Learning to Build a Sustainable Future

Charles Xie and Saeid Nourian

The Intelligent Learning Technology Laboratory

The Concord Consortium

In the United States, energy consumption of residential and commercial buildings adds up to nearly 40% of the total energy usage. If we can figure out how to save a portion of it—without compromising the comfort of our homes, offices, and schools, then we do not have to burn as much fossil fuel as we do now. In this sense, energy efficiency is also called the "fifth fuel."

Energy3D is a simple computer-aided design (CAD) program for designing energy-efficient buildings that, besides using energy conservation measures such as insulation, take advantage of renewable energy such as solar and geothermal energy to reduce heating costs in the winter and cooling costs in the summer for hundreds of locations in the world. Generously funded by the National Science Foundation of the United States, Energy3D has been developed for students like you to learn basic science and engineering concepts and skills needed to build a sustainable world. No matter where you are and who you are, you can download and use this software completely free of charge.

System Requirements

Energy3D runs on Linux, Mac OS X, and all versions of Windows.

This book will begin with showing you, step by step, how to use Energy3D to sketch up a simple building, configure it, and analyze its energy performance. After going through the introduction, you will learn how to apply the concepts and tools used in these basic steps to design energy-efficient buildings, solar farms, and urban communities. Exploiting renewable energy to increase the livability and sustainability of human dwellings is an important topic in contemporary architectural engineering. So your work will be crucial to the wellbeing of the Earth and all the people living on it!
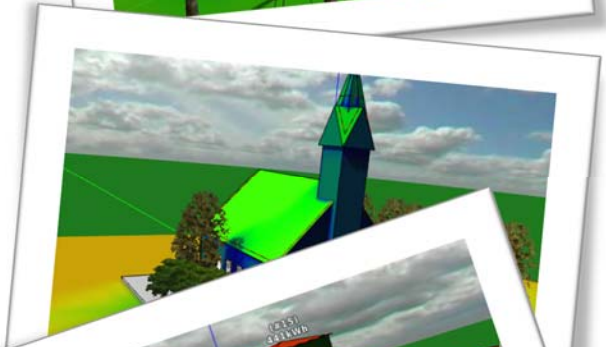
Let's get started!

Acknowledgments

Dedicated to our families, friends, and teachers, without whose support this book would have been impossible.

------------ CX & SN

Chapter 1: Building Construction

If you have never heard of CAD or done any 3D design using a computer before, relax. **It takes only a few steps to sketch up a simple house in Energy3D!**

The following sections show these steps. You should read the images in each section first (pay attention to the text in the yellow boxes) and then the text in the section for more information.

1.1 Add a Platform

You can think of a platform as a rectangular

Box 1.1 What is CAD?

Computer-aided design (CAD) is the use of computers to assist in the planning, creation, revision, analysis, optimization, and communication of a design. CAD software can greatly increase the productivity of the designer, improve the quality of design, and accelerate the speed of production. Advanced CAD systems such as Dassault Systèmes's CATIA have empowered engineers to design Boeing 777 entirely on computer—even before any part had actually been manufactured.

---

parcel of land. You can create multiple buildings in Energy3D, but **each building must be based on its own platform**. Note that, in Energy3D, a building is defined as a space enclosed by one and only one set of *connected* walls.

Figure 1.1
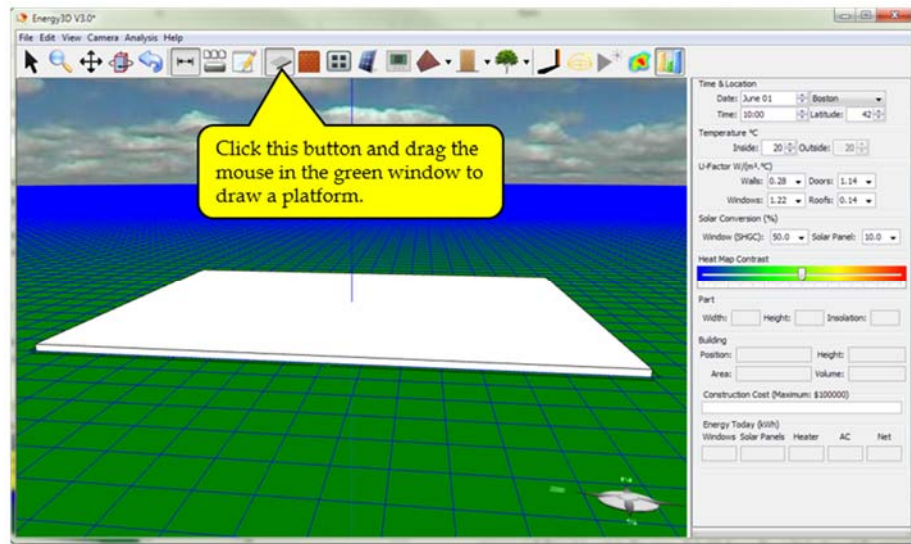
To resize a platform, drag its corners. To delete a platform, click on it and press the Delete key. To undo a deletion (or any other action), press Ctrl+Z on Windows or Command-Z on Mac. Note that, however, sometimes an existing platform can be fixed by the person who created it for the purpose of complying with the reality that you only have a fixed area of land. Such a fixed platform cannot be resized or deleted.

1.2 Add Walls

The grid lines on the platform visually guide you to set the position, direction, and length of a wall (Figure 1.2). If it does not look easy to add or change a wall, try the following to look for a better viewing angle or point: 1) hold down the left button of the mouse and drag it to rotate the view, 2) hold down the right button of the mouse and drag it to pan the view, or 3) scroll the mouse wheel to zoom in and out (or use the Zoom Tool in the Task Bar for faster zooming).

If drawing in 3D is difficult to you, Energy3D also provides an alternative mode in which you can draw walls in 2D—similar to drawing a floor plan. To enter that mode, select "2D Top View" under the Camera Menu, or simply press Ctrl+T on Windows or Command-T on Mac. If you want to quickly add multiple walls, see Box 1.2 for a tip.
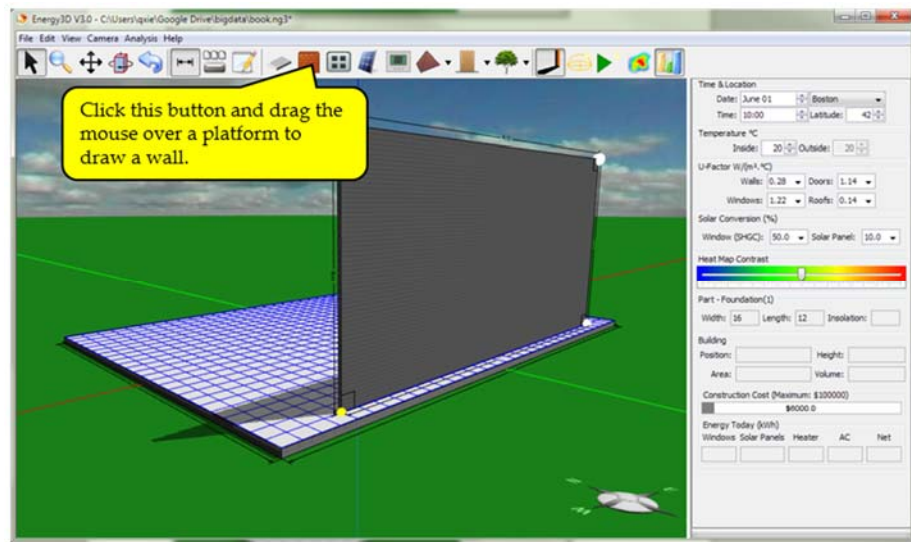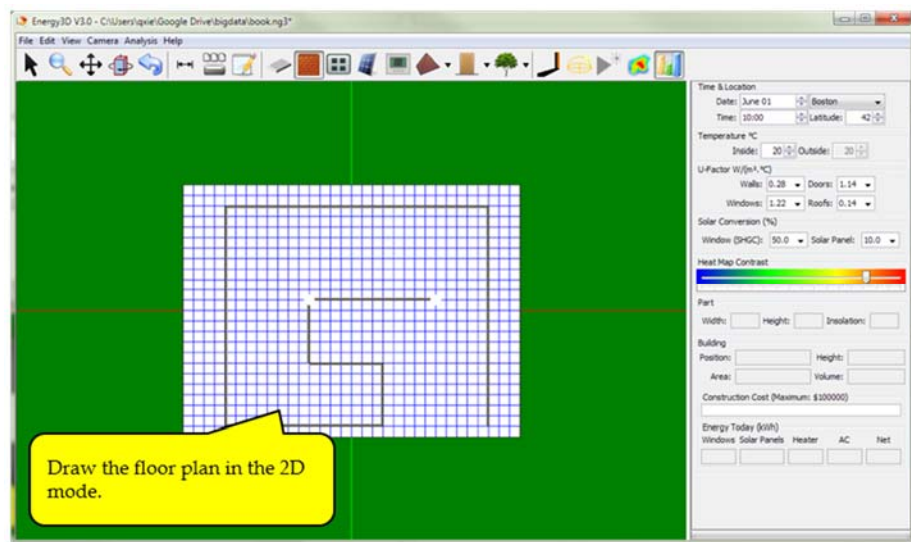
Figure 1.2a

Figure 1.2b

To change the direction and length of a wall, drag the white dots on its *lower* edge. To change its height, drag the white dots on its *upper* edge. To remove a wall, click on it and then press the

Delete key. You can join two walls by dragging a white dot of one wall to a white dot of the other wall. The two walls will then stick to each other automatically.

**Box 1.2 Quickly add multiple elements of the same type**

In order to add a certain type of element to the scene in Energy3D, you have to select the corresponding mode in the Task Bar. By default, once you are done with adding an element, the Task Bar always resets to the default mode. If you want to add another element of the same type, you will have to click that mode again.

There is a quicker way to add multiple elements of the same type: You can just double-click on the corresponding button on the Task Bar, it will then stay in that mode after you drop an element—until you click another button to select another mode.

1.3 Close the Gap

The walls create the basic shape of a building. Make sure that all the walls are joined to form a closed space. Only after all the walls are joined will a building be considered as ready for performance analysis (a building with an open gap will not be accepted!).

Figure 1.3
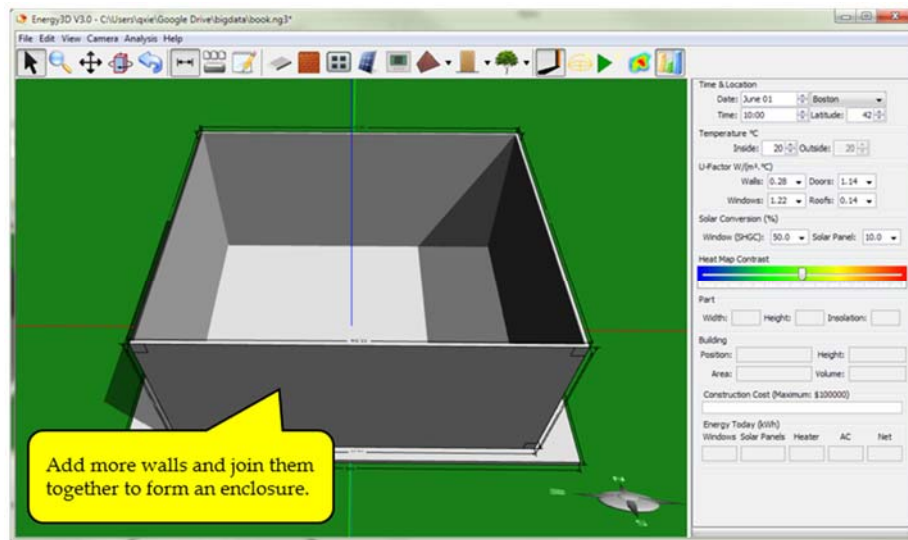
1.4 Add and Reshape a Roof

Adding a roof needs only a couple of mouse clicks. Three different types of roof are available in Energy3D: pyramid roof (as shown in Figure 1.4a), hip roof, shed roof, and custom roof. Other common roofs are special cases of these types. For instance, a flat roof can be created by lowering the apex of a pyramid roof or the top edge of a hip roof to the level of its base (Box 1.3). If you have a complex floor plan, you will likely need to use a custom roof for the building to look good.

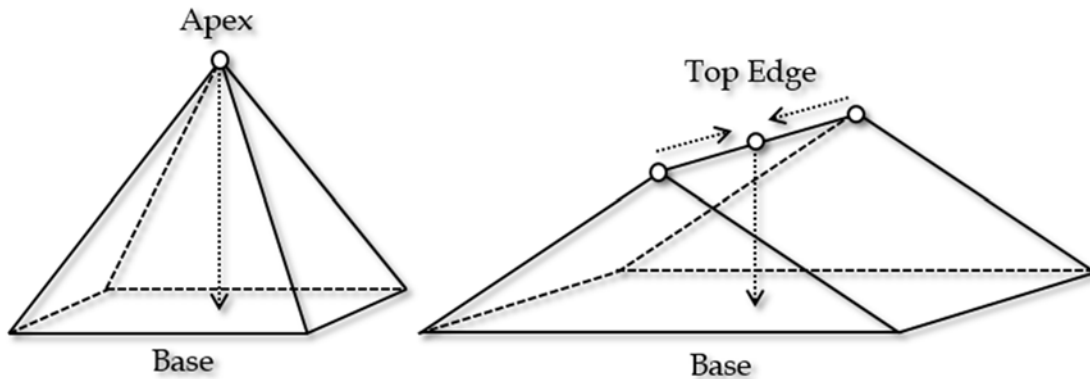**Box 1.3 Make a flat roof from a pyramid roof or a hip roof**
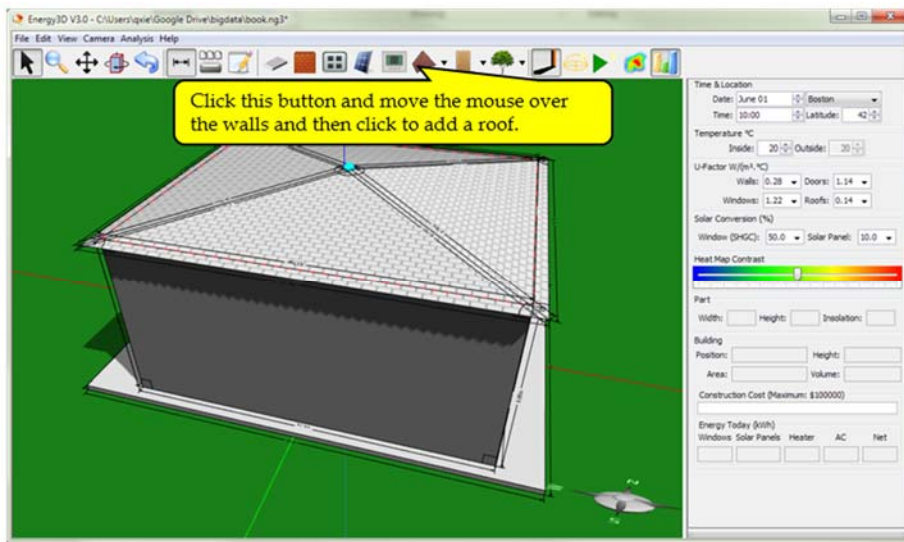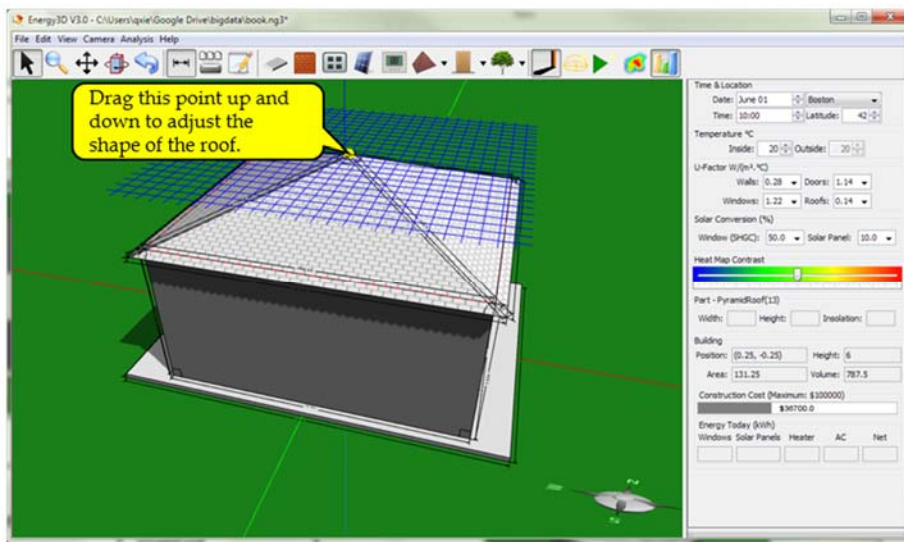
Figure 1.4a

Figure 1.4b

To delete a roof, click on it and then press the Delete key. To change the roof type, delete the

roof first, select a different type of roof from the dropdown menu (which opens when you click the arrow button next to the Roof Button), and then move the mouse over to the building and click on it. To adjust the shape of a roof, drag the small white dot(s) on top of it (Figure 1.4b).

The angle of a roof may be important when you are considering putting solar panels on it. Furthermore, changing the angle may also alter the surface area of the roof, thereby having an impact on the heat flow between the inside and the outside.

1.5 Resize and Move a Building

Resizing a building is a handy feature because it allows you to focus on designing the shape of the building without having to worry about its exact size at the beginning. After you have completed the shape design, you can then resize the building in any way—making it square or elongated, tall or short, it is all up to you. (Note: When a platform is fixed, you can only change the height of the building on it.)

Figure 1.5
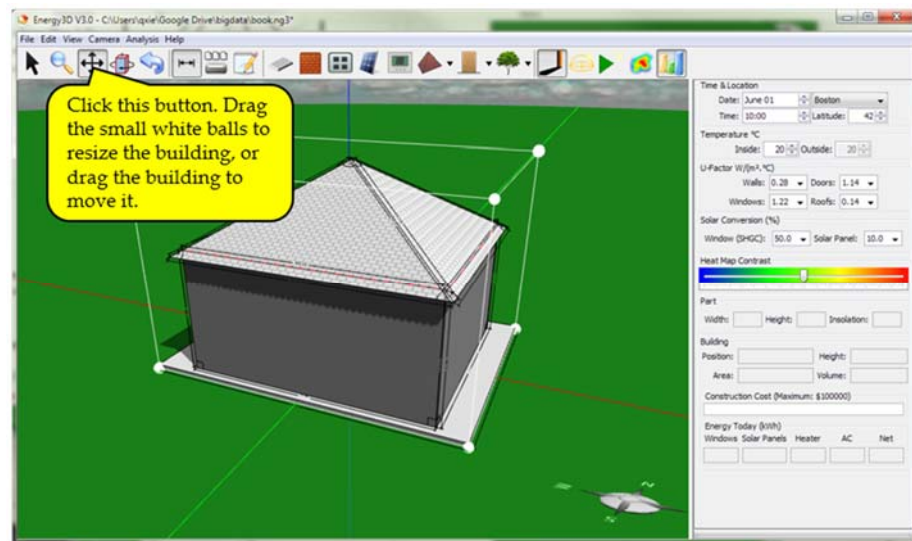
To resize a whole building, drag the small white dots. To move it around, drag the building (note: when the platform is fixed, the building cannot be moved). To delete a building, click on its platform and then press the Delete key.

1.6 Add, Resize, and Move Windows

Windows are important to a building because they let the sunlight in to provide natural lighting in all seasons and heating in the winter (and, of course, a view for the occupants). In the summer, however, adding too many windows might result in excessive heating that dramatically increases the cost of air conditioning. To control the percentage of solar energy shined into a building, you can set a property called the Solar Heat Gain Coefficient (SHGC) for each window. A higher SHGC allows more solar energy to pass through the window.

You can add multiple windows to a wall (but do not overlap them). To resize a window, drag the small white dots at its corners. To move a window, drag it around within the wall. To delete a window, click on it and then press the Delete key.

Figure 1.6
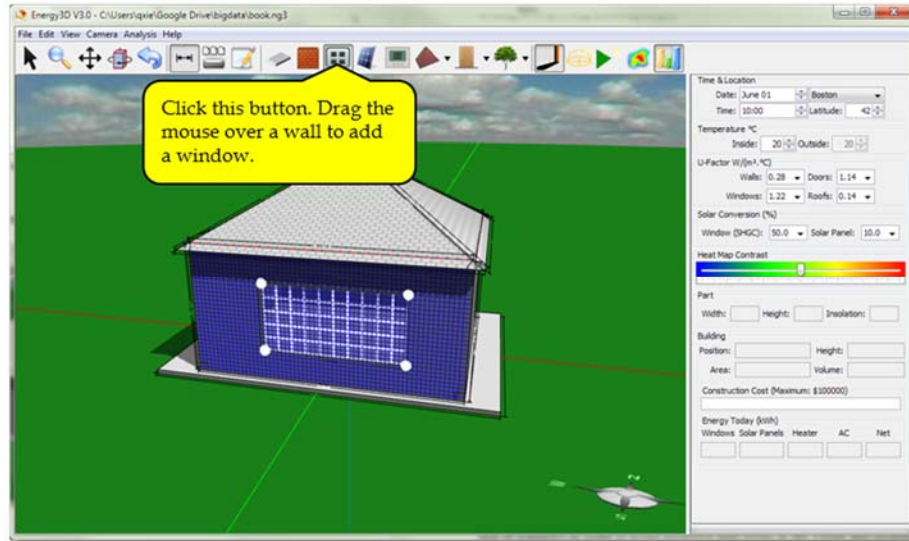
1.7 Add and Move Solar Panels

Photovoltaic (PV) modules, commonly known as solar panels, are used to convert solar energy into electricity to power a building. The quantity of electricity that a s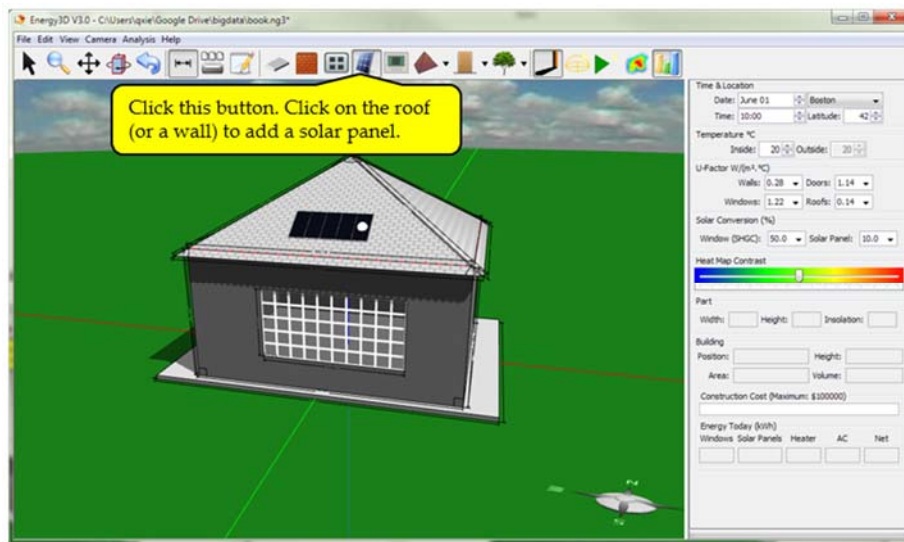olar panel can generate during a day depends on its efficiency, its orientation, and the length of the day. How to choose these design options will be discussed in a later chapter.

Figure 1.7

You can add multiple solar panels on the roof or a wall (though it is uncommon to mount solar panels on walls). To move a solar panel, just drag it around. To delete a solar panel, click on it and then press the Delete key.

1.8 Add and Move Trees

Trees around a house not only add natural beauty but also can improve energy efficiency, if planted in the right positions. Deciduous trees to the south of a house let sunlight shine into the house through south-facing windows in the winter while blocking sunlight in the summer, thus providing an eco-friendly solution to heating and cooling of the house using the trees' shedding cycles. Trees to the west and east of a house can also create significant shading to help keep the house cool in the summer.

Figure 1.8
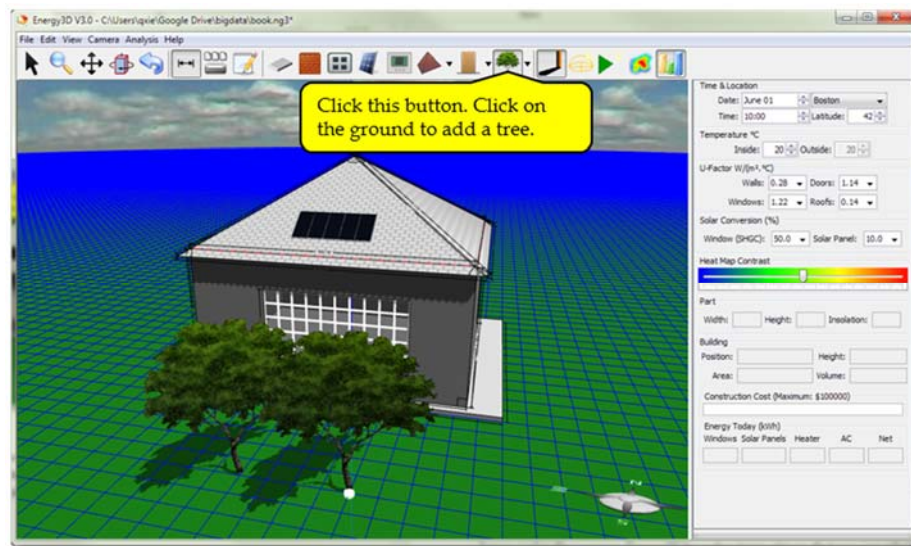
Energy3D has several types of deciduous and evergreen trees of different heights that you can choose to add to your design. These types are available from the dropdown menu (which opens when you click the arrow button next to the Tree Button). To move a tree, drag its trunk. To delete a tree, click on it and then press the Delete key.

1.9 Rotate a Building

Sometime you want to rotate a building to explore the best orientation. If there is only one building in the model, it will be automatically selected when the Rotation Button is pressed. If there are multiple buildings, you will have to pick one. To pick a building, just click on its platform.

You can click the Rotation Button multiple times to rotate the selected building step by step. For your convenience, to rotate a building continuously, hold down the Rotation Button.

Figure 1.9
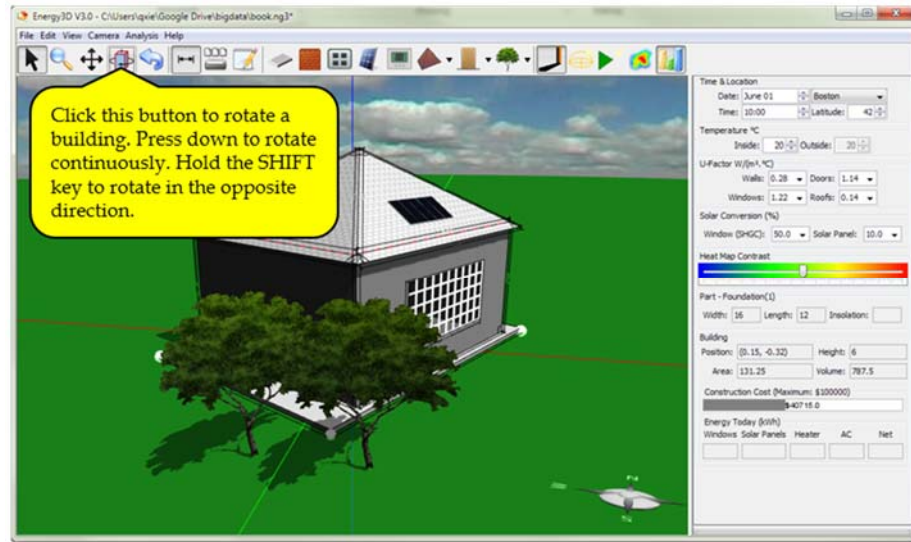
To rotate in the opposite direction, hold down the SHIFT key at the same time when you click or hold down the Rotation Button.

2.0 Cut, Copy, and Paste in 3D

Like in other programs, you can cut, copy, and paste an element in Energy3D. These operations are slightly more complicated in the 3D space than those in 2D programs. Currently, only the following types of elements are copyable:

- Windows
- Solar panels
- Sensors
- Trees
- Humans

Compared with dropping an object, copying may provide a faster alternative. For example, if you want to have a window with exactly the same size as an existing one, you can simply copy and paste it to create another one.

If you have got to this point, congratulations! You have created your first house in Energy3D. That was easy, wasn't it?

Exercises

Exercise 1.1: Design a Cape Cod style house (a two-story house with a steep pitched roof, the edges of which lower to the height of the first story) that looks like the one shown in the picture to the right. Hint: You have to apply end gables to the roof.

Exercise 1.2: Design a U-shaped ranch (a single-story house) that looks like the one shown in the picture to the right. Hint: You have to use a custom roof and apply end gables to it.
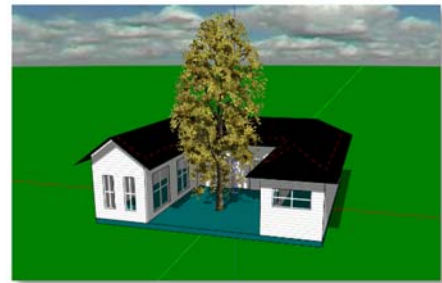
Chapter 2: Solar Energy Analysis

Many nations have legislated that, by the end of 2020, all newly constructed buildings must consume "nearly zero net energy." To meet this goal, new buildings must be able to produce as much energy as possible to meet their occupants' needs. A key is to take advantage of the free and unlimited energy from the Sun.

Your next job after constructing a building is to evaluate how much energy it can get from the Sun in different seasons. In the following sections, you will learn how to perform solar analysis for a simple building. Just as the construction steps in the previous section, **it takes only a few clicks to analyze how a building gains solar energy in Energy3D!** But first, let's learn key science and engineering concepts related to solar energy. Some of these concepts involve some math. But never mind about the math—Energy3D will do the calculations for you. You will see this from the examples in this chapter.

2.1 Solar Science

2.1.1 Insolation

Insolation (short for incident solar radiation) is a measure of solar radiation energy shining on a horizontal surface area and recorded during a given time. Figure 2.1.1 shows an insolation map of the US, on which red represents high insolation and blue represents low insolation.
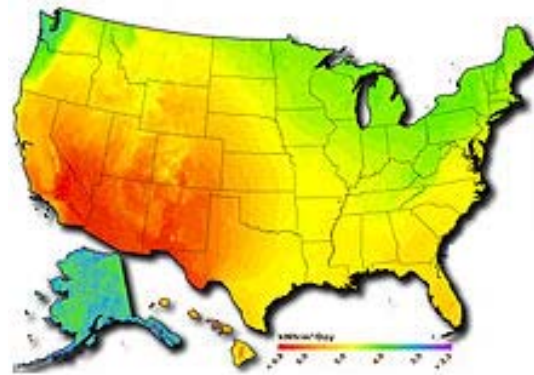
Figure 2.1.1: A US map of yearly insolation (Image from Wikipedia).

2.1.2 Albedo

Albedo is the ratio of the reflected radiation from a surface to the incident solar radiation. Albedo is zero for a perfectly black surface (meaning the radiation energy is completely absorbed by the surface) and one for a perfectly white surface (meaning that the radiation energy is completely reflected by the surface). The albedo of land is in the range between 0.1 and 0.4. The albedo of green grass is about 0.25 whereas that of fresh snow is as high as 0.9.

An important factor that affects the albedo of a building part is its color. For example, a dark-color roof has a lower albedo whereas a light-color roof has a higher albedo. The effect of the color of the roof on the energy efficiency of a building depends on the season. For example, a dark-color roof may help save some heating cost in the winter but increase its cooling cost in the summer.

2.1.3 Projection Effect

The intensity of solar energy that strikes a surface depends on the Sun's angle relative to the surface. The solar radiation input is the strongest when the surface directly faces the Sun. As the angle between the ground and the sunlight beams decreases, the intensity of solar radiation on the ground weakens (Figure 2.1.2). This is known as the *projection effect*, described by the following formula:

$$E = E_{\text{max}} \times \cos\theta \qquad (2.1.1)$$

where E_{max} is the maximum solar energy that hits the surface at noon and θ is the angle between the sunlight beam and the normal direction ($\theta = 0°$ at noon, $\theta = 90°$ at sunrise, and $\theta = -90°$ at sunset).

The projection effect is not limited to a horizontal surface. It applies to surfaces in any orientation. Figure 2.1.3 shows the projection effect for a vertical surface, such as a window. In this case, the intensity of solar radiation reaches the maximum when the Sun is in the lowest position in the sky and it gradually becomes weaker when the Sun rises.

The project effect is important to consider when you decide the orientations and layouts of solar panel arrays on building roofs or in solar farms.

Figure 2.1.2: The projection effect in the case of a horizontal surface.
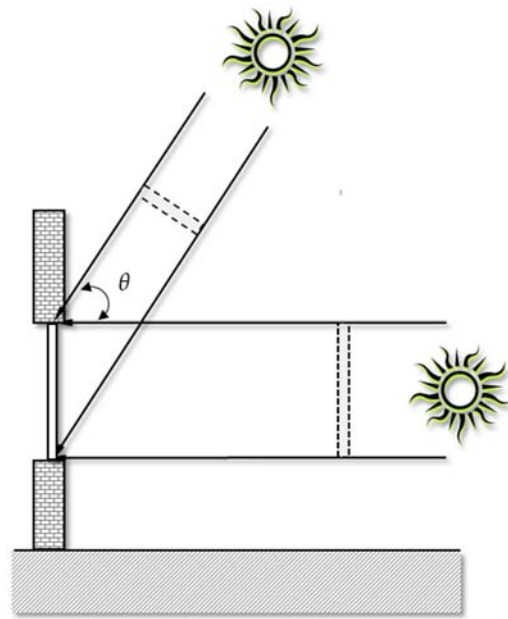
Figure 2.1.3: The projection effect in the case of a vertical surface.

2.1.4 Extraterrestrial Radiation

Extraterrestrial radiation E_a is the power of solar radiation per square meter on a plane outside the atmosphere of the Earth and perpendicular to the Sun. Extraterrestrial radiation varies from time to time as the Earth moves around the Sun in an elliptical orbit and the Earth-Sun distance varies. This variation is described by the following equation:

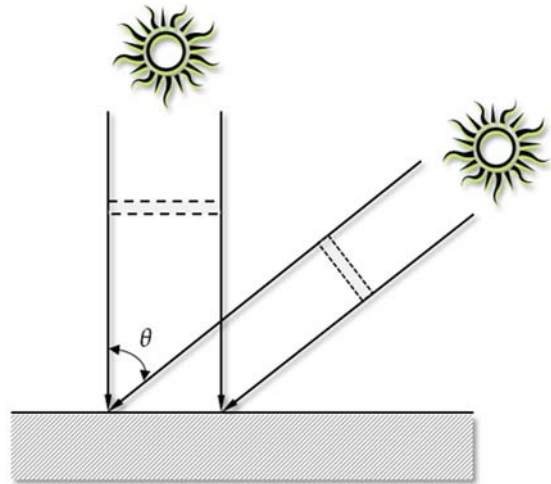$$E_a = E_{\text{sc}} \times \left(\frac{R_{\text{av}}}{R}\right)^2 \qquad (2.1.2)$$

where E_{sc} is the *solar constant* (which equals to 1361 W/m² — the extraterrestrial radiation when the Earth-Sun distance is at its mean of the year), R_{av} is the mean Earth-Sun distance, and R is the Earth-Sun distance in a given day, which can be calculated using the following formula:

$$\left(\frac{R_{av}}{R}\right)^2 = 1.00011 + 0.034221\cos(\beta) + 0.00128\sin(\beta) + 0.000719\cos(2\beta) + 0.000077\sin(2\beta)$$

$$(2.1.3)$$

where $\beta = 2\pi \times \text{DOY}/365$ and DOY is the day of the year. The extraterrestrial radiation roughly fluctuates between 1325 W/m² and 1415 W/m² throughout the year.

2.1.5 Air Mass

As solar radiation travels through the atmosphere, it interacts with the molecules in the air and are scattered or absorbed by them, causing the radiation energy that ultimately reaches the ground to be less. This effect is more significant in early morning or late afternoon than at noon because the solar radiation at those times has to travel a longer distance in the atmosphere before hitting the ground and, therefore, has a higher chance of being scattered or absorbed in the atmosphere (Box 2.1.1). This is also why stars appear to be less bright in the horizon than just above the head.

Box 2.1.1 The Beer-Lambert Law

The Beer-Lambert Law states that the intensity of light decreases exponentially while it travels in a medium:

$$I = I_0 e^{-\alpha L}$$

where I_0 is the initial intensity of light, I is the intensity of light after it travels a distance L in the medium, and α is the decay coefficient.

In solar energy engineering, the *air mass*[1] defines the length of the sunlight's path through the atmosphere. It is expressed as a ratio relative to the length of the vertically upward path, i.e. towards the zenith (Figure 2.1.4):

$$\text{AM} = \frac{L}{L_0} \qquad (2.1.4)$$

where L_0 is the thickness of the atmosphere. The air mass varies with time, date, and the latitude. As a good approximation, it is
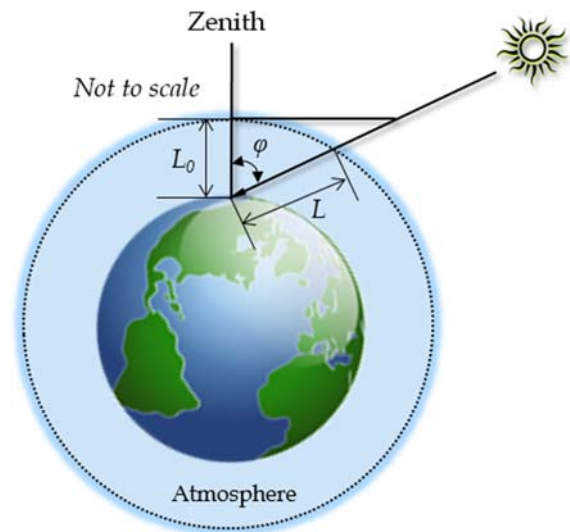

Figure 2.1.4: The attenuation of solar radiation in the atmosphere depends on the travel length.

---

[1] Not to be confused with air mass in meteorology, which defines a volume of air that can be as large as thousands of square miles.

Get Energy3D at http://concord.org/energy3d

roughly $1/\cos(\varphi)$, where φ is the zenith angle. A more accurate approximation can be derived if we consider the curvature of the Earth:

$$AM = \sqrt{(r+c)^2 \cos^2 \varphi + (2r+1+c)(1-c)} - (r+c)\cos\varphi \qquad (2.1.5)$$

where r is the ratio of the radius of the Earth R_E and the thickness of the atmosphere L_0 (r ≈ 708) and c is the ratio of the altitude of the location and the thickness of the atmosphere ($c = h/L_0$).

A good estimate of the relationship between the peak of the solar radiation intensity I_n (occurring when the surface directly faces the Sun) and the air mass is given by:

$$I_n = E_a \times 0.7^{AM^{0.678}} \qquad (2.1.6)$$

Note that the above formula has two levels of exponents.

2.1.6 Direct, Diffuse, and Reflected Solar Radiation

Any surface on the Earth receives three different kinds of thermal radiation: direct, diffuse, and reflected. The *direct radiation* is the solar radiation that travels to the surface from the Sun without being absorbed or scattered. The *diffuse radiation* is the portion of solar radiation scattered or re-emitted by the atmosphere in all directions, which can be as little as 15% when the Sun is high in the sky or as much as 40% when the Sun is low. The *reflected radiation* is the radiation bounced off non-atmospheric objects such as the ground or the objects on it.
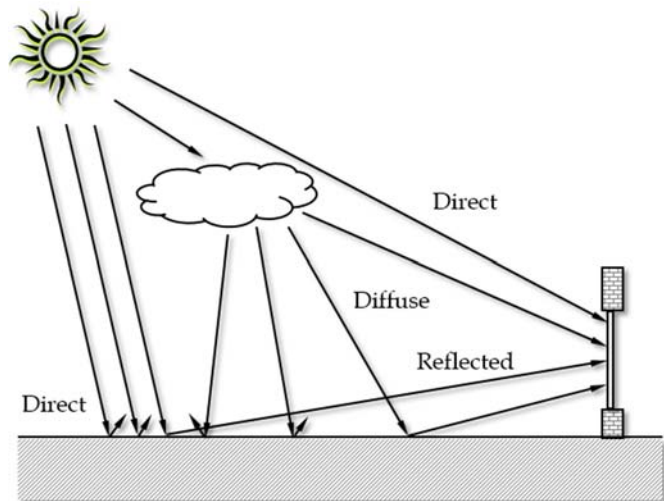
Figure 2.1.5: Direct, diffuse, and reflected radiation on the ground and on a window.

Energy3D adopts a revised mathematical model of solar radiation recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). According to this model, the total radiation on a surface is the sum of these three types of radiation, described as follows:

$$I = sI_n \left(\cos\theta + C\frac{1+\cos\xi}{2} + A\frac{1-\cos\xi}{2} \right) \qquad (2.1.7)$$

where s is the percentage of average sunshine hours of the month at the location, θ is the incident angle of the direct sunlight relative to the surface normal, C is a month-dependent

parameter defined by ASHRAE[2], A is the albedo of the background, and ξ is the angle between the surface and the horizontal. When the surface is horizontal ($\xi=0$), the diffuse radiation is the maximum and the reflected radiation is the minimum (assuming that most reflection comes from the ground). When the surface is vertical ($\xi=90°$), the diffuse radiation becomes the minimum and the reflected radiation reaches the maximum.

2.2 Solar Analysis with Energy3D

Energy3D has several built-in simulation tools that can be used to visualize and analyze the solar energy performance of buildings.

2.2.1 Observe the Sun Path with the Heliodon Simulator

Energy3D provides an interactive simulation of the Sun's 24-hour trajectory at any given date and latitude. You can observe the Sun path using the **Heliodon Simulator** as shown in Figure 2.2.1. If you click the Shadow Button and the Sun Animation Button on the Task Bar, you can watch how an object casts shadow on the ground and how sunlight shines into the building as the Sun moves across the sky.

Figure 2.2.1

The Heliodon Simulator shows the Sun path at any given location on any given day.
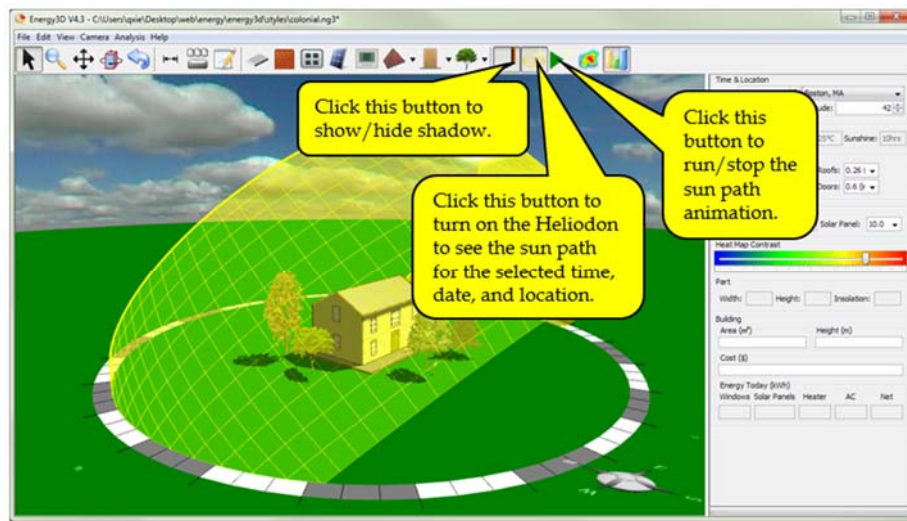
Shadow can help you see which side of a building gets more or less sunlight at a given time. But it can be more useful. For example, the animation can help you decide the positions of the windows. If an Equator-facing window is installed at a higher position, a larger portion of its upper part will be in the shadow of the overhang in the summer, resulting in less solar heating of the building through the window. When it comes to the winter, a higher position of the window does not prevent sunlight from shining into the building as the Sun moves at a lower path in the sky.

---

[2] For example, see L.T. Wong & W.K. Chow, Solar radiation model, *Applied Energy,* **69** (2001) 191–224

## 2.2.2 Calculate the Daily Solar Radiation and Visualize its Distribution

The shadow simulation only shows the solar radiation at a particular moment in time. It does not capture the effect of the length of the day, which varies from season to season and from location to location. A more accurate measure is the total solar radiation of the day.

The *solar energy potential* (or *solar potential* for short) is the total amount of solar energy a building receives from all of its opaque surfaces exposed to sunlight during a period of time (e.g., over a day), regardless of the energy that may be reflected by those surfaces. The *absorbed solar energy* is the portion of the solar potential that is actually absorbed by those surfaces. It usually depends on their albedo values.

In Energy3D, you can use the **Solar Radiation Simulator** to evaluate the daily solar potential or daily absorbed solar energy of your building. The simulator calculates the total solar energy received or absorbed by the entire building over a day, as well as its distribution over all the surfaces (and a large square of ground). To show the distribution, each unit area on the ground, a roof, or a wall is drawn in different colors according to the radiant energy it receives or absorbs (Figures 2.2.2 and 2.2.3). This false-color distribution is commonly known as a *heat map*. Typically, blue in a heat map represents a low value and red represents a high value. The heat map that shows the solar potential of a building may help you decide where you should put windows and solar panels in order to maximize or minimize their solar energy inputs.

Figure 2.2.2

A heat map that shows the distribution of solar energy potential on the surface of a house in Boston in the summer.
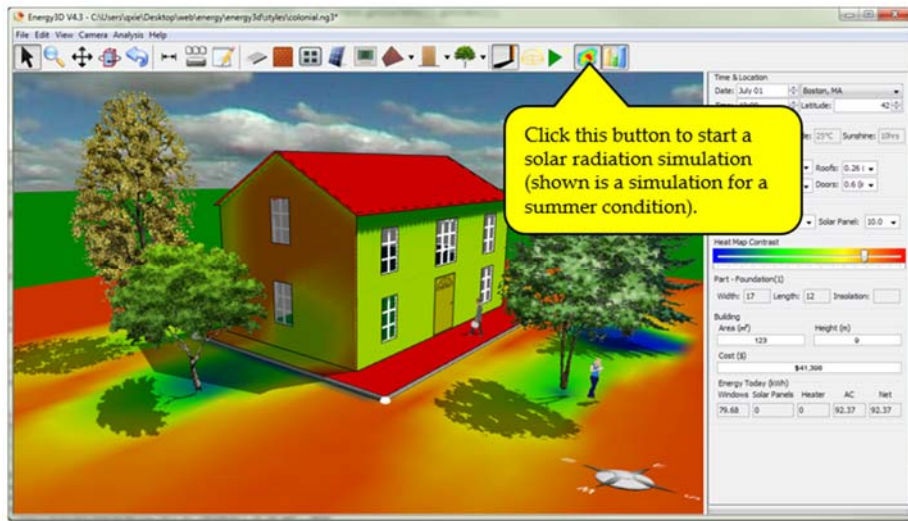
2.2.3 Compare Solar Radiation in Different Seasons

As the Sun path varies in seasons, the solar potential of a building changes. The winter and summer situations are of particular interest as the energy demands for heating or cooling are the highest during those months. These are the seasons in which solar energy has a larger effect on the overall energy efficiency of a building.

Figure 2.2.3

A heat map that shows the distribution of solar energy potential on the surface of a house in Boston in the winter.
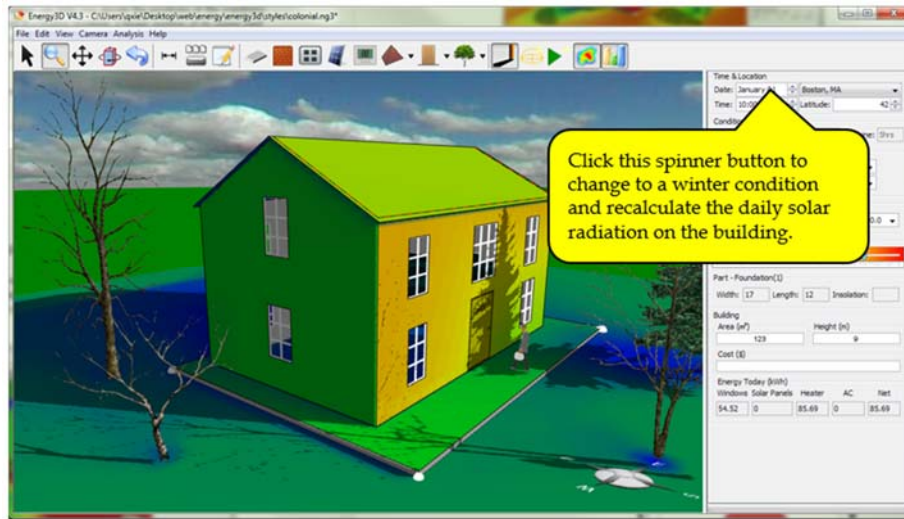
The Date Spinner Button in the panel on the right side of the Energy3D software allows you to choose any day of the year for your solar analysis. Once you have changed the date, the current heat map goes off and you have to run a new simulation to re-calculate the solar potentials on all the building parts and update the solar radiation heat map.

The Color Scale Slider is for adjusting the color contrast of the heat map to maximize visual differences. To ensure consistency, **when comparing the heat maps generated for different days or locations, do not change the color scale**.

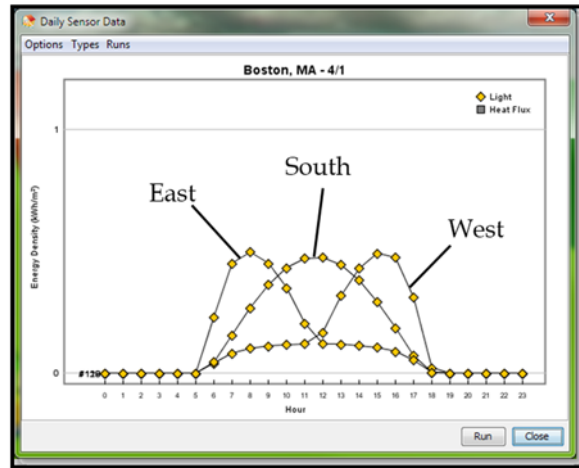### 2.2.4 Compare Solar Radiation at Different Hours of a Day

You can also place virtual sensors on different sides of a house and compare their readings at different hours of a day in different seasons. To collect this kind of sensor data, use the "Analysis > Collect Daily Sensor Data…" menu. A graph window will open to show the hourly sensor data. When you close the graph window, select "Yes" when you are asked "Do you want to keep the results of this run?" This will keep the results of the current run, to be displayed in the graph the next time you collect new data.

Figure 2.2.4 shows the solar radiation density (unit: kWh/m²) measured by three sensors put on the east, south, and west-facing sides on the first days of January, April, July, and October, representing typical conditions of the four seasons. These results show that in the winter, the south-facing side receives the most solar radiation, compared with the east and west-facing
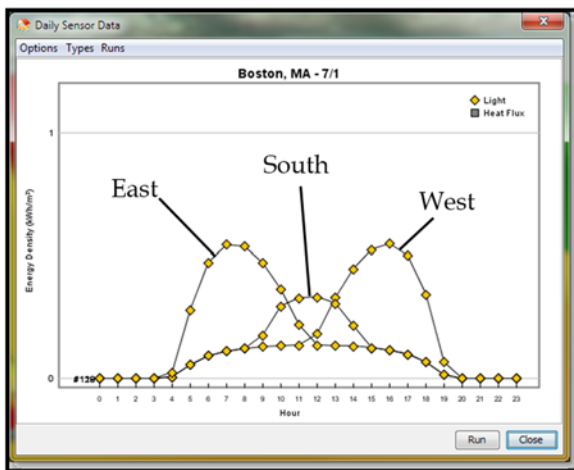
sides. In the summer, however, it is the east and west-facing sides that receive the most solar radiation. In the spring and fall, the maximum radiation densities of the three sides are comparable but they peak at different times.
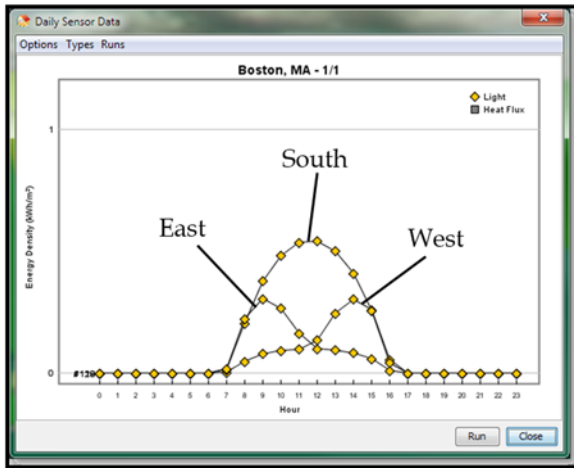
(a) January, 1st

(b) April, 1st

(c) July, 1st
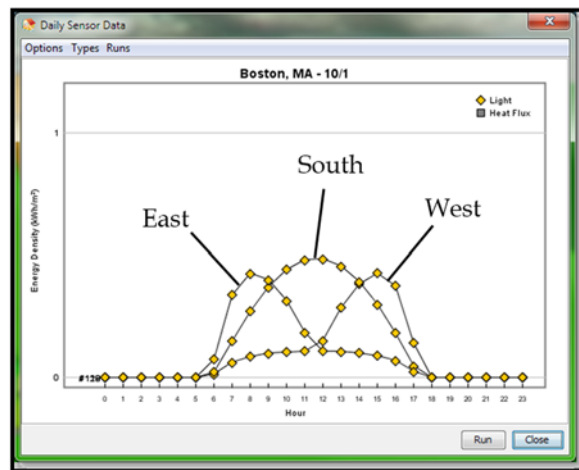
(d) October, 1st

Figure 2.2.4: A comparison of solar radiation densities on the east, south, and west-facing sides of a house at different hours of a day in four seasons.

If you take a closer look at Figure 2.2.4, you should notice that, while the radiation density on the south-facing side always peaks at noon, those on the east and west-facing sides vary by seasons. In the summer, radiation density peaks around 8 am on the east-facing side and around 4 pm on the west-facing side. In the winter, these peaks occur around 10 am and 2 pm. This difference is due to the shorter day and the lower position of the Sun in the winter.

2.2.5 Compare Solar Radiation at Different Latitudes

The energy efficiency of the building that you are designing depends on its location, as insolation differs from latitude to latitude. You can easily investigate insolation as a function of latitude by horizontally placing a sensor on the ground and then collecting the sensor data using the "Analysis > Collect Annual Sensor Data…" menu. A graph window will open to show the annual sensor data. When you close the graph window, select "Yes" when you are asked "Do you want to keep the results of this run?" This will keep the results of the current run, to be displayed in the graph the next time you collect new data.

You can change the latitude using the Latitude Spinner and collect a new set of data. Figure 2.2.5a shows the insolation pattern from the North Pole to the South Pole. The area under each curve represents the annual solar energy shining at a location of the corresponding latitude (Figure 2.2.5b). An interesting result is that the Equator does not actually have the highest peak value (the Poles do) and its peak values are not measured in the summer but in the spring and fall. However, because insolation does not differ much from season to season in the Equator, the total solar radiation it gets is still the largest on our planet. This is why the Equator is hot all year round. In comparison, notice that the North Pole does not get any solar energy from October to March and the South Pole does not get any solar energy from April to October.

2.2.6 Investigate Solar Radiation through a Window

You can also place sensors on different sides of a house to measure the solar radiation they receive in order to estimate how much solar energy a
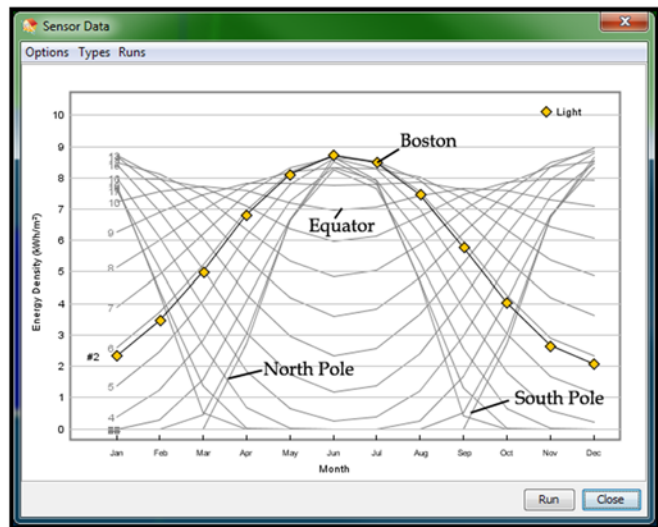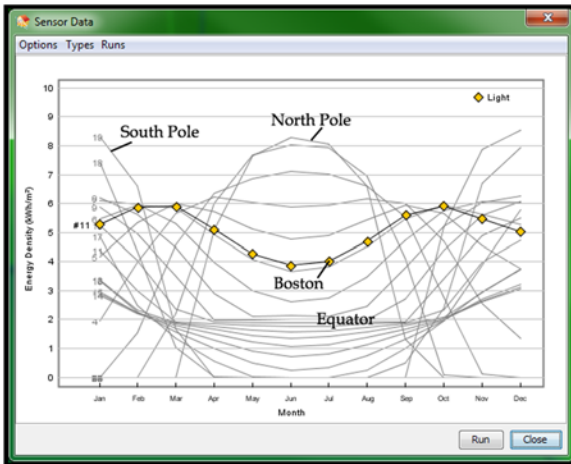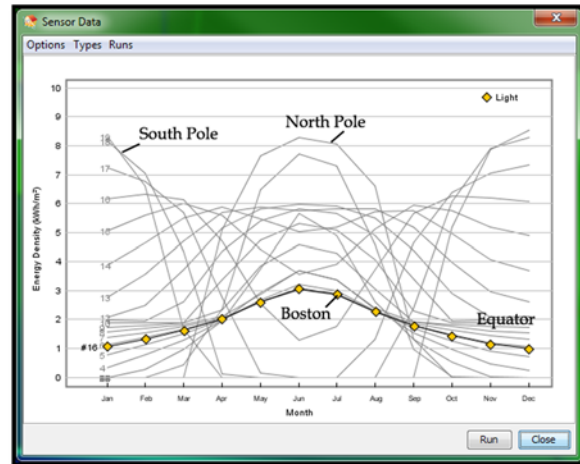

(a)
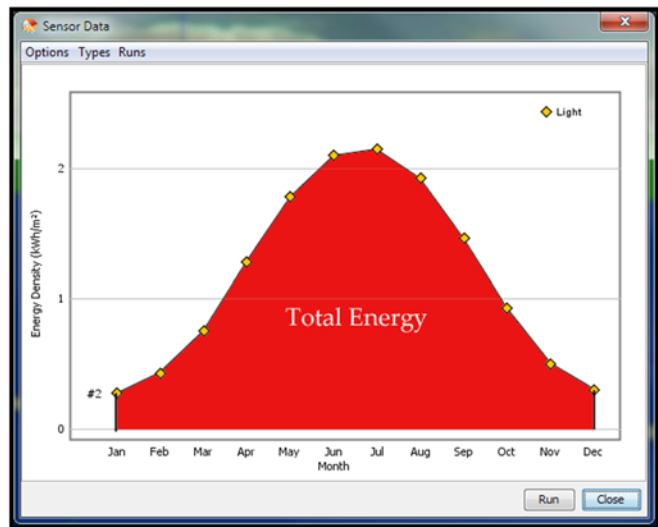
(b)

Figure 2.2.5: (a) From Pole to Pole: Solar radiation over the course of a year measured by a light sensor placed on a horizontal surface in Energy3D (Note that these results are computed without considering the effect of weather, i.e., we assume a condition of clear sky all the time). (b) The area under each curve represents the total solar energy over a year.

window on each side may get throughout the year. This can help you decide how many windows you should put on each side.

Figure 2.2.6 shows the solar radiation measured by sensors placed on the south, north, east, and west-facing sides of a building at different latitudes of the Earth, with Boston's data highlighted

(a) South-facing   (b) North-facing
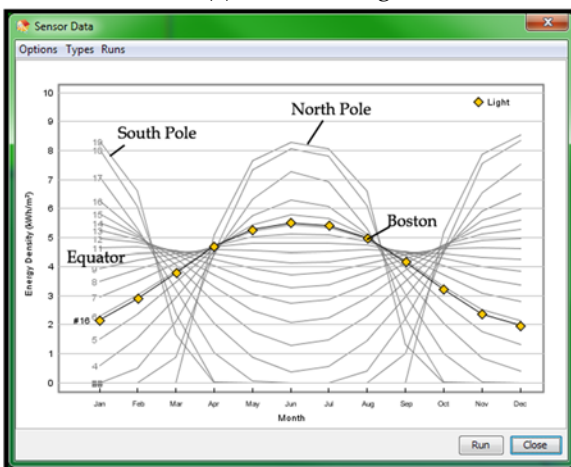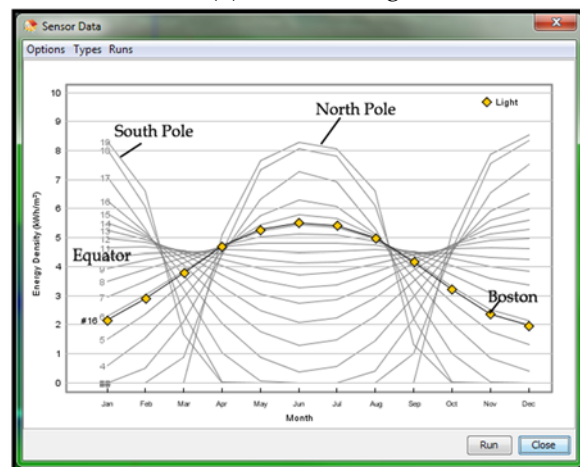
(c) East-facing   (d) West-facing

Figure 2.2.6: From Pole to Pole: Solar radiation over the course of a year measured by a south-facing (a), a north-facing (b), an east-facing (c), and a west-facing (d) light sensor in Energy3D. (Note that these results are computed without considering the effect of weather, i.e., we assume a condition of clear sky all the time).

using a line decorated with symbols. An interesting result is that a south-facing window in the northern hemisphere gets peak solar energy in the spring and fall (Figure 2.2.6a). In the southern hemisphere, however, a south-facing window gets mostly diffuse and reflected radiation in the region's winter. The trend is reversed for a north-facing window (Figure 2.2.6b). In both northern and southern hemispheres, an east-facing window gets a considerable amount of solar radiation in the summer (Figure 2.2.6c), as does a west-facing window (Figure 2.2.6d).

If we put together the sensor data from four sides of a building in Boston in a single graph (Figure 2.2.7), it shows that a south-facing window gets the most solar energy per unit area over the course of a year whereas a north-facing window gets the least. However, a west or east-facing window gets the most solar energy per unit area in the summer. To avoid excessive solar heating in the summer, the total area of east or west-facing windows should be limited.

How do we make sense of these results? Let's compare the solar radiation on the south-facing window in the winter and in the summer, respectively, with the Heliodon showing (Figure
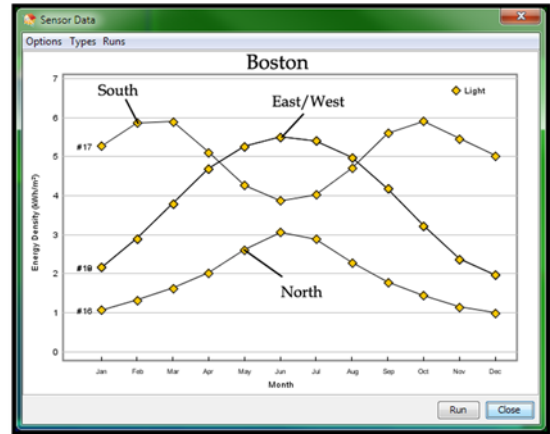
Figure 2.2.7: The solar radiation power densities on the south, north, east, and west-facing walls of a building in Boston.

2.2.8). The window faces the Sun more directly in the winter than in the summer. Even if the day is shorter in the winter than in the summer, the daily radiation adds up to be higher due to the projection effect (Figure 2.1.3). But this advantage is compromised by the air mass effect
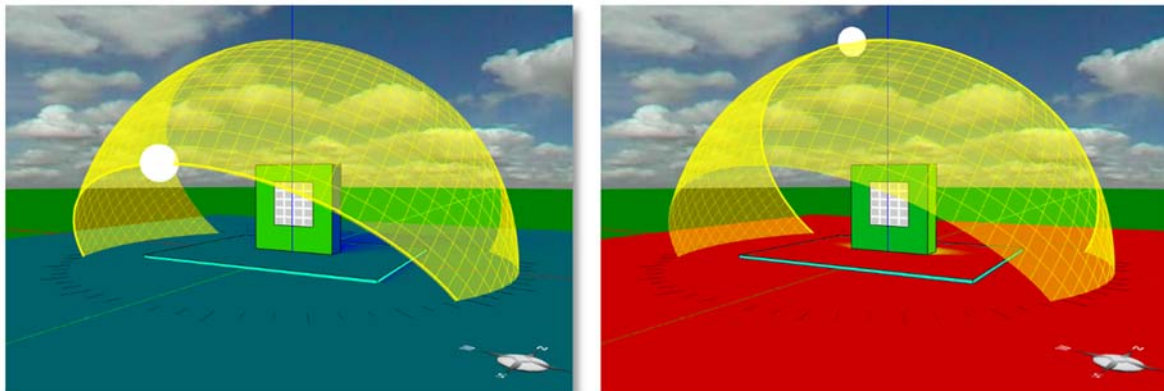
Figure 2.2.8: A south-facing window in the winter (left) and in the summer (right).
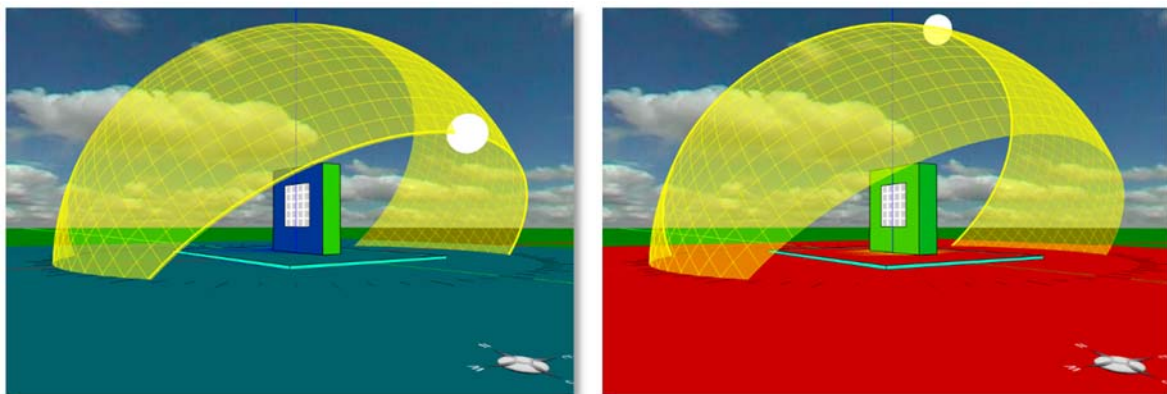
Figure 2.2.9: A west-facing window in the winter (left) and in the summer (right).

caused by the lower path of the Sun in the winter. As a result of these counteracting factors, the south-facing window ends up gaining most solar energy in the spring and autumn.

The reason that the west-facing window gets maximum solar energy in the summer is because 1) the time it is exposed to the Sun is the longest in the summer and 2) the Sun is higher in the sky (Figure 2.2.9). Although the west-facing window gets no solar energy at precisely noon in any season, there is a projection effect at other times that favors the summer heating.

2.2.7 Consider the Weather Factors

The above analyses do not consider the weather factors. In reality, we do not have clear sky every day. After considering the average sunshine hours using data from the National Oceanic
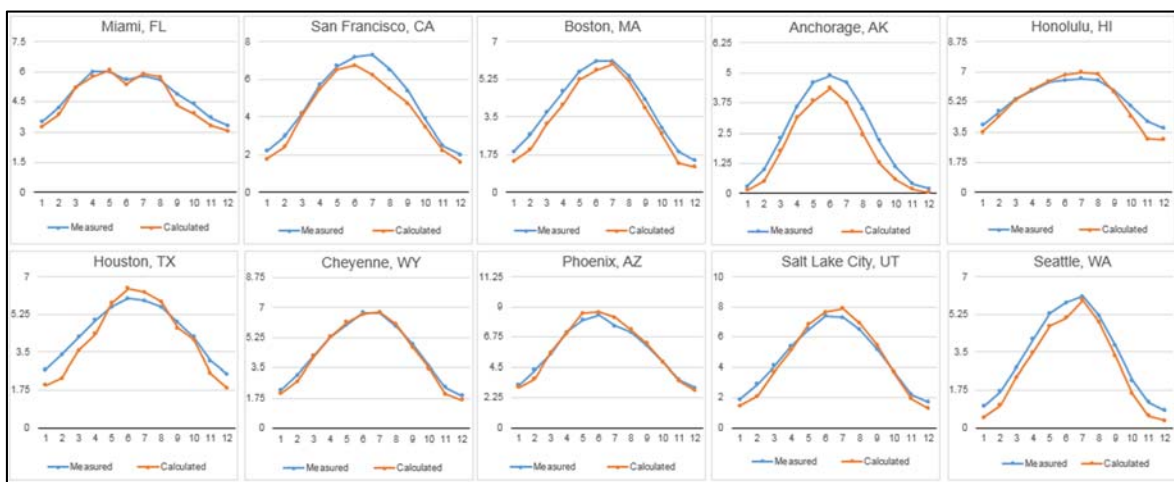
(a)

(b)

Figure 2.2.10: Comparison of Energy3D's predictions with the measured data for ten US locations. (a) The power density of solar radiation on a horizontal surface; (b) The power density of solar radiation on a south-facing, vertical surface.

and Atmospheric Administration[3], the predicted solar radiation results agree reasonably well with the measured data from the National Solar Radiation Data Base[4] collected by the US Department of Energy from 1961-1990 (Figure 2.2.10).

Exercises

Exercise 2.1: Download the Energy3D file for just a window from http://energy.concord.org/energy3d/exercises/window-test.ng3. Open it in Energy3D. Change the location to Singapore. Click the window to select it and then run "Analysis > Run Annual Energy Analysis for Selected Part…" Change the location to Moscow and then repeat this analysis. What do you find from comparing the results?

Exercise 2.2: With the above model open in Energy3D, rotate the window to face southwest, southeast, northwest, and northeast directions by clicking on the Rotation Button on the Task Bar. Repeat the annual energy analysis for the window for any city in the world that you choose. Does the window get more annual solar energy in any of these orientations other than in the south-facing orientation?

---

[3] http://www.nws.noaa.gov/tg/siteloc.php
[4] http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/state.html

Chapter 3: Building Thermal Analysis

While the temperature of the environment changes dramatically from season to season, humans are only comfortable within a very narrow temperature range. The thermal performance of a building is represented by the efficiency with which it uses energy to maintain the thermal comfort for its occupants. A high-performance building costs a relatively smaller amount of energy to heat in the winter and cool in the summer while keeping the temperature inside a building comfortable.

This chapter will start with some basic concepts about heat transfer. Using these concepts, you will learn how the properties of each element of a building impact the overall performance of the building. You will also learn how these properties are related by scientific laws and how different elements jointly affect the building performance. Finally, you will put this knowledge into practice through designing a high-performance home using Energy3D.

3.1 Heat Transfer Basics

A system gains or loses thermal energy through heat transfer from or to another system. The fundamental modes of heat transfer are conduction, convection, and radiation. Before we introduce them, let's review what heat is and how it is represented.

3.1.1 Thermal Energy and Heat

The thermal energy of a system is the internal energy of its molecules related to its temperature (which is related to how fast the molecules move or vibrate). The change of thermal energy in a system when its temperature changes from T_1 to T_2, which we often call heat and denote as Q, is given by:

$$Q = \rho V c (T_2 - T_1) \qquad (3.1.1)$$

where ρ is the density of substance in the system, V is the volume of the system, and c is the specific heat of the substance. Eq. (3.1.1) assumes that the density, specific heat, and temperature are the same everywhere within the system. In reality, however, these properties may vary from one point to another within a thermal system.

3.1.2 Heat Flux

The rate of heat transfer at a given position and in a given direction is known as *heat flux* $\vec{\phi}$, the amount of thermal energy that passes, in a unit time, through a
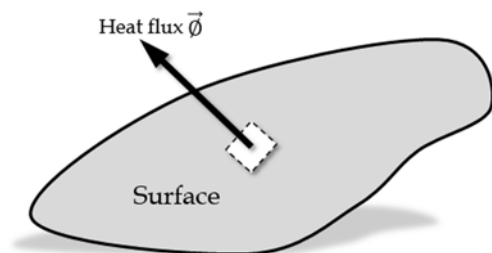
Figure 3.1.1 Heat flux through a unit area on a surface.

unit area of a surface that is perpendicular to the direction at that position (Figure 3.1.1). The SI unit of heat flux is W/m². The heat flux at a point of a surface is typically represented by an arrow whose head points to the direction of heat flow and whose length is proportional to the intensity of heat flow.
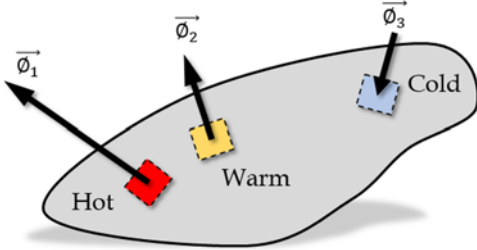

Figure 3.1.2 Heat flux distribution over a surface.

A way to visualize where an object gains or loses heat is to draw an array of heat flux vectors over its surface (Figure 3.1.2). If the vector points into the surface, the object is gaining heat at the vector's position. If the vector points outward, the object is losing heat at that point. The picture of heat flux distribution allows us to study a thermal system that is gaining and losing heat at the same time but at different places.

3.1.3 Thermal Conduction

In the process of conduction, thermal energy passes from molecules to molecules without the assistance of macroscopic movement such as blowing air or flowing liquids. The rate of heat flow in this case is governed by the following relationship (Figure 3.1.3):

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x} \qquad (3.1.2)$$

Figure 3.1.3 Thermal conduction between two objects.

where ΔQ is the thermal energy change of the hot or cold object within a time period of Δt, ΔT is the temperature difference across a distance Δx, k is the thermal conductivity (the ability to conduct heat) of the material, and A is the area in which heat flows through. This relationship is known as *Fourier's Law of Thermal Conduction*. This law can be rewritten using the concept of heat flux as:

$$\emptyset = -k\frac{\Delta T}{\Delta x} \qquad (3.1.3)$$

This suggests that the heat flux through the area A is greater when 1) the temperature difference ΔT is larger, 2) the distance Δx is shorter, or 3) the thermal conductivity is higher (e.g., using metal instead of wood).
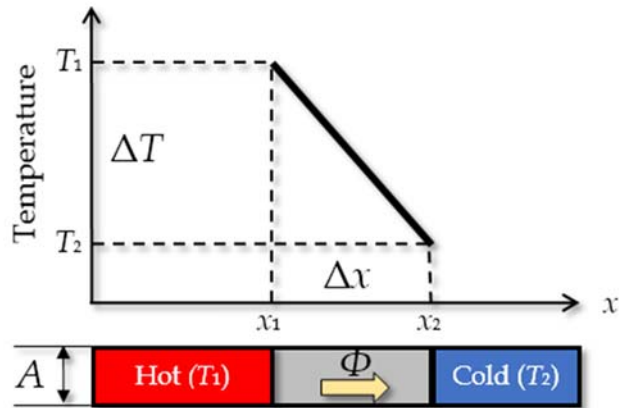
3.1.4 Thermal Convection

In the process of convection, thermal energy passes from one position to another through the flow of a fluid (a liquid or a gas).[1] In other words, a flowing fluid spreads the thermal energy it carries. A common example of convection is the rise of warm air from a hot surface. Through the rising warm air, the thermal energy from the hot surface is passed to any object above it.

Within a fluid, convection is a complex process. But we can estimate the convective heat flux from a surface to a fluid using the following simple formula (Figure 3.1.4):

$$\emptyset = h(\mathrm{T} - T_\infty) \qquad (3.1.4)$$

where h is the convective heat transfer coefficient of the fluid, T is the temperature of the surface, and T_∞ is the temperature of the bulk fluid. Eq. (3.1.4) is sometimes known as *Newton's Law of Cooling* (though the law is not limited to the cases of convection and cooling only). The formula suggests that the heat flux is greater when the temperature difference between the fluid and the surface is larger and the heat flow stops when there is no difference in temperature.
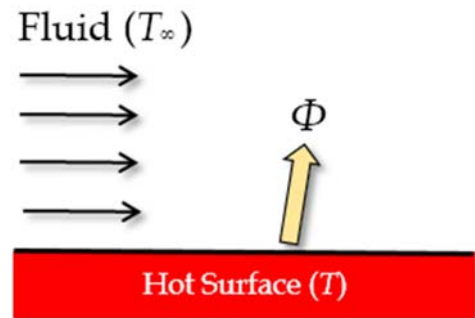
Figure 3.1.4 Thermal convection from a hot surface.

3.1.5 Thermal Radiation

In the heat transfer mode of radiation, objects exchange energy through radiation—you can imagine radiation as tiny packets of light energy that travel at the speed of light (which is called photons). Unlike conduction and convection, radiation can travel through vacuum (which is how solar radiation reaches the Earth through the outer space).

All objects emit thermal radiation. The energy radiated by an object per unit time is proportional to the fourth power of its absolute temperature T (in Kelvin, $0°C \approx 273K$):

$$\emptyset = \epsilon \sigma T^4 \qquad (3.1.5)$$

Figure 3.1.5 Radiation heat transfer between two objects.

where σ is the Stefan-Boltzmann constant and ε is the emissivity of the object's material (i.e., its ability to emit thermal radiation). This formula, known as the *Stefan-Boltzmann Law*, suggests

---

[1] There is no convection in a solid as substances in the solid state cannot flow.

Get Energy3D at http://concord.org/energy3d

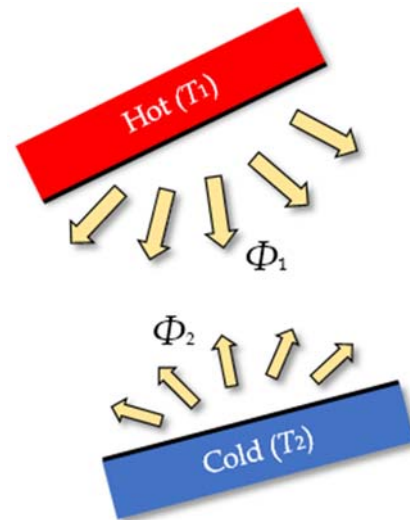that an object at a higher temperature emits much more energy than an object at a lower temperature (Figure 3.1.5). If both objects absorb radiation equally well, then the cold object gets more energy from the hot one than it gives. The gain and loss of this net energy raise the temperature of the cold object and lower that of the hot one. It thus appears that radiation can also transfer heat from the hot object to the cold one.

3.1.6 R-value and U-value

Heat transfer is not always friendly to a house. The heat transfer across the *building envelope*—the shell of a house that separates the inside and outside, should generally be minimized. *Insulation* refers to materials or techniques used to slow down heat transfer in order to keep the inside of a house warm in the winter or cool in the summer. The building and construction industry commonly uses the R-value (also called R-factor) as a measure of insulation. For an insulation piece that has a thickness L, with temperatures

> **Box 3.1.1 The circuit analogy**
>
> Heat transfer resembles current flow to some extent. If you happen to be familiar with Ohm's Law in electricity ($I=V/R$), you can imagine the heat flux as electric current (I), the temperature difference as voltage (V), and the R-value as the resistance (R).

at the two sides being T_2 and T_1, the R-value represents the insulation's ability to resist heat transfer under the given temperature difference (the effect of the R-value on heat transfer is similar to that of electric resistance on electric current, see Box 3.1.1):

$$\varnothing = \frac{T_2 - T_1}{R} \quad , \quad R = \frac{L}{k} \quad (3.1.6)$$

The R-value depends on the thickness L and the thermal conductivity k of the insulation. The thicker the insulation or the lower its thermal conductivity, the larger the R-value.

Similar to conductance in the science of electricity, the U-value (also called U-factor), the inverse of the R-value, represents the material's ability to transfer heat:

$$\varnothing = U(T_2 - T_1) \quad , \quad U = \frac{1}{R} \quad (3.1.7)$$

In the building and construction industry, the R-value or U-value of a building component usually represents its ability to resist or facilitate all three modes of heat transfer—not just conduction. In the US, the R-value is used for measuring insulation in most parts of the building envelope (such as walls, floors, and roofs), except for windows for which the U-value is used

> **Box 3.1.2 Unit conversion**
>
> The conversion between SI and US units of R-value is:
>
> 1 h·ft²·°F/Btu = 0.17611 m²·°C/W
>
> For U-value:
>
> 1 Btu/(h·ft²·°F) = 5.67826 W/(m²·°C)

instead. In the rest of the world, the U-value is generally used for measuring insulation of all the elements of the entire building envelope. To simplify the user interface, Energy3D uses the U-value. It also uses the SI unit for U-values, which is W/(m²·°C). Box 3.1.2 shows how to convert

between the SI and US units. Table 3.1.1 shows some typical U-values for different types of windows.

Glazing Type	Wood or Vinyl Frame with Insulated Spacer		Aluminum Frame with Thermal Break & Conventional Spacer	
	Btu/(h·ft2·°F)	W/(m2·°C)	Btu/(h·ft2·°F)	W/(m2·°C)
Single glass	N.A.	N.A.	1.07	6.08
Double glass ½" air space	0.48	2.73	0.62	3.52
Double glass e=0.2, ½" air space	0.39	2.21	0.52	2.95
Double glass e=0.1, ½" air space	0.37	2.10	0.49	2.78
Double glass e=0.1, ½" argon space	0.34	1.93	0.46	2.61
Triple glass e=0.1, ½" argon spaces	0.23	1.31	0.36	2.04
Quadruple glass e=0.1, ¼" krypton spaces	0.22	1.25	N.A.	N.A.

Table 3.1.1 Typical U-values of windows (Source: ASHRAE Handbook – Fundamentals, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, GA, 1993).[2] e is the emittance of the low-E coated surface.

---

[2] https://windows.lbl.gov/pub/selectingwindows/window.pdf

3.2 Building as a System

As a building is a complex system consisting of many interconnected components, its thermal performance is determined by all of its components. As a designer, you must consider not only the components individually, but also the system as a whole, in order to achieve optimal overall performance. This problem solving skill is referred to as *systems thinking* (Box 3.2.1). This book will guide you to practice this important engineering skill through designing with Energy3D creatively.

To design for high performance of a building, we have to understand the energy exchange between it and the environment, as well as the energy flow within it. Figure 3.2.1 illustrates how energy flows into and out of a building in the winter and summer, respectively. In order to maintain the temperature inside a building, the thermal energy that it contains must remain unchanged—any shortage of thermal energy must be constantly compensated and any excessive thermal energy must be constantly removed. Viewed from the perspective of *system dynamics*—a subject that studies the behavior of complex systems, the total thermal energy of a building is a *stock* and the energy gains or losses through various components are *flows*. Therefore, the diagram in Figure 3.2.1 is also commonly known as a *stock-and-flow diagram*.
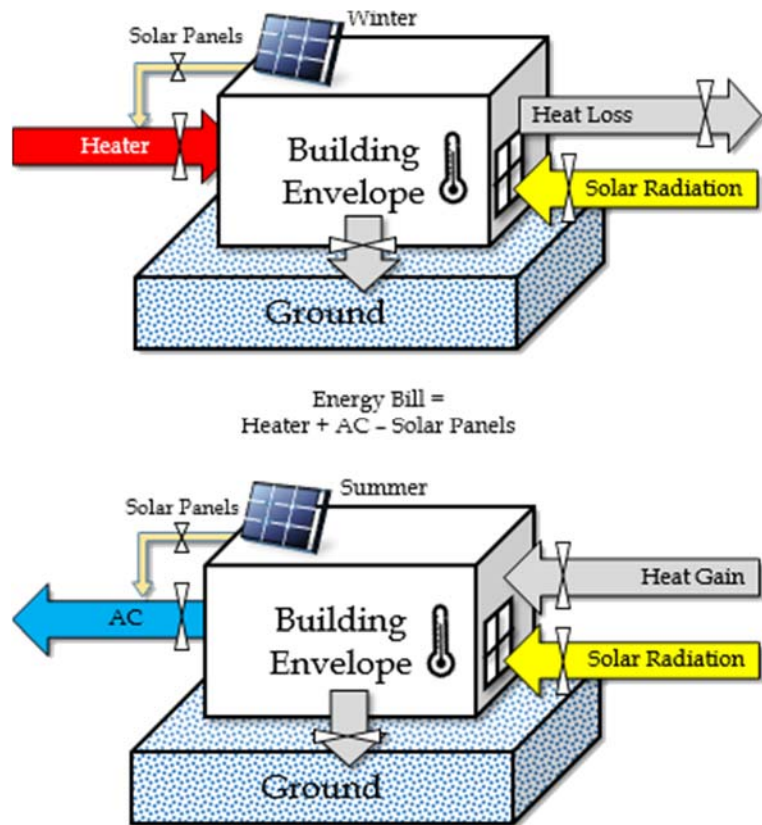

Figure 3.2.1 A stock-and-flow diagram of energy inputs and outputs of a building in the winter and in the summer.

3.2.1 Heating and Cooling of a Building

Heating, ventilating, and air conditioning (HVAC) is the technology to maintain indoor environmental comfort (including thermal comfort and indoor air quality). Every modern building has an HVAC system. The energy consumption of its HVAC system accounts for a large portion of its energy bill. For simplicity, we do not cover ventilation and indoor air quality in the current version of this book and do not go into the details of exactly how heaters and air conditioners work or how they are installed in buildings. We just assume that there is always a heater and an air conditioner in each building that are responsible for keeping the inside of the building at a constant temperature (typically, T_{in} = 20°C) throughout the year. This allows you to concentrate on designing features for the building envelope such as its shape, roof, and windows and renewable energy solutions such as solar panels.

The thermal energy gained or lost per unit time — the rate of heat flow — through a surface area A_i of a building component i at time t is:

$$p_i(t) = A_i U_i[T_{in} - T_{out}(t)], \qquad with \ T_{out}(t) = \begin{cases} T_{ground}(t) & i \text{ is the ground floor} \\ T_{air}(t) & \text{otherwise} \end{cases} \qquad (3.2.1)$$

where A_i is the surface area of the building component i, U_i is its U-value, $T_{ground}(t)$ is the temperature of the ground at time t (more on this in a later section), and $T_{air}(t)$ is the outside air temperature at time t.[3] At time t, the total heat flow across the building envelope is the sum of heat flow through all of its components:

$$p(t) = \sum_i A_i U_i[T_{in} - T_{out}(t)] \qquad (3.2.2)$$

If the inside temperature is higher than both the outside air temperature and the ground temperature, the building loses thermal energy to the environment everywhere on the building envelope. If the inside temperature is lower than both the outside air temperature and the ground temperature, the building gains thermal energy from the environment everywhere on the building envelope. The interesting cases are when the inside temperature is between the outside air temperature and the ground temperature. In these cases, the heat flow between the building and the outside and the heat flow between the building and the ground cancel out, resulting in a lower total heat gain or loss.

As the outside air temperature $T_{air}(t)$ and, to a lesser degree, the ground temperature $T_{ground}(t)$, vary from time to time, the heat flux changes from time to time. In any given day d, the total heat flow through A_i is the sum of the heat flow over the 24-hour cycle. The total quantity of

---

[3] The outside air temperature in Energy3D comes from the weather data provided by the National Oceanic and Atmospheric Administration for the location the building is designed for.

heat that flows across the entire building envelope in a year is the sum of heat flow through all of its components over 365 days:

$$Q = \sum_{d=1}^{365} \sum_{k=1}^{N} \left| \sum_{i} A_i U_i [T_{\text{in}} - T_{\text{out}}(t_d + k\Delta)]\Delta \right|, \quad \Delta = \frac{24 \times 60 \times 60}{N} \quad (3.2.3)$$

where N is the number of time intervals in which a day is divided for this calculation. We must take the absolute of the heat flow computed for each interval in Eq. (3.2.3) so that the positive and negative heat fluxes at different times do not cancel each other out when we sum them up. The result of Eq. (3.2.3) is the total energy cost of using the heater and air conditioner:

$$Q = E_{\text{H}} + E_{\text{AC}} \quad (3.2.4)$$

The actual attribution of heating and cooling costs depends also on the season. The following two subsections discuss this dependence in further detail.

3.2.2 The Effect of Windows

Solar radiation shines into a building through its windows. Part of this energy is absorbed by the inside of a building and converted into thermal energy to warm it up. This effect is a double-edged sword to the energy efficiency of a building. While the effect decreases the heating cost in the winter, it increases the cooling cost in the summer. Effectively, this changes the total heat flow in the following way:

$$Q' = \begin{cases} Q - S & \text{winter} \\ Q + S & \text{summer} \end{cases} \quad (3.2.5)$$

where S is the total amount of solar energy transmitted into the building through all of its windows.

Not all solar radiation can go through a window. A certain portion is reflected or absorbed by the window (Figure 3.2.2). The *solar heat gain coefficient* (SHGC) of a window specifies the percentage of solar radiation that it actually transmits. Table 3.2.1 lists the SHGCs of a variety of windows.

The amount of solar energy that a building gains through a window depends on the size, height, orientation, and SHGC of the window, as well as the location of the building and the time and
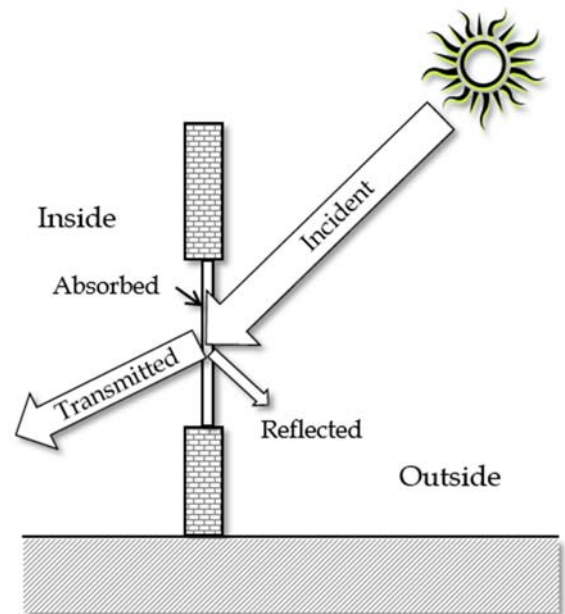

Figure 3.2.2 Solar radiation is absorbed, reflected, or transmitted by a window.

date. In addition, objects in the surrounding can reduce the amount if they block the sunlight. You should consider these dependencies while designing windows for your building and choose their SHGC properties wisely to achieve optimal performance for the whole year.

Glazing Type	SHGC
Single glass, clear	0.66
Single glass, bronze tint	0.56
Single glass, green tint	0.55
Double glass, clear, ½″ air space	0.59
Double glass, bronze tint, outer pane, ½″ air space	0.49
Double glass, green tint, outer pane, ½″ air space	0.47
Double glass, clear, e=0.2, ½″ air space	0.51
Double glass, "Southern" low-E, e=0.08, on tint, ½″ air space	0.29
Double glass, spectrally selective, e=0.04, ½″ argon space	0.33
Triple glass, e=0.08, ⅜-½″ air or argon spaces	0.39

Table 3.2.1 Typical solar heat gain coefficients of windows. Source: WINDOW 4.1, Lawrence Berkeley National Laboratory, Berkeley, CA, 1994.[4]

3.2.3 The Temperature of the Ground

A building exchanges heat with not only the outside air but also the ground. Most buildings rest on a foundation whose temperature has a variation pattern different from that of the air temperature. You may experience this difference when you walk into the basement of a house from the outside in the summer or in the winter.

The ground temperature is modeled using the Kusuda-Archenbach model,[5] which relates the ground temperature with the depth y and the day of year d as follows:

$$T_{\text{ground}}(y, d) = T_{\text{mean}} - T_{\text{amp}} e^{-y\sqrt{\frac{\Omega}{2\alpha}}} \cos\left[\Theta + \Omega(d - d_0) - y\sqrt{\frac{\Omega}{2\alpha}}\right] \quad (3.2.6)$$

where $\Omega = 2\pi/365$, d_0 is the lag in days due to the effect of heat capacity of the ground ($d_0 = 30$ days by default), a is the thermal diffusivity of the ground, Θ is 0 for the northern hemisphere and π for the southern hemisphere, T_{mean} is the annual mean of the air temperature at the location, and T_{amp} is the amplitude of the annual fluctuation of daily average air temperature (*not* the amplitude of the daily fluctuation).

---

[4] https://windows.lbl.gov/pub/selectingwindows/window.pdf
[5] T. Kusuda and P.R. Archenbach, Earth Temperature and Thermal Diffusivity at Selected Stations in the United States, *ASHRAE Transactions*, **71**, (1965) 61-75
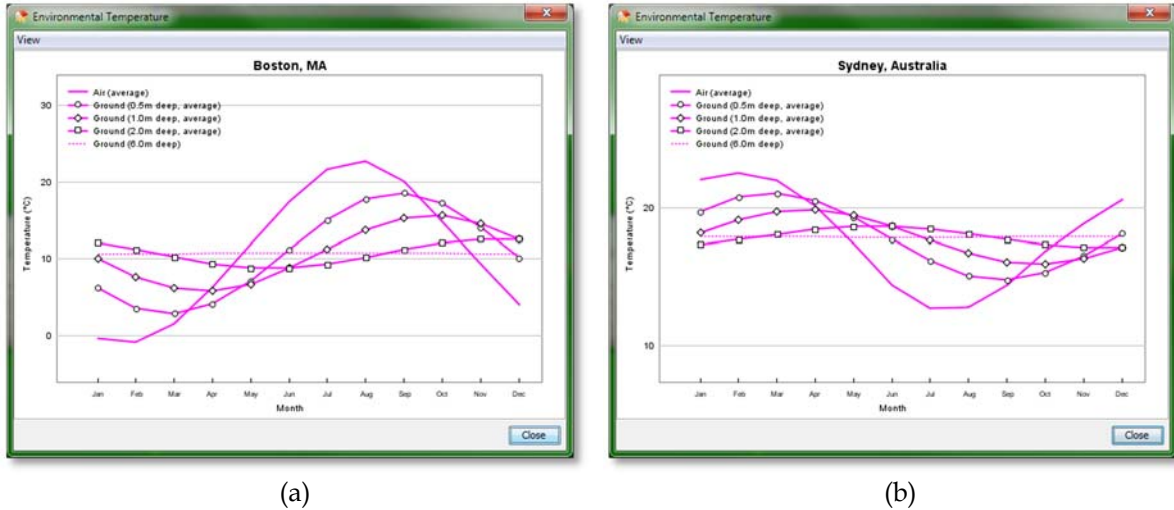
| (a) | (b) |

Figure 3.2.3 The average temperatures of the ground at various depths throughout a year in Boston, USA (a) and Sydney, Australia (b). The average air temperatures are also plotted for comparison.

Energy3D provides a tool "Show Annual Environmental Temperature…" under the Analysis Menu for you to examine the seasonal changes of air and ground temperatures. Figure 3.2.3 shows the results of ground temperatures at three different depths, 0.5m, 1m, 2m, and 6m in Boston, USA and Sydney, Australia, as well as the air temperatures, in different days of the year. As the depth increases, the annual temperature fluctuation decreases. The ground temperature at the depth of 6m is almost constant throughout the year. Depending on the latitude, this constant temperature is between 10°C and 16°C—roughly the mean annual air temperature at that location. This means that it is higher than the air temperature in the winter and lower than the air temperature in the summer. The geothermal heat exchanger takes advantage of this effect to heat a house in the winter and cool the house in the summer.

To model the heat transfer between a building and the ground, we extend Kusuda and Archenbach's work to obtain the ground temperature of a given minute m on a given day d (we determine that minute is sufficiently small to be used as the time unit for energy simulations in Energy3D):

$$T_{\text{ground}}(y, d, m) = \quad T_{\text{ground}}(y, d) - \frac{1}{2}\big[T_{\text{high}}(d) - T_{\text{low}}(d)\big]e^{-y\sqrt{\frac{\Omega}{2\alpha}}}\cos[\omega(m - m_0)] \quad (3.2.7)$$

where $\omega = 2\pi/1440$, m_0 is the lag in minutes due to the effect of heat capacity of the ground (m_0 = 120 minutes by default), T_{high} is the highest air temperature of the day, and T_{low} is the lowest air temperature.
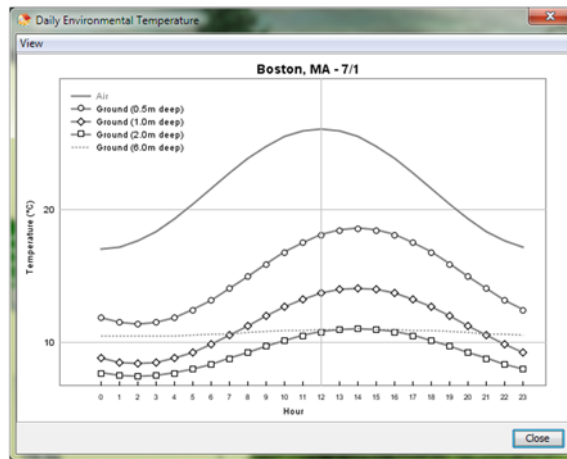
Energy3D provides a tool "Show Daily Environmental Temperature…" under the Analysis Menu for you to examine the daily changes of air and ground temperatures. Figure 3.2.4 shows the results for Boston and Sydney. Note that July 1st is winter in the southern hemisphere.
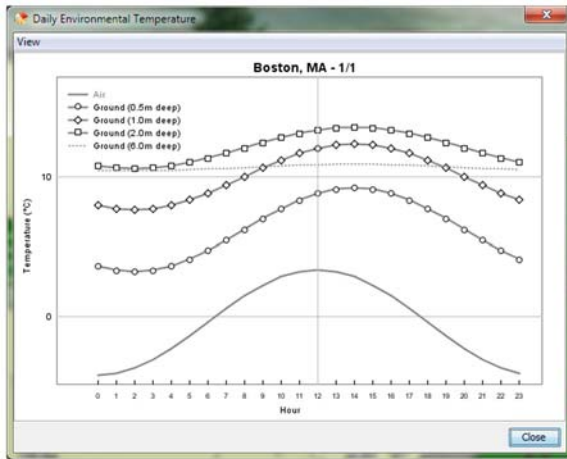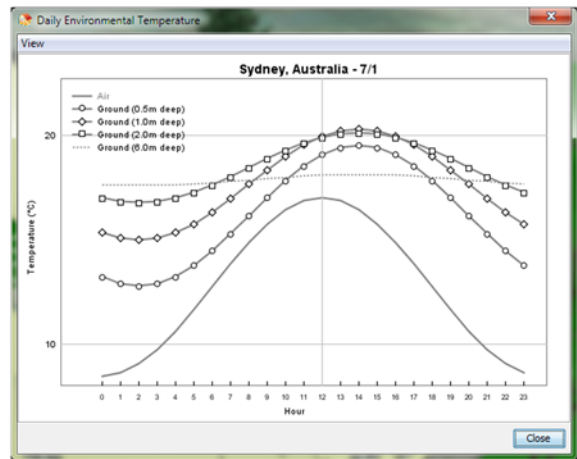
(a)
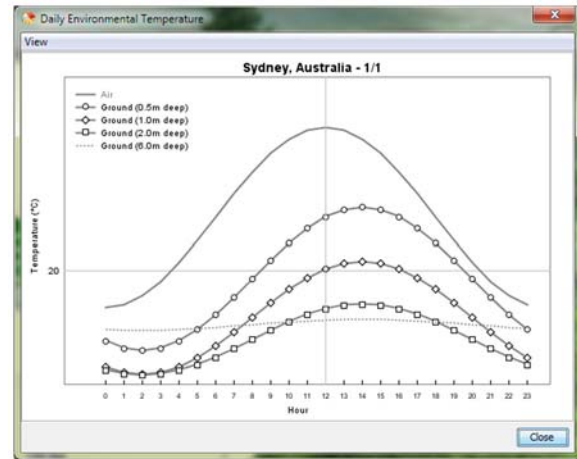
(b)

(c)

(d)

Figure 3.2.4 The temperatures of the ground at various depths on January 1st and July 1st in Boston, USA (a, c) and Sydney, Australia (b, d), respectively. The air temperatures are also plotted for comparison.

3.2.4 Renewable Energy Generation

With renewable energy technologies such as solar panels and geothermal heat pumps, a building can produce energy on-site for its own use or for sharing with others through the electrical grid. In Energy3D, you can add solar panels in your design. We assume that all the energy harvested by a solar panel is used by the building to offset the heating or cooling cost. Therefore, your *net* energy spending throughout a year is

$$E_{\text{Net}} = E_{\text{H}} + E_{\text{AC}} - E_{\text{SP}} \qquad (3.2.8)$$

You can choose solar panels with different energy conversion efficiency. High-efficiency solar panels are more expensive, but they produce more electricity throughout a year. Although the initial investment may be higher, you may be able to reach the break-even point faster. The

orientation of a solar panel is also important. If you face a solar panel in the wrong direction, it will be unable to perform no matter how high its efficiency of energy conversion is.

3.2.4 Design Strategies

Eq. (3.2.8) suggests that the strategies for creating a *zero-energy building* that consumes no net energy over the course of a year or, even better, an *energy-plus building* that produces more energy than it consumes over the course of a year, are:

- Reducing as much heating and cooling costs as possible
- Producing as much renewable energy as possible

These strategies must be considered within the constraint of a budget.

Exercises

_____

Exercise 3.1: How much energy will you save if you reduce the inside temperature by one degree throughout the year? You can investigate this with Energy3D. To begin with, download an existing house model: http://energy.concord.org/energy3d/exercises/colonial.ng3. Open it in Energy3D. Before changing anything, run "Analysis > Run Annual Energy Analysis for Building…" until the analysis is complete. When you close the graph window of the analysis task, choose to keep the results. Then decrease the inside temperature by 1˚C and repeat the analysis. The difference in the net energy is what you can save by lowering down the indoor temperature.

Exercise 3.2: As you can see from the analysis graph when doing Exercise 3.1, lowering down the indoor temperature in the winter decreases the heating cost in the winter but increases the cooling cost in the summer. Suppose you can only set a single temperature for the whole year with the thermostat. Your task now is to investigate the change of energy cost if you *increase* the inside temperature by 1˚C following the same procedure described in Exercise 3.1.

Exercise 3.3: Now change the location of the building from Boston to Miami and repeat the above two investigations. What would you recommend to the homeowners of the two cities if they can only set the inside temperature once for the whole year: Increase or decrease it?