

EnergyPlus: A New-Generation Energy Analysis and Load Calculation Engine for Building Design

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Abstract

Many building energy simulation programs developed around the world are reaching maturity. Many use simulation methods (and even code) that originated in the 1960s. Without substantial redesign and restructuring of the programs, continuing to expand their capabilities has become difficult, time-consuming, and prohibitively expensive. However, recent phenomenal advances in analysis methods and computational power have increased the opportunity for significant improvements in the flexibility and comprehensiveness of these tools. As a result, a project was launched in 1995 to begin development of a new energy analysis program. Originally intended to be a combination of the best features of the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs, the current goals for EnergyPlus far exceed those initial ideas. In addition, in a departure from previous programs, the development team has restricted itself to the calculation only so as to allow private industry the ability to develop and maintain targeted interfaces for various industries. The program is written in Fortran 90 and boasts a modular structure aimed at greatly simplifying the further enhancement of the program by the original development team and other researchers. This paper provides a general overview of the development of EnergyPlus, a brief look at its current status, and a review of its probable release schedule.

Introduction: What is EnergyPlus?

In the mid-1990s, as computing power continued to grow rapidly and the drive to maximize the efficiency of federal research dollars reached full speed, one area that seemed to be lacking a bold new initiative was the field of building energy analysis and load calculations software. Private industry programs continued to have limited market share focused primarily on providing clients with the ability to size and select plant equipment such as boilers and chillers. Public-sponsored programs such as BLAST (BLAST Support Office 1992) and DOE-2 (Winkelmann et al. 1993) were reaching “critical mass” and were facing the prospect of significantly reduced federal funding. It was at that critical time when the U.S.

Department of Energy (DOE) launched a plan to address the various problems associated with the public domain programs.

Despite their success in providing architects and engineers with reasonable estimates for building thermal loads and energy consumption, BLAST and DOE-2 had become too expensive to maintain and enhance. The addition of new calculational models to either program or fixing problems in their existing models required a significant amount of training in both programming in general and the respective programs. While the rapid technological growth and expansion of building related systems kept researchers at the University of Illinois at Urbana-Champaign, U.S. Army Corps of Engineers Construction Engineering Research Laboratories, and Lawrence Berkeley National Laboratories well stocked with projects to work on, there simply was not enough expertise available to meet the increasing simulation demands of design professionals. Moreover, the sponsorship of two separate programs, while understandable in the very early phases of energy analysis development back in the 1960s and 1970s, had outlived its usefulness and resulted in a duplication of federally sponsored efforts.

In this environment, DOE began planning for a new generation of simulation tools. After the first step of creating an inventory of all of the existing DOE-sponsored tools (Crawley 1996), workshops were held to obtain recommendations and ideas from program users and developers (Crawley et al 1997). Based on the results of these workshops and the combined experience of the various research groups responsible for BLAST and DOE-2, DOE crafted a plan to develop a new-generation energy simulation tool called EnergyPlus.

EnergyPlus is a new building performance simulation program that combines the best capabilities and features from BLAST and DOE-2 along with new capabilities. Developed using the heat balance based load calculation algorithm found in IBLAST (a research version of the BLAST program), it consists of new Fortran 90 code that was either created specifically for EnergyPlus or that was reengineered from one of the legacy programs. The use of Fortran 90 as the programming language for EnergyPlus also allows for the creation of a well-organized, modular program structure that facilitates adding new features and links to other programs. The modular nature of EnergyPlus is a key feature because it will hopefully allow researchers with very limited experience with the program to quickly add new modules to the program, thereby maximizing the impact of new research and at the same time minimizing the cost and time commitment of such projects.

In addition, EnergyPlus is primarily a simulation engine. One of the reasons for this is the broad range of potential users the program might end up having. For example, an architect might be interested in monitoring energy consumption during the entire design phase of a program, a mechanical engineer may be interested in investigating various mixed air strategies on a particular air handling system, a homeowner could be interested in the yearly energy savings that might be realized from installing double pane windows with a low-emissivity coating instead of standard double pane windows, etc. While each type of user requires the same calculation to be performed, each will have different knowledge levels, skills, and goals. Thus, the simulation engine can be the same for all users but the interface to the simulation program will likely be very different. Private industry has shown itself to be much more capable of creatively responding directly to the demands of the highly diversified consumer market in this area. The EnergyPlus project will allow interface developers to tailor their products to their respective industries without having to produce the complex energy analysis program while also allowing all of the interfaces to be based on the same calculation engine.

Modularity

Work on EnergyPlus began by modularizing (restructuring) code from the heat balance engine in IBLAST, a research version of BLAST with integrated loads and HVAC calculation (Taylor et al. 1990, 1991). Normally such restructuring would result in major rewrites involving a long development period and very extensive testing to ensure the new code performs as intended. To avoid this problem, we devised a process we call ‘Evolutionary Reengineering (ER)’ that incrementally moves the program from old unstructured legacy code to new modular code by incorporating new code with old. Throughout the process, existing code still works with user input data and is extended to generate parameters needed by the new code modules. In this way the new modules can be verified without having to completely replace the entire functional capability of the old program with new code before it can be tested. As the process proceeds, old routines are replaced by new routines and data structures. This makes the transition evolutionary and permits a smooth transition with a greater capability for verification testing.

One of the most encouraging results of the modularization process was the new clarity it brought to the program code’s main simulation loops. At the outermost program level, the Simulation Manager controls the interactions between all simulation loops from a sub-hour level up through the user selected time step and simulation period—day, month, season, year, or several years. Actions of individual simulation modules are directed by the simulation manager, instructing simulation modules to take actions such as initialize, simulate, keep records, or report.

The simulation manager was created to specifically address the legacy issues of spaghetti code and lack of structure in DOE–2 and BLAST. The simulation manager provides several critical benefits:

- major simulation loops are contained in a single subroutine
- modules are self-contained and more object-based
- data access is controlled
- new modules are easily added

Structure

In the DOE/DOD workshops (Crawley et al. 1997), there was strong consensus that a more flexible and robust tool with additional capabilities is needed. Recurrent themes for simulation needs throughout the workshops were design, environment, economics, and occupant comfort and safety. Designers need tools that provide answers to very specific questions during design. They want tools that provide the highest level of simulation accuracy and detail reasonably possible but that do not get in the user’s way. One of the highest priorities was an integrated (simultaneous) simulation for accurate temperature and comfort prediction.

In response to these findings, an integrated simulation became the underlying concept for EnergyPlus—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), 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 technique in EnergyPlus, the most serious deficiency of the BLAST and DOE–2 sequential simulations—inaccurate space temperature prediction due to no feedback from the HVAC module to the loads calculations—is solved. Accurate prediction of space temperatures is crucial

to energy efficient system engineering—system size, plant size, occupant comfort and occupant health all depend 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
- Interzone air flow

As shown in Figure 1, there are three basic components to EnergyPlus—a Simulation Manager, a Heat and Mass Balance Simulation module (based on IBLAST), and a new Building Systems Simulation module. The Simulation Manager controls the entire simulation process.

The Building Systems Simulation Manager handles communication between the heat balance engine and the HVAC water and air loops and their attached components (coils, boilers, chillers, pumps, fans, etc.) The hardwired ‘template’ systems (VAV, Constant Volume Reheat, etc.) of DOE-2 and BLAST have been replaced with user-configurable heating and cooling equipment components. This gives users much more flexibility in matching their simulation to the actual system configurations. The Building Systems Simulation Manager also manages data communication between the HVAC modules, input data, and output data structures.

A comparison of major features and capabilities of EnergyPlus, BLAST, IBLAST, and DOE-2 are shown in Tables 1-3.

Heat and Mass Balance Calculation

The underlying building thermal zone calculation method in EnergyPlus is a heat balance model in which room air is modeled as well stirred with uniform temperature throughout. (The modular structure of EnergyPlus allows more detailed room air convection calculations—such as CFD or zonal methods—to be included later in the program.) It is also assumed that room surfaces (walls, windows, ceilings, and floors) have:

- uniform surface temperatures,
- uniform long and short wave irradiation,
- diffuse radiating surfaces, and
- internal heat conduction.

Figure 2 shows the structure of the EnergyPlus integrated solution manager that manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager. The Surface Heat Balance Module simulates inside and outside surface heat balance, interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer (water vapor) effects. The Air Mass Balance Module deals with various mass streams such as ventilation air, exhaust air, and infiltration. It accounts for thermal mass of zone air and evaluates direct convective heat gains. Through this module that we are connecting to COMIS (Fuestel 1990) for improved multizone airflow, infiltration, indoor contaminant, and ventilation calculations.

In addition to the basic heat balance engine from IBLAST, three new modules based on capabilities from DOE-2 have been created: daylighting simulation (Winkelmann and Selkowitz 1985), WINDOW 5-based window calculation (Arasteh et al. 1994), and anisotropic sky. The Daylighting Module calculates

hourly interior daylight illuminance, glare from windows, glare control, electric lighting controls, and calculates electric lighting reduction for the heat balance module. The Window Module incorporates capabilities from WINDOW 4—accurate angular dependence of transmission and absorption for both solar and visible radiation, and temperature-dependent U-value. Users describe a window as a combination of glazing, gas-fill, and shade layers. Sun control can be modeled with controllable interior or exterior shades or with electrochromic glazing. The sky model includes non-isotropic radiance and luminance distribution of the sky based on the empirical model by Perez (1990, 1991) as a function of sun position and cloud cover. This non-uniform radiance distribution improves calculation of diffuse solar on tilted surfaces (walls and sloped roofs).

Building Systems Simulation Manager

After the Heat Balance Manager completes its simulation for a time step, it calls the Building Systems Simulation Manager, which controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions. EnergyPlus does not use a sequential simulation method (first building loads, then distribution system, and then plant) as found in DOE-2 and BLAST since this imposes rigid boundaries on program structures and limits input flexibility. Instead, the Building Systems Simulation Manager has been designed with several objectives:

- fully integrated simulation of loads, systems, and plant
- modular
- extensible

Integrated simulation allows capacity limits to be modeled more realistically and provides tighter coupling between the air- and water-side of the system and plant. Modularity is maintained at both the component and system level. This eases adding new components and flexibly modeling system configurations and, at the system level, equipment and systems are clearly connected to zone models in the heat balance manager. To implement these concepts, loops are used throughout the Building Systems Simulation Manager—primarily HVAC air and water loops. Loops mimic the network of pipes and ducts found in real buildings; later, EnergyPlus will simulate head and thermal losses that occur as fluid moves in each loop.

The air loop simulates air transport, conditioning, and mixing and includes supply and return fans, central heating and cooling coils, heat recovery, and controls for supply air temperature and outside air economizer. The air loop connects to the zone through the zone equipment. Zone equipment includes diffusers, reheat/recool coils, supply air control (mixing dampers, fan-powered VAV box, induction unit, VAV dampers), local convection units (window air-conditioning, fan coil, water-to-air heat pump, air-to-air heat pump), high temperature radiant/convective units (baseboard, radiators), and low temperature radiant panels. Users can specify more than one equipment type for a zone.

For the air loop, the solution method is iterative, not single-pass as in DOE-2 and BLAST. In order to specify equipment connections to a loop, nodes are defined at key locations around the loop with each node assigned a unique identifier. Node identifiers store loop state variables and set-point information for that location in the loop. An iterative solution technique is used to solve for unknown state variables along with control equation representations. These representations connect the set points at one node with the control function of a component, such as fan damper position or cooling coil water flow rate. In this schema, all the loop components are simulated first, and then the control equations are updated. This procedure continues until the simulation converges. Preliminary experience with this solution technique shows that in most cases convergence occurs rapidly without requiring an excessive number of iterations.

There are two water loops for HVAC plant equipment—a primary loop (for supply equipment such as boilers, chillers, thermal storage, and heat pumps) and a secondary loop (for heat rejection equipment such as cooling towers and condensers). Equipment is specified by type (gas-fired boiler, open drive centrifugal chiller) and its operating characteristics. In the first release of EnergyPlus, curve-based equipment models (such as in BLAST and DOE-2) will be supported. However, because of the modular code, it will be easy for developers to add other types of models.

As in the air loop, the primary and secondary plant loops use explicit nodes to connect equipment to each loop. Connections between the air loop and zone equipment and the primary and secondary loops are made through the node data structure and must be explicitly defined in the input file.

A similar loop approach is proposed for future expansions to the program including a new electrical loop for simulating electrical systems—supply (utility, photovoltaic modules, and fuel cells), demand (plug loads, lighting, and other electrical loads), and measurement (meters). In the longer term, EnergyPlus users will have more systems and equipment options through a link to SPARK (Buhl et al. 1993), a new equation-based simulation tool. SPARK is a better solver for complex iterative problems and is currently in beta testing. SPARK already has a library of HVAC components based on the ASHRAE primary and secondary toolkits. EnergyPlus will continue to have system types (in input file templates) but developers and advanced users will be able to build complex new HVAC models with SPARK.

Input, Output, and Weather Data

Instead of user readability, the EnergyPlus input and output data files are designed for easy maintenance and expansion. The input file simple is kept simple in order to accept simulation input data from other sources such as CADD systems, programs that also do other functions, and preprocessors similar to those written for BLAST and DOE-2. An EnergyPlus input file is not intended to be the main interface for typical end-users. It is expected that most users will use EnergyPlus through an interface from a third-party developer. To make it easy for current DOE-2 and BLAST users to move to EnergyPlus, utilities have been written that convert BLAST and DOE-2 input to the new EnergyPlus input. A comparison of input for BLAST, DOE-2, and EnergyPlus is shown in Table 4.

During a simulation, EnergyPlus saves results for each time step in an output data structure. The Heat Balance time step is user-specified with a default of 15 minutes. HVAC results may proceed at the Heat Balance time step or at smaller time steps in order to reach stability. The EnergyPlus output processor provides these results in a simple variable-based format (comma separated text file) that can easily be read by post-processing programs or even spreadsheets.

The other major data input is weather. Rather than a binary file created by a separate weather processor, again a simple text-based format was chosen, similar to the input data and output data files. The weather data format includes basic location information in the first eight lines: location (name, state/province/region, country), data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings period, typical and extreme periods, two lines for comments, and period covered by the data. The data are also comma-separated and contain much of the same data in the TMY2 weather data set (NREL 1995). EnergyPlus does not require a full year or 8760 (or 8784) hours in its weather files. In fact, EnergyPlus allows and reads subsets of years and even sub-hourly (5 minute, 15 minute) data—the weather format includes a ‘minutes’ field. It also comes with a utility that reads standard weather service file types such as TD1440 and DATSAV2 and newer ‘typical year’ weather files such as TMY2 and WYEC2.

In summary, all the data files associated with EnergyPlus—input, output, and weather—have simple, self-contained formats which can be easily read and interpreted by other programs—spreadsheets, databases, or custom programs. By working with third party interface developers early, it was determined to keep these files simple and easy to use by other programs that building designers use.

EnergyPlus Status, Version 1.0 Release, and Beyond

The first working version of EnergyPlus, an alpha version, was completed in December 1998 for internal testing by the team. This was followed by various beta versions of EnergyPlus to outside users and developers made available throughout 1999. Further beta releases are expected in 2000 with Version 1.0 of EnergyPlus planned for release in January 2001.

During the year leading up to the release of Version 1.0, planning will begin for Version 2.0 of EnergyPlus based on new features suggested by users, developers, and the team. Working with a coordinating group of users and developers, features and capabilities for that release will be prioritized and ultimately selected. The current plan is to release updates to EnergyPlus on a regular, 18-month release cycle. Some new features already under development are a connection to the COMIS airflow program, improved ground heat transfer, electrical system simulation, and solar thermal and photovoltaic modules. It is anticipated that as EnergyPlus is released and used in practice interest in the program will continue to grow and the number of researchers involved in the program will expand.

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Figures

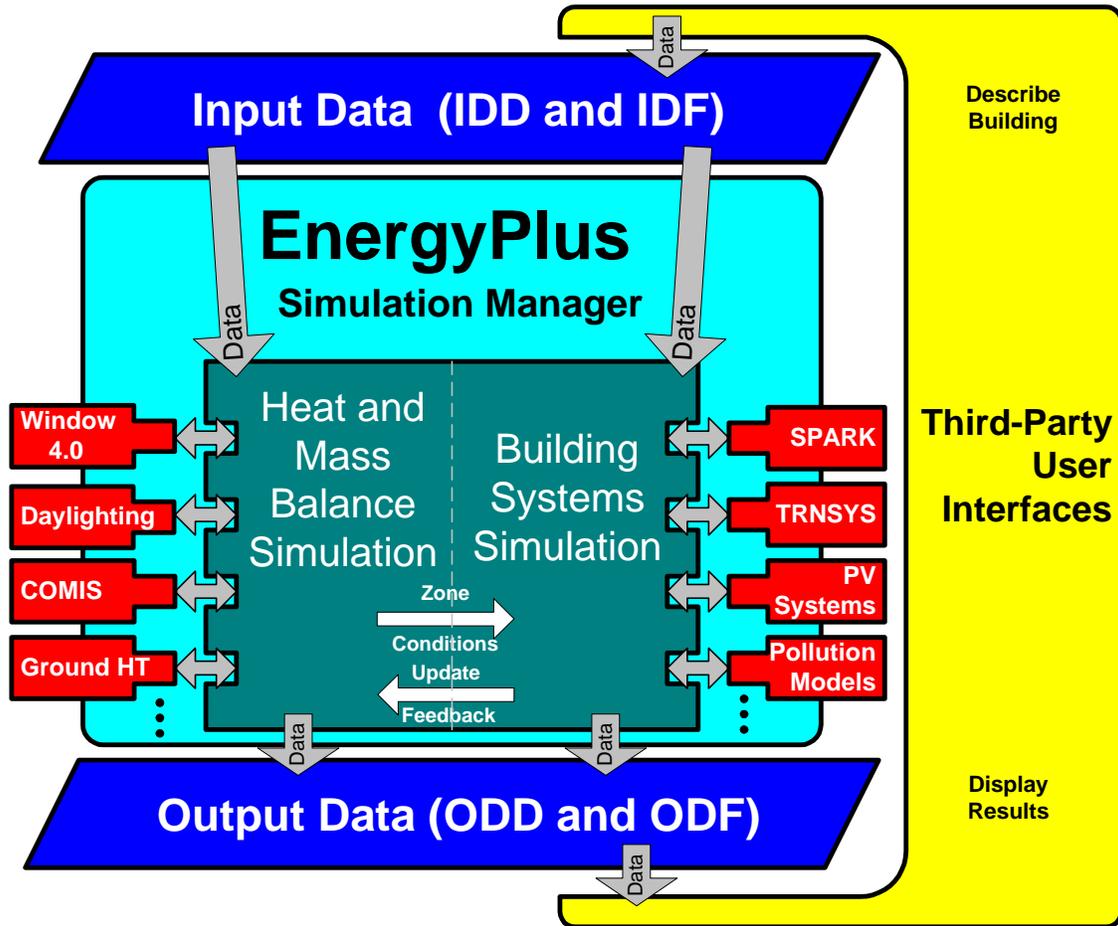


Figure 1 Overall EnergyPlus Structure

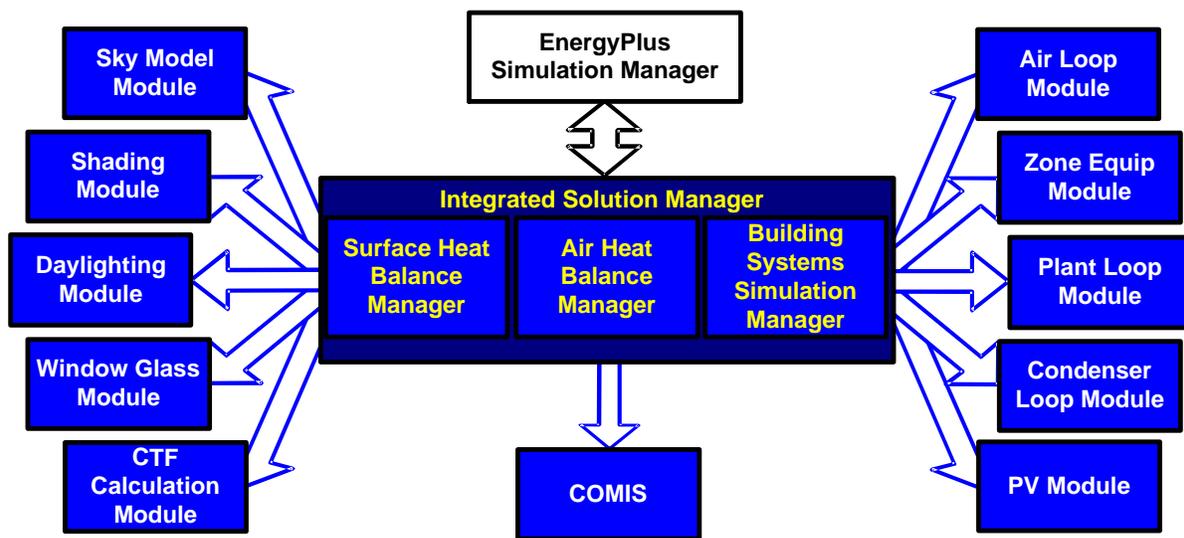


Figure 2 Integrated Simulation Manager

Tables

Table 1 Comparison of General Features and Capabilities

General Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Integrated, Simultaneous Solution <ul style="list-style-type: none"> Integrated loads/systems/plant Iterative solution Tight coupling 	No	No	Yes	Yes
Multiple Time Step Approach <ul style="list-style-type: none"> User-defined time step for interaction between zones and environment (15-minute default) Variable time-step for interactions between zone air mass and HVAC system (≥ 1 minute) 	No	No	Yes	Yes
Input Functions <ul style="list-style-type: none"> Users can modify code without recompiling 	Yes	No	No	Yes
New Reporting Mechanism <ul style="list-style-type: none"> Standard reports User-definable reports with graphics 	No	No	No	Yes

Table 2 Comparisons of Loads Features and Capabilities

Loads Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Heat Balance Calculation <ul style="list-style-type: none"> Simultaneous calculation of radiation and convection processes each time step 	No	Yes	Yes	Yes
Interior Surface Convection <ul style="list-style-type: none"> Dependent on temperature and air flow Internal thermal mass 	No Yes	Yes Yes	Yes Yes	Yes Yes
Moisture Absorption/Desorption <ul style="list-style-type: none"> Combined heat and mass transfer in building envelopes 	No	No	Yes	Yes
Thermal Comfort <ul style="list-style-type: none"> Human comfort model based on activity, inside dry bulb, humidity, and radiation 	No	Yes	Yes	Yes
Anisotropic Sky Model <ul style="list-style-type: none"> Sky radiance depends on sun position for better calculation of diffuse solar on tilted surfaces 	Yes	No	No	Yes
Advanced Fenestration Calculations <ul style="list-style-type: none"> Controllable window blinds Electrochromic glazing 	Yes	No	No	Yes
Glass layer library <ul style="list-style-type: none"> Spectral data for over 200 commercially-available glazing types (conventional, reflective, low-E, spectrally selective, etc.) 	No	No	No	Yes
Daylighting Illumination and Controls <ul style="list-style-type: none"> Interior illuminance from windows and skylights Step, dimming, on/off luminaire controls Glare simulation and control Effects of dimming on heating and cooling 	Yes	No	No	Yes

Table 3 Comparisons of HVAC Features and Capabilities

HVAC Systems and Equipment Feature	DOE-2	BLAST	IBLAST	EnergyPlus
Fluid Loops <ul style="list-style-type: none"> • Connect primary equipment and coils • Hot water loops, chilled water and condenser loops, refrigerant loops 	Yes	No	No	Yes
Air Loops <ul style="list-style-type: none"> • Connect fans, coils, mixing boxes, zones 	No	No	No	Yes
User-configurable HVAC systems	No	No	No	Yes
Hardwired Template HVAC systems	Yes	Yes	Yes	No
High-Temperature Radiant Heating <ul style="list-style-type: none"> • Gas/electric heaters, wall radiators 	No	Yes	No	Yes
Low-Temperature Radiant Heating/Cooling <ul style="list-style-type: none"> • Heated floor/ceiling • Cooled ceiling 	No	No	Yes	Yes
Atmospheric Pollution Calculation <ul style="list-style-type: none"> • CO₂, SO_x, NO_x, CO, particulate matter and hydrocarbon production • On-site and at power plant • Calculate reductions in greenhouse gases 	Yes	Yes	No	Yes
SPARK Connection	No	No	No	Yes
TRNSYS Connection	No	No	No	Yes

Table 4 Comparison of BLAST, DOE-2 (BDL) and EnergyPlus Input

		BLAST	BDL (DOE-2)	EnergyPlus
Location (Simple Input)	Description	Location defined in library. Library includes name, latitude, longitude, elevation, and time zone.	Location information defined by input, defaults to information on weather file	Location information defined by input.
	Input Syntax	LOCATION = Name;	BUILDING-LOCATION Latitude = W, Longitude = X, Altitude = Y, Time-Zone = Z ..	LOCATION, Name, Latitude, Longitude, Elevation, TimeZone;
	Example Input	LOCATION = CHICAGO;	BUILDING-LOCATION LATITUDE = 41.98 LONGITUDE = 87.90 ALTITUDE = 673 TIME-ZONE = 6 ..	LOCATION, Chicago Illinois USA, 41.98, 87.90, 205, -6;
Material (More Complex)	Description	Material defined in library. Library includes material name, conductivity, density, specific heat, resistance, roughness, and moisture properties.	Material from library or defined in input, includes thickness, conductivity, density, specific heat, or resistance. Thickness restated during Layer input (optional).	All material information defined by input.
	Input Syntax	TEMPORARY MATERIAL: Uname = (L=usn1, K=usn2, CP=usn3, D=usn4, ABS=usn5, TABS=usn6, R=usn7, TRANS=usn8, IR=usn9, FILMTRANS=usn10, REF=usn11, SC=usn12, roughness,asg); END;	A = Material, Thickness = W, Conductivity = X, Density = Y, Specific Heat = Z ..	MATERIAL, Name, Thickness, Conductivity, Density, Specific Heat, Roughness, Moisture Permeance, Moisture Resistance;
	Example Input	Brick = (L=0.3333, K=5.6, CP=0.19, D=120, ROUGH);	BRICK = MATERIAL THICKNESS = 0.3333 CONDUCTIVITY = 5.6 DENSITY = 120 SPECIFIC-HEAT = 0.19 ..	MATERIAL, Brick, 0.1016, 0.721, 1922,837,46,0.022;