



## ENERGY SIMULATION



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*Energy simulation is a computer-based analytical process that helps building owners and designers to evaluate the energy performance of a building and make it more energy efficient by making necessary modifications in the design before the building is constructed. Use of energy simulation software is necessary to show compliance with Indian Energy Conservation Building Code (ECBC) via “Whole Building Performance Method.” This Tip Sheet helps in understanding the basic concepts and processes involved in carrying out building energy simulation.*

**I**n the last few years, commercial buildings have emerged as one of the fastest growing sectors in India. This phenomenon, combined with the expectations to create more comfortable indoor environmental conditions, is placing increasing energy demand on the already stretched supply side infrastructure. The energy performance of a building depends on how a building has been designed from an energy efficiency perspective and how well the system integration issues have been addressed. The way a building behaves and performs is governed by envelope design (walls, windows, roofs, etc.), selection of building materials, and design and selection of building systems (lighting, cooling, heating, ventilation, etc.) to meet the thermal and visual comfort of occupants and other functional requirements.

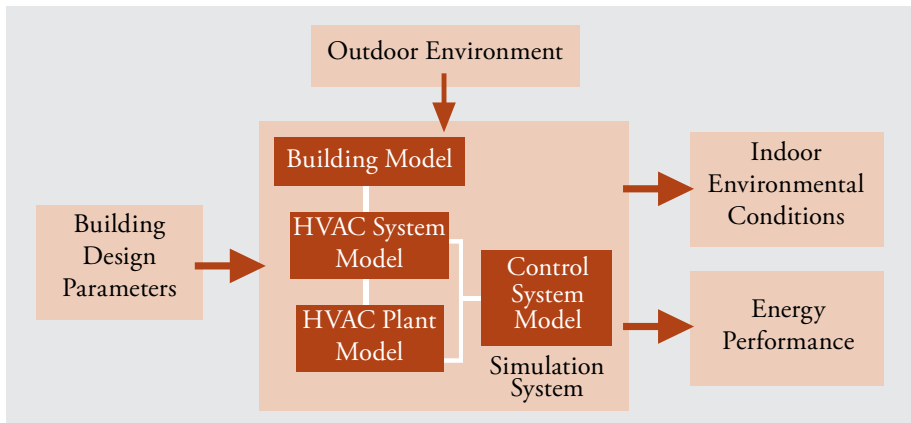
A building interacts with its external as well as internal environment. A good building designer needs to account for the external factors such as air temperature, humidity, solar radiation, wind speed and direction, etc., which may vary significantly throughout the year, and balance it with thermal and visual comfort requirements,

internal heat gains, etc. For example, a designer may decide to have large glazed façade for better aesthetic value and to increase the amount of daylight entering the building. This can lead to reduced lighting load but may increase the cooling load on Heating Ventilation and Air-conditioning (HVAC) system due to higher heat gains through glazing. In real practice, understanding and analyzing the total energy performance of a building is very complex and the building designers find it extremely difficult to establish energy performance with reasonable accuracy through conventional computation methods. Usually “rules of thumb” deployed by consultants and the “expert advice” of equipment suppliers play a major role in selection and sizing of building components and systems. This may not be the most effective way to design large complex commercial buildings and may lead to poor energy performance throughout the life of the building. Just like prevention is better than cure, it is easier and more cost-effective to incorporate energy-efficient issues at the time of new construction than through a retrofit process.

Technological advancements in computer software have provided several tools that can help the designers to predict and analyze the energy performance of a building with good accuracy and with substantial reduction in effort. Such programs allow for sensitivity analysis of various design options and decisions—from the conceptual and schematic phases to the detailed specification of building components and systems (See Fig. 1).

These computer-based energy simulation programs model the thermal, visual, ventilation and other energy-consuming processes taking place within the building to predict its energy performance. A simulation program takes into account the building geometry and orientation, building materials being used, building façade design and characteristics, climatic parameters, indoor environmental conditions, occupant activities and schedules, HVAC and lighting systems and other parameters to analyze and predict the energy performance of a building (See Table 1).

Certain energy simulation programs are designed to work for individual building components such as wall, roof, building



**Fig. 1: Energy Simulation Schematic**

form and fenestration. Some tools are specifically used for modeling one or more parameters such as lighting, heat transfer across building envelope, natural ventilation, and shading elements. Whole building simulation tools are widely used and are applied to the entire building as an integrated system to capture the interactive effects of building components and systems.

Energy performance simulation tools allow designers to:

- Consider the building as a single integrated system
- Predict thermal behavior of buildings in relation to its outdoor environment
- Predict the impact of daylight and artificial light inside the building
- Model the impact of wind pattern and ventilation and assess its effect on energy use
- Estimate the size/capacity of equipment required for thermal and visual comfort
- Calculate the effect of various building components on each other and predict resulting conditions and impact on energy use
- Assess the changes in energy consumption through sensitivity analysis with respect to design changes affecting building geometry and materials, components, systems, etc.

In May 2007, the Ministry of Power launched Energy Conservation Building Code (ECBC) for its adoption on a voluntary basis in buildings with a connected load of 500 kW or greater or a contract demand of 600 kVA or greater. This range was broadened to 100 kW / 120kVA in a recent amendment to the Energy Conservation Act, 2001. In this context, it is important for the building designers to understand and utilize energy simulation programs to satisfy ECBC compliance requirements.

### How a Simulation Program Works

A building's energy requirements change continuously, under different conditions

of weather, occupancy, operation, etc. The sequence of calculations is repeated many times to simulate an annual operation cycle. The results of all the repeated calculations are then compiled to produce the total yearly energy consumption and costs.

For input and calculation purposes, the building is divided into "thermal zones." Each thermal zone has certain load characteristics, and is served by specific types of conditioning, lighting, and other energy-consuming systems. The program does most of its calculations separately for each zone. A zone should have well-defined boundary conditions which may be made up of partitions (e.g., dry wall or air).

All the sophisticated energy simulation programs perform four basic groups of calculations. Different programs link these calculations in various ways. It is important to understand the general flow of calculations as explained below.

**Table 1: Data Required for Energy Modeling**

Category	Purpose	Source
Geographical location (climate)	Accurate load calculation based on external environment	Weather file
Geometry <ul style="list-style-type: none"> <li>• Plan</li> <li>• Section</li> <li>• Elevation</li> </ul>	Model geometrical attributes of buildings and any site specific features (shading, reflection by tree or building)	Architectural drawings
Construction <ul style="list-style-type: none"> <li>• Wall</li> <li>• Roof</li> <li>• Window</li> <li>• Overhangs</li> </ul>	Model building envelope attributes for thermal load and daylighting calculations	<ul style="list-style-type: none"> <li>• ECBC</li> <li>• ISHRAE</li> <li>• CBRI</li> <li>• Software library</li> <li>• Vendors</li> <li>• ASHRAE</li> </ul>
Daylighting and lighting <ul style="list-style-type: none"> <li>• Layout</li> <li>• Technology and controls</li> </ul>	<ul style="list-style-type: none"> <li>• Visual comfort</li> <li>• Reducing LPD</li> <li>• Integration with daylight</li> </ul>	<ul style="list-style-type: none"> <li>• Lighting consultant</li> <li>• Vendors</li> <li>• ISLE/IES</li> </ul>
Internal Load <ul style="list-style-type: none"> <li>• Usage (e.g. number of hours)</li> <li>• Schedule</li> <li>• People, equipment, lighting</li> </ul>	Accurately capture sources of internal heat gain within building	<ul style="list-style-type: none"> <li>• Client</li> <li>• Energy modeler</li> <li>• Benchmarking data</li> <li>• Nameplate data</li> </ul>
HVAC (type and controls) <ul style="list-style-type: none"> <li>• Component specification</li> <li>• Control strategy</li> <li>• Layout and distribution</li> </ul>	<ul style="list-style-type: none"> <li>• Sizing the system</li> <li>• Design optimization</li> <li>• Comfort satisfaction</li> </ul>	<ul style="list-style-type: none"> <li>• HVAC consultant</li> <li>• ASHRAE/ISHRAE</li> <li>• ARI</li> <li>• ECBC</li> </ul>

### 1. Space Loads

The program starts by calculating the end-use energy requirements of the zones. It calculates heating and cooling loads by adding conduction gains and losses, solar gain, heat gained or lost from outside air, humidification or dehumidification, and internal heat gains.

Weather-related data needed for these calculations is usually taken from a weather file (typically an average of 30 years of weather data compiled in a computer readable format). Solar gains are calculated, based on the interaction between building envelop and environmental factors. The program requires manual input of physical characteristics of the structure, as well as of non-weather related loads, such as lighting, electrical equipment (computers, etc.), occupants, desired temperature and humidity, service water heating, specialized process loads, etc. Typically, the user inputs the peak load of each type, along with an hourly schedule of the percentages of peak load.

Most energy analysis programs provide the option of performing these load calculations alone, without the need to perform the calculations described next. For example, in designing a new building, the space load calculations allow the designer to refine the building exterior to reduce solar heat gain, or to find the most economical amount of wall insulation.

### 2. System Loads

This includes the space loads, calculated previously, plus the extra energy needed

to run the conditioning equipment, or “systems.” In typical systems, most of this extra energy is used by fans. The “systems” include air handling systems, fan-coil units, air conditioners, radiators, etc., but usually not the central plant equipment.

This part of the program requires manual input to describe the efficiency

characteristics of the equipment. The equipment operating schedules may also be entered manually, to account for usage during occupancy hours. In some cases, the system’s characteristics can be selected from the program’s equipment data library.

For each system, the program highlights the maximum energy consumption that

occurs during the yearly cycle. The designer uses these maximum loads to determine the size of the conditioning equipment.

### 3. Central Plant Loads

For detailed calculations, the program compiles all loads on a zone-by-zone basis. Next, the program adds all the

## Key Technical Terms

**Construction and Layers:** For building simulation, each type of building section is termed as one construction. For example, a single brick wall with plaster and without plaster are two different types of constructions. Each construction, similar to the architectural drawing representation, is a built-up section using different materials, termed as “layers” in simulation. Therefore, when describing a construction, layers must be specified in their order of appearance (always from outside to inside in most of the simulation programs). The sequence of layers has a significant impact on the heat and moisture transfer across that section.

**Equipment Sizing:** Besides calculating the heat load, simulation programs are also equipped with the capability to calculate the size of HVAC equipment. To do this, they need basic information such as equipment efficiency. Standard sizes which are available can also be supplied by the user and the software will calculate the number of such systems required for the building. An energy simulation program’s ability to distinguish, and use to advantage, the concept of “coincident” versus “non-coincident” peak load calculations can lead to more accurate plant sizing.

**Hourly Simulation:** Energy use is simulated in a building for every hour of the year. For this purpose, hourly weather data is required and the simulation engine has to be capable of handling heating/cooling load calculations on an hourly basis, and account for the effect of heat storage in thermal mass. It may be noted that simplified simulation programs generate approximate hourly simulation results only, which are sometimes considerably off from the more detailed hourly results generated by other programs.

**Input File:** It contains the description of the building in a form that can be understood by the simulation program. This contains

building geometry, construction details (walls, roof, windows etc.), building usage schedule, and information about HVAC and lighting systems. This file acts as the interface between the weather file, the simulation engine, and the output file manager of simulation program. Most simulation programs can make use of common formats of 2-D drawing files e.g. “dxf” files, by using them as background images for quicker creation of building geometry.

**Output File:** A simulation run may generate more than one output files. Two of the most important files are the main output file that contains hourly results and the error file that carries information about possible errors, including warnings. In some cases, there is no fatal error that will stop the program from running but warnings will highlight probable logical mistakes.

**Parametric/Sensitivity Analysis:** The process of optimizing the energy performance of a building by running different scenarios for efficient building system and construction types.

**Schedule:** It specifies the hourly usage pattern of any zone or its equipment. Separate schedules can be specified for different types of days, such as an occupancy schedule set up for 0800hrs to 1700 hrs on weekdays, 0900 hrs to 1300 hrs on Saturdays, and no usage on Sundays and public holidays. Different zones may have different schedules and within each zone, different equipment, lighting, plug loads may have different schedules. However, to keep the task simple, it is recommended to group zones having similar loads and schedules.

**Simulation Engine:** The simulation engine is the heart of any simulation program. These engines are based upon different algorithms for calculating the energy consumption in the modeled building. The engine works in

coordination with the weather file and the input file to produce desired outputs. As a rule of thumb, if the engine is capable of using hourly equations, the modeler should try to create a building model with significant detail. In situations with simplified engines, where calculations are approximated, spending time and efforts on providing minor details is not needed. Such engines are useful only for a broad comparison of major energy conservation options and should not be used for generating energy performance numbers.

**Thermal Zone:** It is a term used in energy simulation to represent a space (volume) within the building, catered to by one air conditioning unit. With the help of “zoning” building plans are simplified to reduce the modeler’s work. Normally, within one thermal zone usage pattern, set point temperature and other conditions are identical. Building spaces that would experience similar heating and cooling loads are generally grouped under one zone.

**Visualization:** Some simulation programs have in-built capability to create 2-D and 3-D models of a building based on the description provided. Others, such as Energy Plus, require descriptions of building geometry in the form of coordinates. These programs also offer the ability to visualize the building by coupling with a drafting software. Separate add-on type programs are available to facilitate easy creation and visualization of building geometry using a visual interface.

**Weather File:** This file contains hourly information about weather at the location under consideration. Different simulation programs use weather files in different formats but consist of nearly the same data such as solar radiation, temperature, humidity, wind speed, wind direction, rainfall, atmospheric pressure, cloud cover, etc.

zone loads as total load on the central plant equipment, which includes boilers, chillers, electric generators, cogeneration plants, thermal storage systems, solar collectors, etc. The program further adds the energy consumption of central plant auxiliary equipment, such as hydronic system pumps and cooling tower fans.

For this part of the calculation, the program requires manual input to describe the plant equipment and its operating schedules. In some cases, plant equipment characteristics can be selected from the program's equipment data library.

This part of the program yields the "bottom line" energy input to the facility as a whole. This includes energy that is used directly, such as electricity consumption for lighting and plug loads.

#### 4. Economic Calculations

All the programs can provide energy consumption information, and some can provide energy cost estimates as well. To do this, the program requires manual input of energy costs and rate schedules.

There are programs that can also calculate the life-cycle costs of alternatives. This requires manual input of equipment and construction costs, at least for the features or equipment being compared. Some programs can incorporate desired rate of return, discount factor, and other economic variables in the calculation.

#### Manual Load Calculations vs. Computer Energy Analysis

A manual load calculation is used primarily to select equipment size based on maximum-load conditions. It uses the space loads, as discussed above, and it is done only for the single instance of peak load conditions.

For example, when selecting an air conditioning system for a building, a consultant makes a load calculation to estimate the peak cooling requirement. This is done by calculating the individual load components, and then adding them. For cooling, the load components are solar gain, conduction gain through the walls

and roof, heat gained by air leakage, and dehumidification. Heat generated from lighting system, people and equipment in the building, together referred as "internal heat load", also contributes significantly to buildings loads.

Basic peak-load calculations are simple. They can be done manually and they are adequate for many applications. However, manual calculations are not always accurate. One cause of error is that the components of load do not all peak at the same time. Another limitation is inability to deal with thermal storage effects. The degree of detail is limited, e.g. it is not practical to include the precise orientation of the surfaces in a manual calculation.

A number of computerized load calculation programs are now available. They provide greater accuracy, eliminate the drudgery of arithmetic and provide a checklist to make sure that all load components are included. There is a range of complexity among computerized programs. Some are relatively simple. The most detailed load calculations are provided by using the space loads portion of an energy analysis program, as discussed previously.

In general, the capacity of heating and cooling equipment may be much greater than the peak conditioning load caused by weather conditions. Heating and cooling equipment is usually sized to provide a reasonably short warm-up or cool-down interval after starting. For this reason, many designers and contractors do not use load calculations and instead they select equipment capacity using simple rules of thumb, based on the size and mass of the building. To promote energy efficient designs, "rules of thumb" should be discouraged.

#### Simulation Program Outputs

All the major programs offer the following outputs:

- **The input data:** The report usually repeats the input data for ease of review. This includes data drawn from the

program's data libraries. For example, the output may indicate the indoor air temperature and humidity that were calculated for each hour based on weather file as well as the thermal and optical properties of the glazing used in the building.

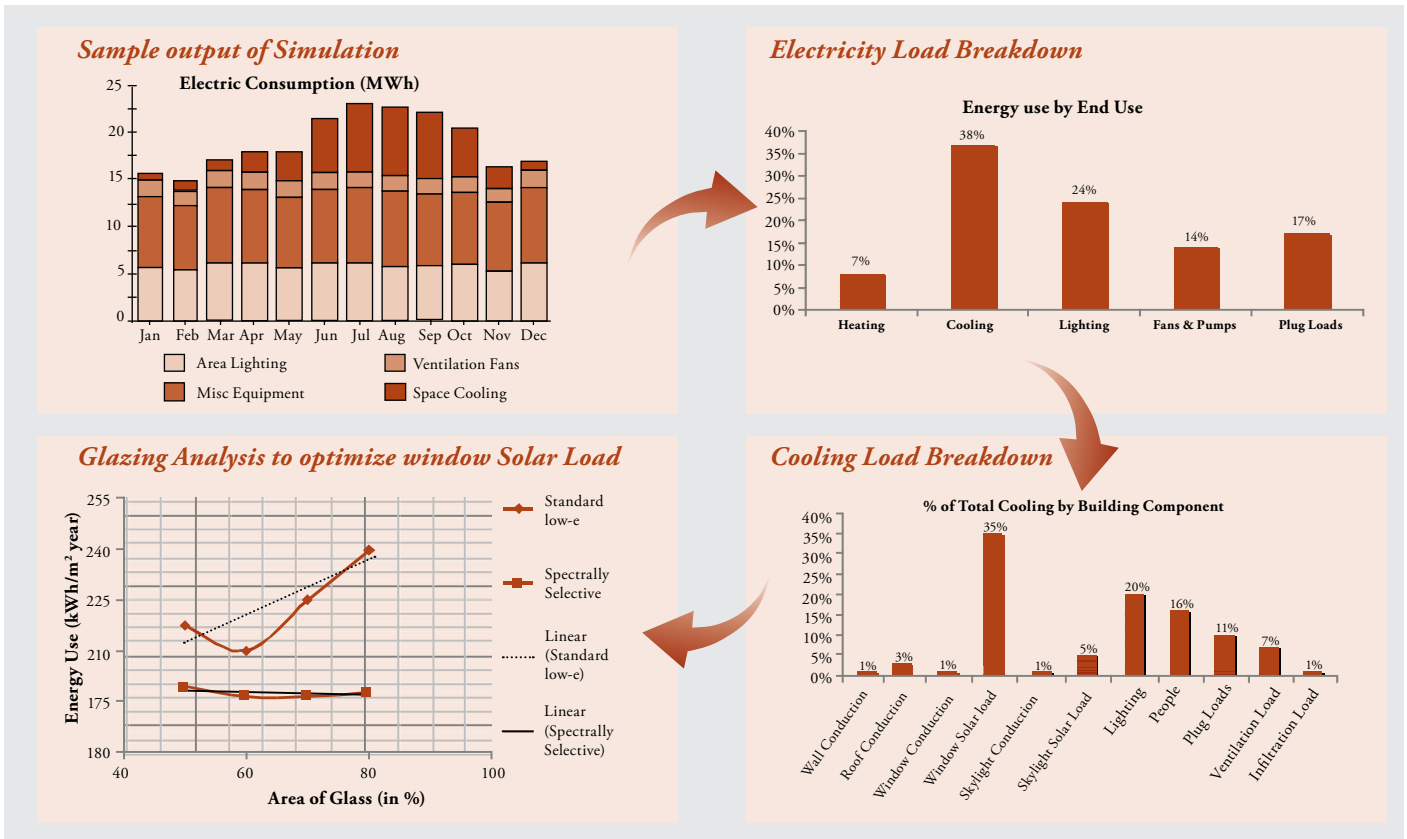
- **Building loads:** Loads are divided into heating, cooling, lighting, process, etc. Some programs may report the components of these loads. For example, cooling load may be divided into solar, conduction latent and internal heat loads. The loads for individual hours may be displayed. Most programs report the time of occurrence of each peak load.
- **Equipment sizing data:** Normally, equipment capacities are selected by using the calculations of peak equipment load. For example, the program may report peak air flow of air handling units, peak steam flow from boilers, peak energy input to individual chillers, etc.
- **Energy consumption:** The output can be represented in many ways that include types of load, by different intervals i.e. hourly, monthly and yearly and also by system types i.e., chiller plant, AHU, etc. Table 2 shows typical electric consumption output and its load breakdown in several steps in Figure 2.
- **Energy costs:** These are derived directly from the consumption calculation, making corrections for variations in price at different times. The costs can be reported separately by fuel type, e.g., electricity, fuel oil, natural gas, etc.
- **Life-cycle cost:** This is the total cost for energy over a facility's life cycle, or other longer period of time. This output includes the effects of changes in fuel price, inflation, and interest rates.

All the major simulation programs allow the designer to specify the type

**Table 2: Electric Consumption (MWh) in a typical facility**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
<b>Area Lights</b>	5.53	5.24	6.05	6.04	5.53	6.04	6.05	5.79	5.78	5.79	5.26	6.05	69.16
<b>Misc. Equipment</b>	7.58	7.04	7.99	7.87	7.58	7.87	7.99	7.79	7.67	7.79	7.27	7.99	92.43
<b>Ventilation Fans</b>	1.61	1.53	1.77	1.77	1.61	1.77	1.77	1.69	1.69	1.69	1.53	1.77	20.17
<b>Space Cooling</b>	0.62	0.96	1.16	2.22	3.13	5.72	7.23	7.37	6.96	5.10	2.32	0.86	43.66
<b>Total</b>	15.34	14.77	16.97	17.9	17.85	21.4	23.04	22.64	22.22	20.37	15.38	16.67	225.42





**Fig. 2: Simulation Output and its Load Breakdown**

of output information needed, and the degree of detail. The loads can usually be displayed by individual zones. Similarly, the characteristics of each system can be displayed separately. All the major programs can report in a variety of tabular and graphical formats.

### Technical Tips for Energy Simulation

#### How to Use the Program

An energy simulation program is used in the same way whether one is designing a new facility or making improvements to an existing facility. In both cases, the first step is to input the characteristics of a “baseline” facility configuration. In retrofits, the baseline is the existing facility. The baseline input is an important part of energy simulation exercise (See Table 3). Once this investment of effort is made, one can easily modify the inputs and re-run the program to simulate the effect of the modifications.

To optimize the design, one can change the input characteristics of individual components or systems (windows, chillers, lights, etc.), and repeat the computer run to see the effect on overall energy consumption and cost. For example, analyzing the retrofit of a single system typically requires a few computer runs. Designing a big, complex facility may require hundreds of runs to achieve high efficiency.

Input is the main difficulty in using energy simulation programs. For the program to calculate loads and energy consumption with a useful degree of accuracy, one needs to “describe” the facility and its systems in sufficient detail. This is a critical and important part of the process and requires experience, subject matter expertise, and computer skill to model the building accurately.

For example, one needs to specify the insulation value of each type of wall, window, roof element, and floor element; an occupancy schedule for each day type; a usage schedule for each type of light fixture; information about each type of heating and air conditioning unit; temperature reset schedules; times when fuel types are changed, etc.

**Table 3: Integration of energy simulation steps with architectural design stages**

Stage	Architecture Design	Energy Simulation Integration
<b>Concept Design/ Programming</b>	Climate, desired indoor conditions for comfort	Weather data
	Orientation, shape and site conditions	Sun path diagram, Solar analysis
	Building massing	Mutual shading analysis
<b>Simple model geometry rule of thumb calculations, % opening (WWR)</b>	Building operation schedule, ventilation rates	Proper zoning
	Basic equipment options, peak load calculations, schematic system design	Monthly/annual simulation
<b>Schematic Design/ Design Development</b>	Geometry: Walls (façades)/openings/projections/volumes/design elements	Sensitivity analysis: Zoning the building by system types with surface information, integration of loads, advanced fenestration calculations, full interior and exterior solar distribution
	Services: Types and placement of systems (structure design, HVAC design/selection, electrical/ lighting, plumbing)	
	Programming schedule: Activity type/ occupancy levels, controls	Hourly simulation
<b>Construction</b>	Tender drawings, system specifications, material selection, working drawings	Energy Conservation Measures (ECMs) and payback

Each zone requires its own input. A small building usually has at least five zones. A large complex building typically has many zones. The more sophisticated programs allow copying input from one zone to another similar zone. For example, a building may have zones that are identical, except for the fact that they are oriented in different directions.

Input requires a great deal of poring over drawings. When simulating existing facilities, it also requires a lot of legwork to inspect actual conditions. In existing facilities, the designer may need to measure some energy loads that are difficult to estimate, such as hot water consumption. To calculate energy cost, the designer needs to input energy prices of different fuels being used by the building.

The temptation is great to “assume” the input data if it is not readily available. The person who inputs the building information needs an intimate knowledge of the facility, so it is generally not advisable to get the analysis performed by a remote service bureau. For retrofit projects, input should be based on data collected on site. In case of new facilities, the designer should do the analysis (or at least review the major assumptions and input parameters).

- **Input data libraries:** An important advantage of energy analysis programs is that they include libraries of input data. Most importantly, they include libraries of weather data for many locations, including all major cities of the world. The weather data is compiled from hourly observations, allowing a high level of detail in calculation. The weather data for almost any location can be simulated by using data from some other suitable location that is available in the weather library.

Some programs have libraries of wall and roof components along with their physical properties which eliminates the tedium of defining a wall or roof from scratch. There are major differences in the structural component data libraries of different programs. The programs also differ in their ability to accurately simulate the thermal characteristics of structures that the user defines as raw components. However, the capabilities of most programs are good enough for typical applications.

- **Sensitivity analysis:** It involves changing a single input over a range of possible values to determine the effect of the variation on the overall output. (This is sometimes called “what-if” analysis.)

One should also use sensitivity analysis to optimize equipment characteristics. For example, it is difficult to size the tank capacity in a heat recovery storage system because it is difficult to predict the amount of recovered heat that may be usable. To analyze such a system, repeat the simulation for a range of tank sizes, as well as for a reasonable variety of heat recovery and heat usage profiles.

Sensitivity analysis tends to be neglected, resulting in projects that fail because actual conditions differ from those expected. It is important to conduct sensitivity analysis for each input which has some degree of uncertainty and which is likely to have a significant effect on performance. Sensitivity analysis increases the number of computer runs, but helps in optimizing design. Some programs can do this automatically.

### How Accurate are Computer Simulations?

- **Range of simulation capabilities:**

An energy analysis program cannot precisely simulate the wide variety of building shapes, equipment, controls, and conditions that exist. The simulation capabilities of energy analysis programs are being expanded continually, but they always lag behind the latest developments in building technology. For example, the major programs only gradually acquired the ability to simulate window shading features, tilted glazing, variable air volume (VAV) systems, temperature reset controls, variable-flow pumping, thermal storage, etc. If the user is an innovator, he/she will not find a program that easily simulates all the configurations that he/she wants to investigate.

Energy analysis programs differ in their strengths and weaknesses. For example, one program may be able to simulate a large range of equipment types, while another provides the most accurate description of thermal characteristics of a wall, and yet another provides the best simulation of complex glazing configurations. It should be ensured that the program chosen is able to simulate the engineering and architectural features that are important for the project.

- **Accuracy of component simulation:**

The user must input the efficiency (input-output) characteristics of each component that uses energy, including part-load performance. This can be done by specifying percentages of maximum output for various percentages of energy

input. The designer may have to call the manufacturer’s engineering department to get part-load information for the equipment that is being simulated. Some energy analysis programs can assist designers with libraries of efficiency curves for different types of mechanical equipment, such as fans, pumps, chillers, and boilers. However, it is a mistake to rely on generic efficiency curves for major items of equipment, because there are major differences among models. For example, different models of centrifugal chillers differ widely in their part-load behavior and in their minimum loads, which are important factors in their overall energy consumption. Programs developed by equipment manufacturers may have accurate performance data for their own specific models of equipment, but not for the equipment of other manufacturers.

The designer may have to manually calculate the efficiency curve for a complex combination, such as a pump driven by a variable-speed drive. In this example, the program may not be able to account for the efficiencies of both the pump and the drive at each percentage of load.

- **Number of calculation intervals:**

There would be no need for computer energy analysis if the energy loads were constant, or if the loads changed in regular, repeating patterns. In HVAC applications, changing weather conditions make it necessary to use a computer to achieve accurate estimates.

The computer achieves accuracy by repeating the entire sequence of calculations for many short time periods. Some energy analysis programs calculate for each hour of the year, assuming a constant load during each hour. This method repeats each calculation 8,760 times, the number of hours per year. This degree of refinement requires relatively long computing times. The newest personal computers may be able to run such simulation in less than one hour per run, and perhaps much less.

- **Number of zones:**

All energy simulation programs are designed to divide the building into zones. They do this as an easy way of dealing with differences in load characteristics. The program user defines the number of zones, and the way the building is divided into zones. This is a major decision that the user has to make at the beginning of input process. A model with larger number of zones provides greater accuracy, but

requires more input work. The computer program calculates energy requirements of each zone separately, so more zones means longer computing time.

It is conventional to create separate zones for each exterior orientation of the building, along with separate interior zones. For example, the user may divide a simple, single-story building into five zones: north, south, east, west, and interior. All five zones in this example differ in envelope heat gains/losses, daylighting, and they may differ in internal heat gains. User typically defines major space volumes with distinct load characteristics as separate zones. Examples of such spaces are office rooms, computer rooms, large conference rooms, and atria.

- **Equipment defects and unpredictable behavior:** The program's simulation results may differ substantially from real performance because components are not ideal. For example, some energy analysis programs calculate theoretical thermal characteristics of walls in excruciating detail. Real wall construction includes sloppy insulation, thermal short circuits through studs, air infiltration, and other factors that substantially degrade thermal performance. Sophisticated program users try to compensate for such predictable flaws by adjusting the input, but it is not possible to predict the performance of brick-layers and carpenters with a great deal of accuracy.
- **Program errors:** There are only a few energy analysis programs in existence that have proven to be reasonably reliable, and all have limitations and flaws. These programs have bugs for the same reasons that all large computer programs have bugs. A common bug in energy analysis programs is failure of the program to accurately simulate the way equipment behaves.

This is a continuing problem. Few people have a good understanding of energy behavior of systems, not many of them write energy analysis programs, and those who do may not remain involved with the program to upgrade and debug it.
- **Input errors and misunderstandings:** The computer cannot read the designer's mind to determine what the designer really means, and it will not fix the designer's input errors. The computer is completely literal in reading the input. Typically, analysis requires hundreds or thousands of input numbers. An error in

any single number will cause an error in the output. Therefore, all inputs need to be meticulous. Some programs can flag input data that falls outside a normal range. This is helpful in catching gross input errors, but errors can still slip through this screen.

### How to Catch Errors

The first computer run usually contains mistakes. Serious mistakes keep the program from running, while subtle mistakes produce wrong answers that may look right. It is, therefore, critical to anticipate the problems discussed previously, debug before running and verify the validity of the results, using the following methods:

- **Read the output in detail:** The first step is to study all the summary reports. Examine them in detail to see if they make sense. If the summary reports appear credible, study the entire output. Track through the calculations to see if the trends make sense. Expect to spend hours checking the output for a building of average complexity.
- **Check reasonableness of capacity calculations:** A difficult to understand result may be caused by an input error. The user may not understand the output correctly or there may be a difference between the user's assumptions and the computer's assumptions. The user may find that the program is not calculating what he thinks it is calculating. For example, the computer may model the behavior of a system differently from the way the user intends the system to work. Only a pencil check can reveal such misunderstandings.
- **Use sensitivity analysis:** When running a sensitivity analysis, see whether the changes in output make sense.

Compare to measured energy consumption: In retrofit applications, check the program's baseline calculation (i.e., the existing configuration) against actual consumption. Use past utilities bills and measurements to determine actual consumption. In new construction the exercise is called Calibrated Energy Simulation where module outputs are compared against actual data (and input tweaked) of building in operation.

### How to Select a Simulation Program

When selecting an energy simulation program, consider both the features of

the program and the support that will be available for it. In summary, look for:

- **Simulation capabilities:** The program should be able to make accurate distinctions between various options the user is considering. Accuracy is less important for features of the user's project that are common to all the options. For example, if the user is doing a sophisticated envelope design to minimize solar cooling loads, he/she needs a program that can accurately calculate complex glazing and shading configurations. On the other hand, the user may not need an elaborate calculation of wall thermal characteristics. All the major energy analysis programs can simulate common building features and systems. The programs differ widely in their ability to simulate unusual features, such as complex envelope shapes, cogeneration, solar energy, thermal storage, and sophisticated control systems.
- **Library data:** Consider the types of weather data, equipment data, envelope component data, and other library data that are offered with the program. Consider whether they contain sufficient detail and specificity to distinguish between alternative designs that the user is considering.
- **Output options:** All programs offer the same general types of output, but some offer considerably more detail than others. Some output formats are more user-friendly.
- **Ease of input:** Some programs require the user to write elaborate input text. Other programs have a simple, orderly fill-in-the-blanks format. The easiest to use will have a graphical user interface to further simplify the process and provide help and tips along the way.
- **Technical support:** A user will likely have trouble, no matter which program he/she chooses. This makes it important to acquire the program from a vendor who provides competent technical support on short notice. Energy analysis programs developed by private companies usually include technical support as part of the purchase price. Check with other customers about the quality and availability of the support provided. Government-sponsored programs are not copyrighted, so there is no single party

with an ownership interest in supporting them. For these programs, there may be several private parties that offer program interfaces for personal computers, which simplifies program learning and helps with the modeling exercises. The quality of support from such vendors can be poor or spotty, because the interface vendor may not have a good understanding of the main program or of the building systems the user wants to simulate. However, user groups can be a very valuable resource in getting responses to queries and enhancing understanding of the program.

## Minimum Modeling Capabilities

These have been broadly defined to allow all capable programs to be considered for approval by the adopting authority, while eliminating programs that would not be able to adequately account for the energy performance of building features under the ECBC.

- **Minimum hours per year:** Programs must be able to model energy flows on an hourly basis for at least 1,400 hours per year. Many programs model for the full 8,760 hours in a year; others use representative days for the different months and seasons.
- **Hourly variations:** Building loads and system operations vary hour-by-hour, and their interactions have a large influence on building energy performance. Approved programs must have the capability to model hourly variations, and to establish separately designed schedules of operation for each day of the week and for holidays, for occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation.
- **Thermal mass effects:** A building's ability to absorb and hold heat varies according to type of construction and system and ventilation characteristics. This affects the timing and magnitude of loads handled by the HVAC system. Simulation programs must be able to model these thermal mass effects.
- **Number of thermal zones:** There are multiple thermal zones in all buildings, and they experience different load characteristics. Approved programs must be able to model at least 10 thermal zones; many simulation programs can handle a far greater number of zones.

- **Part-load performance:** A building's mechanical system rarely experiences full-load operating conditions, so understanding the performance of equipment under part-load conditions is important. Approved programs must incorporate part-load performance curves in their calculations.

- **Design load calculations:** Approved programs must be capable of performing design load calculations to determine required HVAC equipment capacities as per ECBC norms.

The Standard Method of Test can be used for identifying and diagnosing predictive differences from whole building energy simulation software that may possibly be caused by algorithmic differences, modeling limitations, input differences, or coding errors. An overall validation methodology, according to ANSI/ASHRAE Standard 140-2004, consists of three parts:

- Comparative Testing - in which a program is compared to itself or to other programs
- Analytical Verification - in which the output from a program, subroutine, algorithm, or software object is compared to the result from a known analytical or quasi-analytical solution for isolated heat transfer mechanisms under very simple and highly constrained boundary conditions
- Empirical Validation - in which calculated results from a program, subroutine, algorithm, or software object are compared to monitored data from a real building, test cell, or laboratory experiment.

- **Modeling of Glazing:** The ability of the programs to model glazing correctly with angular dependence (refer Window 5 and NFRC IDGB glazing database used by EnergyPlus, eQUEST and DOE2.1E)

## Role of Energy Simulation in ECBC Compliance

The "Whole Building Performance Method" of ECBC gives the requirements for standard design and proposed building energy simulation models. The purpose is to estimate annual energy consumption of the proposed building and to compare it with the energy consumption of the standard design, then to demonstrate that the proposed building consumes energy equal to or less than that of standard

design. The procedure that can be adapted is as follows:

- Based on the designs and specifications given by the client, a model is prepared in a simulation program and annual energy consumption is estimated. This is the "Proposed Building" model.
- A "Standard Design" model is then created and used as a base case; this is based on the requirements given for the standard design as described in Appendix B of ECBC. The annual energy consumption of the standard design model is compared with that of the proposed building model.
- If the proposed building model consumes less energy than, or the same amount as, the standard design model and it meets all the mandatory requirements of the code, then it is compliant with the code. If it consumes more energy than the standard design, then various energy conservation measures can be applied to evaluate their energy savings potential and a group of such measures, based on their life cycle costs, can be combined to reduce annual energy consumption in the building so that it is equal (or less than) that of the standard design. This leads to an improved version of the proposed design model. To develop a model for standard design and proposed building, refer to Table 4. Some points to be considered are:
  1. The building geometry (except fenestration), schedules and plug-loads are the same in both the models.
  2. Both the models must meet the mandatory provisions of ECBC.
  3. Thermal properties, LPD and HVAC specifications are set as per the Table 10.1 of ECBC.
  4. Benefits of shading, higher efficiency in lighting, HVAC and material properties can be taken in the proposed building model.

Once the proposed building model and the standard design model are simulated, they are compared to show the final annual energy consumption and the electricity used by various components such as lighting, space heating, space cooling, pumps, equipment, etc. The proposed building should demonstrate better performance than the standard design.

## Proposed Building Model - Special cases

All the building features, including building size and shape, building



envelope components and assemblies, lighting, water heating, and mechanical system equipment and controls, must be accounted for.

**Specifying Lighting Levels**

A key task in modeling the proposed design is assigning space use classification to different areas of the building. These classifications are used to assign lighting

power budget assumptions and to differentiate areas within the building that may have different operating schedules and characteristics (thermostat settings, ventilation rates, etc.).

**Table 4: Modeling requirements for ECBC (Source: Energy Conservation Building Code, Revised Version May 2008)**

Case	Proposed Building	Standard Design
<b>Building Envelope</b>	<p>All components of the building envelope in the proposed design shall be modeled as shown on architectural drawings or as installed for existing building envelopes.</p> <p>Exceptions: The following building elements are permitted to differ from architectural drawings.</p> <ul style="list-style-type: none"> <li>Any envelope assembly that covers less than 5% of the total area of that assembly type (e.g., exterior walls) need not be separately described. If not separately described, the area of an envelope assembly must be added to the area of the adjacent assembly of that same type.</li> <li>Exterior surfaces whose azimuth orientation and tilt differ by no more than 45 degrees and are otherwise the same may be described as either a single surface or by using multipliers.</li> <li>For exterior roofs other than roofs with ventilated attics, the reflectance and emittance of the roof surface shall be modeled. The reflectance and emittance shall be tested in accordance with § 4.3.1.1.</li> <li>Manually operated fenestration shading devices such as blinds or shades shall not be modeled. Permanent shading devices such as fins, overhangs, and lightshelves shall be modeled.</li> </ul>	<p>The standard design shall have identical conditioned floor area and identical exterior dimensions and orientations as the proposed design, except as noted in (a), (b), (c), and (d) below.</p> <p>a) Orientation: The baseline building performance shall be generated by simulating the building with its actual orientation and again after rotating the entire building 90, 180, and 270 degrees, then averaging the results. The building shall be modeled so that it does not shade itself.</p> <p>b) Opaque assemblies such as roof, floors, doors, and walls shall be modeled as having the same heat capacity as the proposed design but with the minimum U-factor required in § 4.3.1 and § 4.3.2.</p> <p>c) Fenestration: Fenestration areas shall equal that in the proposed design or 40% of gross above grade wall area, whichever is smaller, and shall be distributed uniformly in horizontal bands across the four orientations. No shading projections are to be modeled; fenestration shall be assumed to be flush with the exterior wall or roof. Manually operated fenestration shading devices such as blinds or shades shall not be modeled. Fenestration U-factor shall be the minimum required for the climate, and the solar heat gain coefficient shall be the maximum allowed for the climate and orientation.</p> <p>d) Roof albedo: All roof surfaces shall be modeled with a reflectivity of 0.30.</p>
<b>Lighting</b>	<p>Lighting power in the proposed design shall be determined as follows:</p> <ul style="list-style-type: none"> <li>Where a complete lighting system exists, the actual lighting power shall be used in the model.</li> <li>Where a lighting system has been designed, lighting power shall be determined in accordance with either § 7.3.2 or § 7.3.3.</li> <li>Where no lighting exists or is specified, lighting power shall be determined in accordance with the § 7.3.2 for the appropriate building type.</li> <li>Lighting system power shall include all lighting system components shown or provided for on plans (including lamps, ballasts, task fixtures, and furniture-mounted fixtures).</li> </ul>	<p>Lighting power in the standard design shall be determined using the same categorization procedure (building area or space function) and categories as the proposed design with lighting power set equal to the maximum allowed for the corresponding method and category in either § 7.3.2 or § 7.3.3. Power for fixtures not included in the lighting power density calculation shall be modeled identically in the proposed design and standard design. Lighting controls shall be the minimum required.</p>
<b>HVAC Systems</b>	<p>The HVAC system type and all related performance parameters in the proposed design, such as equipment capacities and efficiencies, shall be determined as follows:</p> <ul style="list-style-type: none"> <li>Where a complete HVAC system exists, the model shall reflect the actual system type using actual component capacities and efficiencies.</li> <li>Where an HVAC system has been designed, the HVAC model shall be consistent with design documents. Mechanical equipment efficiencies shall be adjusted from actual design conditions to the standard rating conditions specified in § 5, if required by the simulation model.</li> <li>Where no heating system exists or no heating system has been specified, the heating system shall be modeled as electric resistance. The system characteristics shall be identical to the system modeled in the standard design.</li> <li>Where no cooling system exists or no cooling system has been specified, the cooling system shall be modeled as an air-cooled single-zone system, one unit per thermal block. The system characteristics shall be identical to the system modeled in the standard design.</li> </ul>	<p>The HVAC system type and related performance parameters for the standard design shall be determined from Table § 10.2. Equipment performance shall meet the requirements of § 5.</p>

The choice of space use classifications is taken from one of the two interior lighting power tables in ECBC: either Table 7.1 (the Building Area method) or Table 7.2 (the Space Function method).

### Modeling HVAC system

The basic rule for modeling an HVAC system is to base the model as completely as possible on actual system design. This includes the system type, equipment capacities and efficiencies, controls, and other ancillary features (such as economizers). The equipment efficiencies may need to be adjusted to meet the needs of the simulation program. Some special cases related to HVAC systems need to be considered:

- **Complete existing HVAC system:** An example might be an existing speculative building that is being built for a tenant.

The subject of the building permit is primarily the interior construction and lighting system and does not include the HVAC system because it had already been built and permitted. In a case like this, the design and budget energy cost models are based on the existing HVAC system. It would also include the existing building envelope, plus the new lighting system and any other new energy features.

- **No existing heating system:** If no heating system exists, a default heating system must be assumed and modeled. It should be a simple, fossil-fueled heating system with sufficient capacity to meet the design heating loads for the building.
- **No existing cooling system:** If no cooling system exists, a default cooling system must be assumed and modeled. It should

consist of one air-cooled single-zone system for each thermal block (a thermal block is a collection of one or more HVAC zones grouped together for simulation purposes and need not be contiguous).

### Building envelope

The basic rule for modeling the building envelope in the design energy calculations is to use the design shown on the final architectural drawings, including building shape, dimensions, surface orientations, opaque construction assemblies, glazing assemblies, etc.

Any simulation program necessarily relies on a somewhat simplified description of the building envelope. It is usually too time-consuming and difficult to explicitly detail every minor variation in the envelope design, and if good engineering judgment is applied, these simplifications won't result in a significant decline in accuracy.

## Simulation Programs

### Types of Programs

- Simplified programs for overall energy consumption assessment, peak temperature prediction, heating/cooling loads calculations
- Sophisticated programs for hourly simulation of heat, light and air movement
- Complex specialist packages for day lighting and artificial lighting, computational fluid dynamics (CFD) for ventilation & air movement study, two-and three-dimensional heat conduction calculations, and moisture migration within the building components

### Available Software Programs

The majority of the programs that are available, focus on a single aspect (such as HVAC, fenestrations, or lighting) of energy efficiency. A limited number of programs handle multiple aspects of a building design through an integrated approach. The popular programs among the architects and building designers perform simulations that one needs for designing efficient buildings.

### Popular Simulation Programs

#### Lighting Programs

Designer can use lighting design and simulation software to model the space and simulate to analyze its performance over a specified period. These software generate photo-realistic images, as well as conduct a luminance or illuminance analysis on a grid of points.

Lumen Designer's user-friendly

interface can create all types of architectural spaces quickly and accurately. Moreover, it can develop a schema for the space quickly with automated routines. It has an industry-wide product database and a library of realistic objects and materials. It renders the space photo-realistically for visualization and provides extensive output, photo-realistic renderings and DXF/DWG import/export.

Radiance is highly accurate ray-tracing software. It is used for the analysis and visualization of lighting in design. The input files to the program specify the scene geometry, materials, luminaries, time, date and sky conditions (for daylight calculations). Simulation results may be displayed as color images, numerical values and contour plots. The primary advantage of Radiance over other lighting programs is that there are no limitations on the geometry or the materials that may be simulated.

Another program, ECOTECT, has a CAD interface and can easily export the model to Radiance for photo-realistic rendering.

#### Whole Building Simulation Programs

EnergyPlus is a building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows. It builds on the most popular features and capabilities of BLAST and DOE-2 but also includes many innovative simulation capabilities such as time steps of less than an hour, modular systems

and plant integrated with heat balance-based zone simulation, multi-zone air flow, thermal comfort, and photovoltaic systems. EnergyPlus is a stand-alone simulation program without a "user friendly" graphical interface. EnergyPlus reads input and writes output as text files.

DesignBuilder provides a user-friendly interface to model the geometric spaces. Moreover, it can export data for further analysis that can be done in EnergyPlus. Other programs like eQUEST and Visual DOE are also used to run the DOE-2 simulation engine to perform energy calculations. The Energy Design Plugin is a free plugin for the Google SketchUp 3D drawing program. The OpenStudio Plugin for Google SketchUp is a free tool that makes it easy to create and edit the building geometry in EnergyPlus input files. The plug-in also allows the designer to launch EnergyPlus simulations and view the results without leaving SketchUp.

ECOTECT can calculate heating and cooling loads for models with any number of zones or any type of geometry. One can assign detailed material properties to all objects as well as annual hourly operational schedules to occupancy, internal gains, infiltration, and individual items of equipment. ECOTECT's ability to predict energy performance of complex buildings may not be on par with EnergyPlus and DOE2 but it is a great concept design tool to determine solar exposure and penetration studies, façade optimization and visualization.

### HVAC zones

An HVAC zone is physically determined by the design of the HVAC system. It includes some number of thermodynamically similar spaces whose loads can be satisfied through use of a single thermostat. The duct outlets or other terminal units controlled by a single thermostat serve the zone. Thermal zoning requires engineering judgment to avoid modeling error and to ensure that it can be reasonably determined. For example, the interior spaces of a multi-

story building may be physically separate spaces on each floor, but they may often be reasonably combined into a single thermal zone in the simulation model of the building because they have similar loads and are served by similar systems.

However, a cafeteria or computer room in an office building would need to be modeled separately, as would lower-floor retail uses. The basic rule is that thermal zone must be defined identically for the standard building design and the proposed design. Zones may be combined,

or multipliers may be used, if all the following conditions are met:

- All of the space use classifications must be the same throughout the thermal zone. This ensures that they have the same load and schedule characteristics.
- For exterior HVAC zones with glazing, the glazing for each zone must have the same orientation, or their orientations must be within 45 degrees of each other. This ensures that they have the same solar heat gain characteristics. This is not to say that zones may not have two or

**Table 5: Comparison of Commonly used Software Programs for Energy Simulation**

	EnergyPlus	eQUEST	DOE2.1E	ECOTECH	TRNSYS
<b>Geometry, Inter-Operability, and Overall Capability</b>					
Import geometry from CAD programs	Yes	Yes	No	Yes	Yes
Export geometry to programs	Yes	No	No	Yes	No
Unlimited zone, system, equipment	Yes	Yes	No	Yes	Yes
Creation of optimized shading devices	No	No	No	Yes	No
Greenhouse gas emission calculation	Yes	Yes	Yes	No	No
<b>Heat Load Calculations</b>					
Hourly load calculation	Yes	Yes	Yes	Yes	Yes
Automatic design day calculation	Yes	Yes	Yes	Yes	No
Solar gain and daylighting calculation with effect of neighboring buildings	Yes	No	No	Yes	Yes
Weather data available with program	Yes	Yes	No	Yes	Yes
<b>HVAC</b>					
User-configured HVAC system	Yes	Yes	No	No	Yes
Automatic sizing	Yes	Yes	Yes	No	Yes
Individual zone and system control	Yes	Yes	Yes	No	Yes
Air-to-air energy recovery systems	Yes	Yes	No	No	Yes
<b>Innovative HVAC System Modeling Capability</b>					
Seasonal heat and cold storage	No	Yes	No	No	Yes
Absorption chillers	Yes	Yes	Yes	No	Yes
Natural ventilation	Yes	No	No	No	Yes
Hybrid natural and mechanical ventilation	No	No	No	No	Yes
Operable windows	Yes	No	No	No	Yes
<b>Controls</b>					
Thermal comfort estimation	Yes	No	No	Yes	Yes
Dimming electric lighting controls	Yes	Yes	Yes	No	Yes
<b>Economic Evaluation</b>					
Life cycle cost analysis	Yes	Yes	Yes	No	Yes
<b>Reports</b>					
Graphical	No	Yes	No	Yes	Yes
Text	Yes	Yes	Yes	Yes	Yes
<b>Availability of Software</b>					
Cost of Software	Free	Free	Free/Priced	Priced	Priced
Web link	www.eere.energy.gov/buildings/energyplus		gundog.lbl.gov		
Front-end User Interface	Sketch-Up (free), Design Builder (commercial)		Visual DOE, EZDOE, eQuest		

## Frequently Asked Questions

### 1. How do I select appropriate software?

- Evaluate the objectives of the client and the design team and the level of analysis needed since different programs/software can be employed for different outcomes.
- Make a decision based on the cost (academic Vs. commercial licensing), capability, type and sophistication of the interface (both for input and output), and after-sales support. “Open Source” software is easily available and generally free of cost. See Table 5

### 2. What kind of background and how much time is needed to learn energy simulation?

Basic exposure and awareness of the capabilities of the software can be achieved in three days – but rigorous practice and advance knowledge about building load calculation, HVAC system sizing and controls, lighting design and controls, interpreting output and developing design optimization strategy can take up to 6-9 months of training and/or supervision.

Architects, Civil Engineers, Mechanical or Electrical engineers with sound building physics background and basic understanding of lighting and HVAC systems are well-suited to learning energy simulation programs.

### 3. What if weather file for the city where project is located is not available?

Use nearby station/city falling within the range of 2° latitude or 2° longitude variation (250 kms apart) and within 100m altitude of the actual city location. Weather data files for about 61 Indian cities are available at: [http://www.eere.energy.gov/buildings/energyplus/cfm/weather\\_data3.cfm/region=2\\_asia\\_wmo\\_region\\_2/country=IND/cname=India](http://www.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=IND/cname=India)

### 4. What range of savings can be expected from energy simulation?

This will depend on many factors including the base building, resources available, knowledge and expertise of the client, and the design and modeling team. Based on past experience, energy

savings can typically range anywhere between 10% to 50%.

### 5. Can one use CAD or BIM drawings for energy simulation work?

One can import 2-D building geometry in DXF format in some of the energy simulation software. Almost all CAD/BIM software offer DXF export facility.

### 6. Where can one get the building materials database required for energy modeling and simulation?

- ECBC Annexure
- National Building Code
- Central Building Research Institute
- ASHRAE Handbook - Fundamentals

### 7. What are reasonable heat generation levels for lighting, people, and equipment (including computers)?

- People: 10 to 15 W/sqm
- Lighting: 5 to 20 W/sqm
- Equipment Loads: 10 to 30 W/sqm

more glazing orientations (a corner office could easily have two), but that zones must have similar orientations. It would be acceptable, for example, to group all of the northeast corner offices on the intermediate floors of an office tower into a single thermal block.

- All of the HVAC zones must be served either by the same HVAC system or by the same kind of HVAC system.

The configuration of the thermal zones must be assumed if the HVAC system is not designed at the time of simulation modeling. This situation is quite common in commercial buildings where the future tenants will determine the zoning of spaces in the building. Things to consider are:

- Separate interior and perimeter spaces: If the HVAC zones are not yet designed,

the space should be divided into two kinds of thermal zones: perimeter zones for interior spaces located within 15 feet of the external wall, and core zones for spaces located more than 15 feet from the external wall.

- Separate orientations with glazing: Glazed exterior walls should be assigned to a different perimeter thermal zone for each major orientation. Orientations within 45 degrees of each other may be combined.
- Separate top, bottom, and middle floors: Spaces exposed to ambient conditions, such as the top floor or an overhanging floor, and spaces in contact with the ground, such as the ground floor, must be zoned separately from zones that are not exposed to ambient conditions, such as an intermediate (typical) floor in a multi-story building.

## Resources

- ANSI/ASHRAE Standard 140-2007, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, Atlanta, GA, USA (<http://www.ashrae.org>).
- ASHRAE 90.1-2007 User's Manual, Atlanta, GA, USA (<http://www.ashrae.org>).
- Bureau of Energy Efficiency, Energy Conservation Building Code, Revised Version, May 2008, Ministry of Power, India
- Donald R. Wulfinhoff, Energy Efficiency Manual, Energy Institute Press.
- Building Technologies Program Web Site, US Department of Energy, 2008 ([http://www.eere.energy.gov/buildings/programs\\_directory](http://www.eere.energy.gov/buildings/programs_directory))



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