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Photovoltaic and Solar Thermal Modeling with the EnergyPlus Calculation Engine

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Introduction

EnergyPlus is a whole-building energy analysis software program being developed by the U.S. Department of Energy. Based on the Heat Balance Model, the program performs a comprehensive simulation of the building envelope, fenestration, HVAC systems, and daylighting (Crawley et al. 2001). EnergyPlus is a fully geometric model intended for annual energy simulations and runs at timesteps from 10-minutes to one hour.

EnergyPlus was recently expanded with the addition of new active solar components for simulating photovoltaic (PV) and solar thermal hot-water systems (e.g., solar collectors). The active solar models were integrated into the program because low- or zero-energy buildings often utilize renewable energy resources to accomplish their energy-saving goals. This paper provides an overview of the new models for PV and solar collectors in EnergyPlus and describes some preliminary efforts to validate the implementations.

Solar and Shading Calculations

PV and solar thermal components take advantage of the detailed solar and shading calculations already implemented in EnergyPlus for the thermal modeling of building surfaces (UIUC & LBNL 2004). The geometry of a standard EnergyPlus surface object determines the area, location, tilt, and azimuth of the PV array or solar collector. Each surface object is defined by a set of up to four vertex coordinates in three-dimensional space.

Incident solar radiation on the PV or collector surface is calculated using the same algorithms used for all exterior surfaces and is calculated separately for beam, sky, and ground reflected components based on surface geometry. Reflections from nearby surfaces, such as other building façades, are also optionally taken into account. Sky radiation is calculated using the Perez anisotropic sky model (Perez et al. 1990). The shading algorithm automatically accounts for self-shading geometries and is based on coordinate transformation methods similar to Groth and Lokmanhekim (1969) and the shadow overlap method of Walton (1983). Shading of the PV array or solar collector by other surfaces, such as nearby buildings or trees, is also taken into account based on the detailed geometry. Likewise, the PV or collector surface can shade other surfaces, for example, reducing the incident radiation on the roof beneath it. Partial transmission through a semi-transparent shading surface is also calculated. Incident solar radiation data are obtained from hourly weather data (such as TMY2) and made available for sub-hourly timesteps by carefully distributing and interpolating data between the hours.

Photovoltaics

EnergyPlus offers three different models for predicting the electricity produced by photovoltaics. Energy production is based on the assumption that the quasi-steady power prediction is constant and continuous over the simulation timestep. The choice of *simple*, *equivalent one-diode* or *Sandia model* determines the mathematical algorithm used to calculate solar electric energy production. The simple model allows the user to input arbitrary conversion efficiencies. The other two models use empirical relationships to more accurately predict PV operating performance based on conditions such as incident radiation and cell temperature.

Simple Model

The simple model is intended to give the user complete control over the PV performance. Instead of modeling efficiencies based on operating conditions, the simple model uses arbitrary, user-defined conversion efficiencies for the PV array and inverter. Especially useful for early phase design analysis, this model allows the user to perform an initial simulation to estimate annual production and peak power without having to specify (or determine) the detailed performance coefficients of a particular PV module. A building integrated mode is available to account for electrical energy removed from building surfaces.

Equivalent One-Diode Model

The equivalent one-diode model is a four-parameter empirical model to predict the electrical performance of crystalline (both mono and poly) PV modules. The model was developed largely by Townsend (1989) and is detailed by Duffie and Beckman (1991). Originally developed as a component for the TRNSYS program by Eckstein (1990), it was ported to EnergyPlus in Version 1.1.1 by Bradley (UIUC & LBNL 2004). The model simulates a PV module with an equivalent circuit consisting of a direct-current source, diode, and one or two resistors. The strength of the current source is dependent on incident solar radiation. The current-voltage characteristics of the diode depend on the temperature of the solar cells: the hotter the module, the lower its electrical output. The model determines current as a function of load voltage. Other outputs include current and voltage at the maximum power point along the current-voltage curve, open-circuit voltage, short-circuit current as well as electrical load met and unmet. The EnergyPlus implementation employs the Eckstein model for crystalline PV modules, using it whenever the short-circuit current-voltage slope is set to zero or a positive value as modified by Ulleberg (2000). The model automatically calculates parameter values from commonly available data, such as short-circuit current, open-circuit voltage, current at maximum power, etc. The model also includes an optional incidence angle modifier correlation to determine how the reflectance of the PV module surface varies with the angle of incidence of solar radiation. There are two modes for calculating the back-of-module temperature. One assumes that the cell temperature is isolated. The other assumes that cell temperature is at the outdoor air temperature, for instance, if wind is significantly cooling the module surface. The performance of an array of identical modules is assumed to be linear with the number of modules in series and parallel.

Sandia Model

The third model available in EnergyPlus for predicting the electricity generated by photovoltaics is referred to as the Sandia model and is based on research at Sandia National Laboratory (King 1996; King et al. 2003). The implementation in EnergyPlus is also based on work done by Greg Barker (2003) for the National Renewable Energy Laboratory who implemented the Sandia model as a custom type for the TRNSYS program. The model consists of a series of empirical relationships with coefficients derived from experimental tests. Once the coefficients for a specific module are available, it is a straightforward matter to use the model equations to calculate five select points on the current-voltage curve. Although the implementation in EnergyPlus assumes that the module only operates at the maximum power point, four other points on the current-voltage curve are calculated and reported so that data are available for analyses outside of EnergyPlus. Since performance depends on cell temperature, there are two modes for predicting the back-of-module temperature. One is appropriate for most rack-mounted PV installations and calculates the cell temperature in isolation. The other mode is appropriate for building integrated applications and obtains the back-of-module temperature from the exterior surface heat balance and is discussed below. Like the equivalent one-diode model, the Sandia model predicts the performance of a single PV module. The performance of an array of identical modules is assumed to be linear with the number of modules in series and parallel. Inverter efficiency can be applied to derate the energy production. An inverter capacity forms a limit for power production from a PV system.

Building Integrated PV

All of the models described above allow PV modules to be co-located with surfaces that form the building envelope of an EnergyPlus model. The simple and Sandia PV models can also model interactions with the exterior surface heat balance through the use of a source term that accounts for energy exported in the form of electricity. The equivalent one-diode model does not currently interact with the surface heat balance. The simple model does not predict efficiency and so it has no use for the surface temperature. However, the Sandia model is tightly coupled to the surface heat balance and uses the result for exterior surface temperature as the back-of-module temperature. The coupling allows for modeling panel temperatures using all the terms of the Heat Balance Model including absorbed direct and diffuse solar radiation, net long-wave radiation with air and surroundings, convective exchange with outside air, and conduction flux in or out of the surface. Davis, et al. (2002) reported good results with similar coupling using finite difference surface conduction modeling. In EnergyPlus, conduction processes are modeled using transform methods to account for heat capacity effects in the user-defined assembly.

Limitations

EnergyPlus does not include models for inverters, charge controllers, batteries, or power-point trackers. The operation of the entire electrical system is assumed to operate in ideal ways. Modules are assumed to be always operating at the maximum power point. For a variety of reasons, actual installations of photovoltaics are often observed to exhibit system-level problems that significantly reduce electricity production. Therefore, this modeling should be considered a method of bracketing the upper end of electricity production rather than an accurate prediction of what the panels will produce in a real installation.

Validation

The EnergyPlus implementations of PV models were validated in a preliminary way by comparing results from the three models to each other and to results from an independent program (DesignPro-G v5.0). A specific type of module was selected and modeled with Chicago weather data and a latitude-tilt mounting angle. The results agreed to within 5%. The effects of coupling PV models to shading and surface heat transfer models were verified by carefully evaluating results against engineering expectations.

Solar Thermal
Flat-plate solar collectors for water heating are currently the only type of active solar thermal component in EnergyPlus. Based on the performance equations found in the ASHRAE standard (1991) and also described by Duffie and Beckman (1991), the model applies to glazed and unglazed flat-plate collectors, as well as banks of tubular (i.e., evacuated tube) collectors. A data set of commercially available solar collectors certified by the Solar Rating and Certification Corporation is provided with the program.

In EnergyPlus, solar collector modules are components that are connected to the HVAC plant loop simulation. A solar heating system for domestic hot water or space heating can be constructed using a combination of solar collectors, pumps, and water heater objects. Multiple collector modules can be combined in series and parallel using the normal EnergyPlus plant connection rules. Solar heating systems use higher-level plant managers to implement common controls, such as differential thermostats.

Currently, thermal storage for solar heating systems is accomplished with the existing EnergyPlus "simple" water heater object. Multiple tank systems with a storage tank and auxiliary water heater are not yet implemented, but they are scheduled for future releases of the program.

Validation
To validate the EnergyPlus implementation of the flat-plate solar collector, results were compared to the TRNSYS Type 1 flat-plate solar collector, which is also based on the same model equations from ASHRAE and Duffie and Beckman. The EnergyPlus model and Type 1 model were compared side-by-side by extracting and wrapping both FORTRAN subroutines with a thin layer of control code to exercise the models. Although the two models require different input variables and units, the control code made all necessary conversions. The results agreed exactly for most conditions, with the exception of very low incident angles where there were only very minor differences.

Conclusion and Future Development
Models for PV and solar thermal hot-water systems were added to the EnergyPlus whole-building energy analysis program. Implementing these models in EnergyPlus was found to be fairly straightforward and advantageous in that the models were easily expanded to account for broader set of system interactions by coupling them to the comprehensive models and algorithms that already existed for solar radiation, surface shading and reflections, dynamic surface heat transfer, and HVAC system components.

Further development of both PV and solar thermal components in EnergyPlus is scheduled for future releases. PV developments will include electrical loops and system models to account for the effects of inverters, batteries, etc. Solar thermal developments will include integrated collector storage (ICS) modules, concentrating collectors, and enhancements to the basic flat-plate model, as well as more thermal storage capabilities in the EnergyPlus plant system such as multiple storage tanks. Hybrid PV and thermal system models and unglazed transpired collectors are also planned.

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