

## ENERGYPLUS: AN UPDATE

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### ABSTRACT

A new building energy simulation program, known as EnergyPlus, was first released in April 2001. Building on the capabilities and features of BLAST and DOE-2, EnergyPlus includes many simulation features that have not been available together in a mainstream building energy simulation program. Some key capabilities include variable time steps, configurable modular systems integrated with heat balance-based zone simulation, multiple comfort models, daylighting and advanced fenestration, multizone airflow, displacement ventilation, flexible system modeling, and photovoltaic and solar thermal simulation. Since EnergyPlus was released in April 2001, more than 24,000 copies have been downloaded. The paper provides an overview of the capabilities and strengths of EnergyPlus in comparison with DOE-2 and BLAST.

### INTRODUCTION

For more than twenty years, the U.S. government supported development of two building energy simulation programs, DOE-2 and BLAST. BLAST (Building System Laboratory 1999), sponsored by the U.S. Department of Defense (DOD), has its origins in the NBSLD program developed at the U.S. National Bureau of Standards (now NIST) in the early 1970s. DOE-2 (Winkelmann et al. 1993), sponsored by the U.S. Department of Energy (DOE), has its origins in the Post Office program written in the late 1960s for the U.S. Post Office. Both programs are widely used throughout the world. The main difference between the programs is in their load calculation method—DOE-2 uses a room weighting factor approach while BLAST uses a zone heat balance approach.

Each program comprises hundreds of subroutines working together to simulate heat and mass energy flows throughout a building. In both cases, simulation methodologies are difficult to trace or expand due to decades of development and a closed 70's vintage software architecture that has resulted in 'spaghetti code' with data and subroutines for particular

simulation capabilities spread throughout the program. To modify either program, a developer must have many years experience working within the code, knowledge of code unrelated to their task, and a significant investment of time and money.

Questioning why the U.S. government supported two programs with comparable capabilities, discussions on merging the two programs began in earnest in 1994. In 1996, DOE began supporting the development of the new program named EnergyPlus. The EnergyPlus development team includes University of Illinois, Lawrence Berkeley National Laboratory, DHL Consulting, Oklahoma State University, GARD Analytics, Florida Solar Energy Center, National Renewable Energy Laboratory, and DOE. In this paper, we present an overview of the structure of EnergyPlus along with a comparison of current capabilities in contrast with DOE-2 and BLAST.

### WHAT IS ENERGYPLUS?

EnergyPlus comprises new, modular structure code based on the most popular features and capabilities of BLAST and DOE-2. It is primarily a simulation engine without a user-friendly graphical interface: input and output are simple comma-separated, ASCII text files, much simpler input than either DOE-2 or BLAST. One of the main goals we set for developing EnergyPlus was to create a well-organized, modular structure to facilitate adding features and linking to other programs. Since BLAST and DOE-2 successfully attracted third-party developers of user interfaces and new modules, from the start we worked with developers interested in creating new simulation modules or developing their own user interfaces.

### ENERGYPLUS STRUCTURE

In response to two workshops on next generation energy tools sponsored by DOE (Crawley et al. 1997), we decided that integrated simulation would be the underlying concept for EnergyPlus. Zone loads

calculated (by a heat balance engine) at a user-specified time step (15-minute default) are passed to the building systems simulation module at the same time step. The building systems simulation module, with a variable time step (down to one minute as needed), calculates heating and cooling system and plant and electrical system response. Feedback from the building systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures if necessary.

By using an integrated solution, EnergyPlus solves the most serious deficiency of BLAST and DOE-2—the absence of feedback from sequential loads, system, and plant calculations that results in inaccurate predictions of space temperatures and system loads. Accurate prediction of space temperatures is crucial to energy efficient system engineering—system size, plant size, occupant comfort and occupant health are dependent on space temperatures. Integrated simulation also allows users to evaluate a number of processes that neither BLAST nor DOE-2 can simulate well. Some of the more important include realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

Figure 1 shows overall EnergyPlus structure, with three basic components—simulation manager, heat and mass balance simulation module, and building systems simulation module. The simulation manager controls the entire simulation process. The heat and mass balance calculations are derived from IBLAST—a research version of BLAST with integrated HVAC systems and building loads simulation.

The building systems simulation manager handles data exchange among the heat balance engine and various HVAC modules and loops, such as coils, boilers, chillers, pumps, fans, and other equipment/components, as well as their input and output data. Gone are hardwired ‘template’ systems (VAV, constant volume reheat, etc.) of DOE-2 and BLAST—replaced by user-configurable heating and cooling equipment components and systems. Users can match the simulation to the actual system configuration. Rather than describe the simulation manager, heat balance simulation manager, and building systems simulation manager here, we refer you to Fisher et al. (1999), Huang et al. (1999), Strand and Petersen (2001), and Winkelmann (2001).

## INPUT, OUTPUT, AND WEATHER DATA

Both DOE-2 and BLAST have structured, readable input files that have evolved over many years. We designed the EnergyPlus input files for easy

maintenance and expansion. We chose to keep the input file simple so that input data could be translated easily from CAD systems, other building-related programs, and pre-processors similar to those written for BLAST and DOE-2. EnergyPlus input files are somewhat readable but can be cryptic and were not intended to be the main interface for typical end-users. We expect most users will use an interface for EnergyPlus from a third-party developer. To make it easy for current DOE-2 and BLAST users to move to EnergyPlus, the team has written utilities that convert BLAST and DOE-2 loads input to EnergyPlus input structure.

The International Alliance for Interoperability has developed an object-oriented data protocol for building information exchange, known as Industry Foundation Classes (IFC) (Bazjanac 2003). Initial implementations of IFC began appearing in building CAD programs in 2001. We provide a utility for creating EnergyPlus input files from CAD-derived IFC files.

EnergyPlus uses a free format input format that contains a complete object-based description of the building and its systems. The basic syntax is: object, data, data, . . . , data; where ‘object’ is a pre-defined keyword denoting a building or system component, such as SURFACE, MATERIAL, LIGHTS, FURNACE, HEATING COIL, or BOILER. This keyword is followed by a list of data values and terminating with a semicolon. These data describe performance characteristics and intended use for that object in the simulation. The output uses a similar philosophy to the input—simple text files with an object, time stamp, data, . . . , data; syntax. Because the output data structure is simple, output post-processors can easily read the data and create more elaborate reports. The one drawback of the simple format is that the output files can be large.

Weather data used by EnergyPlus [described as the EnergyPlus/ESP-r (E/E) format] also uses a simple text-based format, similar to the input and output files. A separate EnergyPlus utility converts standard weather formats such as TD1440 and DATSAV3 and newer typical year weather such as WYEC2, TMY2, and IWEC. Crawley, Hand and Lawrie (1999) describe the E/E weather data format. EnergyPlus (E/E) weather data for more than 560 locations is provided on the EnergyPlus web site—275 locations in the United States, 55 locations in Canada, and more than 230 locations in 70 other countries.

In summary, all data files associated with EnergyPlus—input, output, and weather—have simple self-contained formats that can be easily read and interpreted by spreadsheets, databases, or user interfaces.

## TESTING

A critical part of EnergyPlus development has been continuous testing, with emphasis on comparative and analytical testing. Comparative testing of basic loads algorithms has been completed using ASHRAE Standard 140-2001 (ASHRAE 2001) series of tests, a basic shoebox with windows and shading for both low mass and high mass construction. Testing EnergyPlus against itself has been critical to detect and resolve problems during development. The testing to date demonstrates that EnergyPlus provides results in good agreement with other simulation programs for simple cases. We will continue to aggressively test EnergyPlus throughout future development. As testing results are completed, the results and testing methodologies are posted on the EnergyPlus web site. See Witte et al. (2001, 2004) and Henninger et al. (2003) for information on EnergyPlus testing and validation .

## USER SUPPORT AND TRAINING

We provide support to EnergyPlus users through:

- Email support for specific input/output questions.
- Email list for sharing questions within the user community. More than 600 people participate in this email group, sharing experiences, problems, and ongoing input to the team on new features.
- Multi-day workshops for beginner, intermediate and advanced users.
- Course curriculum outline and PowerPoint slides as a starting point for professors teaching energy simulation (including EnergyPlus).

## COMPARISON OF ENERGYPLUS WITH DOE-2 AND BLAST

In Tables 1 through 9, we compare the capabilities of EnergyPlus with those in DOE-2.1E (version 121) and BLAST (version 3.0 Level 334). An X means the program has full capabilities, a P means it has partial or simplified capabilities, and a \* in the EnergyPlus column means the feature was added in Version 1.2:

- Table 1 General Features
- Table 2 Internal Loads
- Table 3 Building Envelope and Daylighting
- Table 4 Infiltration, Natural Ventilation, and Multizone Airflow
- Table 5 Renewable Energy Systems
- Table 6 HVAC Systems and Equipment
- Table 7 Electrical Systems and Equipment
- Table 8 Energy Use Environmental Emissions
- Table 9 Results Reporting

## SUMMARY

The EnergyPlus building energy simulation program combines the best features of the BLAST and DOE-2 programs along with many new capabilities. We released EnergyPlus Version 1.0 in April 2001 and will release major updates annually. The current version, Version 1.2, was released in April 2004.

Each spring, we reprioritize and update plans for new features and capabilities in future releases based on suggestions by users, developers, and the team. The features planned for major releases over the next several years includes extensive ventilation improvements, electrical system simulation, generalized surface polygons, improved zone air stratification models, underfloor air distribution, pressure-based hydronic loop controls, user-defined functions, and other low-energy buildings features.

## WEB RESOURCES

Information on EnergyPlus, including availability of new releases, user support, training workshops and materials, weather data for more than 560 locations worldwide, licensing, programming standards, technical papers, and complete documentation can be found at <http://www.energyplus.gov>.

A web-based directory of more than 280 building-related software tools from around the world can be found at <http://www.energytoolsdirectory.gov>.

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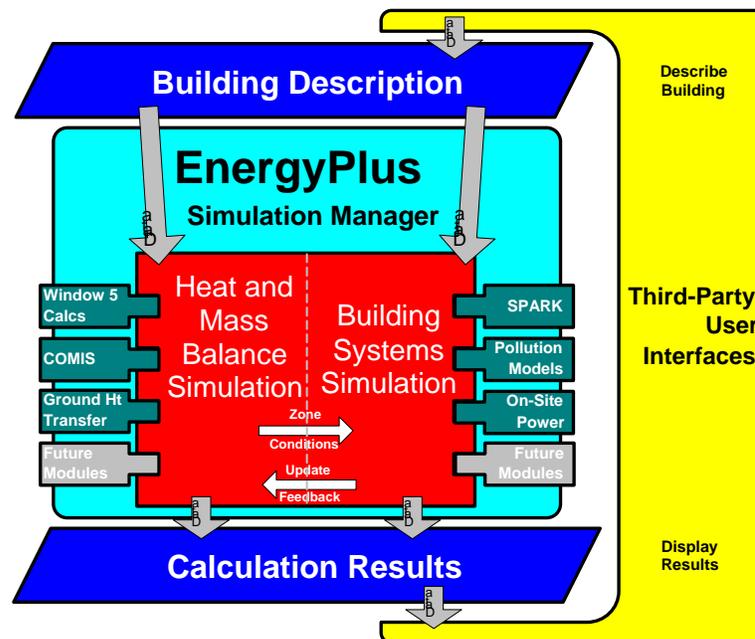


Figure 1. Overall Structure of EnergyPlus

Table 1. General Modeling Features

	DOE-2	BLAST	EnergyPlus
Integrated, Simultaneous Solution			
▪ Simultaneous calculation		1	X
▪ Iterative solution of non-linear systems			X
▪ Tight coupling of loads, systems, plant			X
▪ Accurate space temperature prediction			X
▪ Floating temperature	X	X	X
Multiple Time Step Approach			
▪ User-defined time step for zone/environment interaction (15-min default)		1	X
▪ Variable time intervals for zone air/HVAC system interaction ( $\geq 1$ min)		1	X
Full Geometric Description			
▪ Walls, Roofs, Floors	X	X	X
▪ Windows, Skylights, Doors, and External Shading	X	X	X
Import Building Geometry from CAD Programs			X
Unlimited number of surfaces (walls, windows), thermal zones, systems, and equipment			X

Table 2. Zone Loads

	DOE-2	BLAST	EnergyPlus
Heat Balance Calculation (simultaneous calculation of radiation and convection processes each time step)		X	X
Building Material Moisture Adsorption/Desorption (combined building envelope heat and mass transfer)		1	X
Interior Surface Convection			
▪ Dependent on temperature and air flow		X	X
▪ Internal thermal mass	X	X	X
Human thermal comfort based on activity, inside temperature, humidity and radiation (Fanger, KSU, Pierce two-node, MRT)		X	X
Design day calculations for sizing			
▪ Dry bulb temperature	X	X	X
▪ Dew point temperature or relative humidity			X*
▪ User-specified minimum and maximum			X*

Table 3. Building Envelope and Daylighting

	DOE-2	BLAST	EnergyPlus
Advanced Fenestration			
▪ Controllable window blinds	X		X
▪ Between-glass shades and blinds	X		X
▪ Electrochromic glazing			X
▪ > 200 window types including conventional, reflective, low-E, gas-fill, electrochromic, and WINDOW-5 layer-by-layer custom glazing input	P		X
▪ WINDOW 5 calculations			X
▪ Dirt correction factor for glass solar and visible transmittance	P		X*
▪ Movable storm windows			X*
▪ Solar gain through blinds accounts for different transmittances for sky and ground diffuse solar			X*
▪ Beam solar radiation reflection from outside and inside window reveals			X
▪ Bi-directional shading devices			X
▪ Window blind model (slat-type shading devices such as Venetian blinds) coupled to daylighting, with movable slats and associated slat-angle			X

<sup>1</sup> IBLAST only (IBLAST was a not generally released, integrated version of BLAST).

controls			
▪ Shading device control including scheduling	P		X
▪ Calculation of beam solar radiation passing through interior windows (double-envelope)			X
▪ Window gas fill as single gas or mixture of gases			X
General Envelope Calculations			
▪ Outside convection algorithm			
▪ BLAST/TARP	X	X	X
▪ DOE-2			X
▪ MoWiTT			X
▪ ASHRAE simple		X	X
▪ User-selectable			X*
▪ Radiation-to-air component separate from detailed convection (exterior)			X*
▪ Solar gain and daylighting calculations account for beam and sky diffuse solar reflected from building sections, fins, overhangs, and neighboring buildings, including specular reflection from glazed neighboring buildings			X*
▪ Shading of sky IR by obstructions	X		X
Anisotropic sky model (sky radiance as function sun position, more accurate diffuse solar radiation and illumination)	X		X
Daylighting illumination and controls			
▪ Interior illumination from windows and skylights	X		X
▪ Dimming electric lighting including heating and cooling effects	X		X
▪ Glare simulation and control	X		X
▪ Geometrically and optically complex fenestration systems using bi-directional transmittance			X*
▪ Radiosity interior light interreflection calculation			X*
▪ Shading surface transmittance in detailed daylighting	P		X
▪ Daylight illuminance maps			X
▪ Tubular daylighting devices (illuminance, solar gain, thermal resistance)			X
▪ Daylighting shelves			X
Movable/transparent insulation		X	X
Surface temperatures (wall, window, roof, door)			X
Airflow windows			X
Heat transfer from building to ground	P	P	X
Building integrated photovoltaic systems account for thermal load removed			X*

Table 4. Infiltration, Natural Ventilation and Multizone Airflow

	DOE-2	BLAST	EnergyPlus
Infiltration			
▪ Single zone	X	X	
▪ Nodal multizone			X
Natural ventilation (pressure, buoyancy driven)			X
Automatic calculation of wind pressure coefficients			X
Multizone airflow			X
Mundt room air model			X*
Displacement ventilation model (UCSD)			X*

Table 5. Renewable Energy Systems

	DOE-2	BLAST	EnergyPlus
Photovoltaic power			X*
Flat plate solar thermal collectors			X*
Trombe wall	X	X	X

Table 6. HVAC Systems and Equipment

	DOE-2	BLAST	EnergyPlus
Fluid loops (hot water, chilled water and condenser loops connect equipment)			X
Air loops (connect fans, coils, mixing boxes, zones)			X
Discrete HVAC components (more accurate part-load performance)			X
User-configurable HVAC systems			X
High-temperature radiant heating (gas/electric heaters, wall radiators)	P	<sup>1</sup>	X
Low-temperature radiant heating/cooling		<sup>1</sup>	X
▪ Heated floor/ceiling			X
▪ Cooled ceiling			X
SPARK link for complex and innovative HVAC equipment and systems			X
Air-to-air energy recovery	P	X	X
▪ Sensible-only heat exchanger		X	X
▪ Sensible and latent energy exchange			X
▪ Frost control			X
▪ Flat plate sensible heat exchanger			X
DX cooling coil latent capacity degradation at part load (cycling) conditions			X*
Cooling coils (DX or chilled water) in combination with air-to-air heat exchanger for improved dehumidification performance			X*
High humidity control using DX or chilled water cooling coils	X	X	X
Desiccant dehumidification	X		X
Evaporative condenser option for DX cooling coils	X		X*
▪ Simple effectiveness model			X*
▪ Water usage and water pump power calculated and metered			X*
Air distribution system with conduction losses and air leakage for constant volume systems			X*
Multiple supply air plenums			X*
Simplified demand-controlled ventilation			X*
▪ Ventilation rate per occupant and per floor area			X*
▪ Ventilation air flow schedule			X*
Automatic sizing	X		X
• HVAC components			X*
• Hot water, cold water, and condenser water loops			X*
HVAC Equipment			
• Coldest zone supply air set point	X		X
• Control based on outdoor dry bulb and outdoor wet bulb temperature	P		X
• System night cycle control	X		X
• Gas turbine chiller		X	X
• Heat recovery in gas turbine chiller		X	X
• Electric chillers with double-bundle condenser/heat recovery	X	X	X*
• Gas absorption chiller heater	X	X	X
• Steam absorption chiller	X	X	X
• Free cooling chiller	X	X	X
• Free cooling, hydronic heat exchanger	X		X
• Service water heater	X		X
• Service water heater water consumption			X*
• Stratified water heater tank		X	X*
• Variable speed fan	X	X	X
• Exhaust fan	X	X	X
• Variable speed primary pump	X	X	X
• Air-to-air heat pumps	X	X	X

• Water-to-air heat pumps	X	X	X*
• Water-to-water heat pumps		X	X
• Ground source heat pumps	P		X
• Pond heat exchanger			X
• Ground surface heat exchanger			X
• Ground loop vertical borehole heat exchanger			X
• DX coil	X	X	X
• Fan coil	X	X	X
• Window AC	X		X
• Air-cooled condenser	X	X	X
• Simple evaporative condenser	X	X	X
• Electric baseboard	X	X	X
• Boiler (gas and electric)	X	X	X
• Furnace (gas and electric)	X	X	X
• Unit heater (gas and electric coils)	X	X	X
• Unit ventilator (gas and electric coils)	X	X	X

Table 7. Electrical Systems and Equipment

	DOE-2	BLAST	EnergyPlus
Photovoltaic power			X*
Electric power generators (determine electric utility purchases and surplus)	X	X	X*
Demand limit and track electric operation scheme	X		X

Table 8. Environmental Emissions Due to Energy Use

	DOE-2	BLAST	EnergyPlus
Major greenhouse gases (CO <sub>2</sub> , CO, CH <sub>4</sub> , NO <sub>x</sub> )	X	X	X
Carbon equivalent of greenhouse gases			X*
Criteria pollutants (CO, NO <sub>x</sub> , SO <sub>2</sub> , PM, Pb)			X*
Ozone precursors (CH <sub>4</sub> , NMVOC, NH <sub>3</sub> )			X*
Hazardous pollutants (Pb, Hg)			X*
Water use in power generation			X*
High- and low-level nuclear waste from power generation			X*
On-site and at power plant	X	X	X
National and state-level pollutant emissions factors for electricity, natural gas, residual fuel oil, distillates, residential oil, LPG, gasoline, diesel, and coal			X*

Table 9. Results Reporting

	DOE-2	BLAST	EnergyPlus
Standard Reports	X	X	X
Meters			
▪ Energy end-use (individual metering for lighting, heating, cooling, etc.)	X	X	X
▪ Peak demand	X	X	X
▪ Consumption by energy source	X	X	X
Autosizing Report	X		X
Standardized time-binned report for any variable	P		X
User-definable reports			X
Reports formatted as CSV, text, tab, or HTML			X
Extensive reports of simulation load, system, and state variables at time step with daily, monthly, and annual aggregation			X
Visual surface output (walls, windows, floors, roofs)			X
HVAC system diagramming			X*