower predicted module efficiency.

Conclusions

- The transient model best captures the variability in module temperature compared with a steady-state model.
- The transient model works best when calibrated for a specific location.

References:

1. A.D. Jones and C.P. Underwood, "A Thermal Model for Photovoltaic Systems." *Solar Energy* Vol. 70 No. 4, 2001.
2. D.L. King, W.E. Boyson, and J.A. Kratochvil, "Photovoltaic Array Performance Model." Sandia National Laboratories Report, SAND2004-3535, 2004.

Sandia National Laboratories

(Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.)