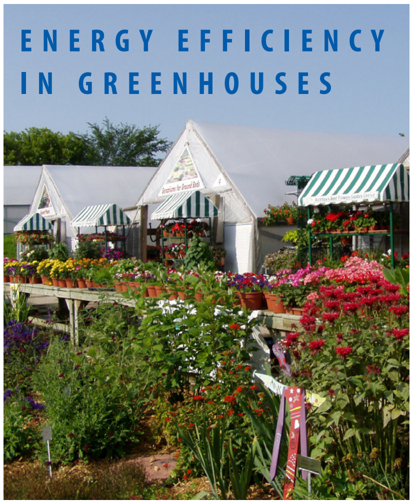


A3907-01

Reducing greenhouse energy consumption—An overview

Scott Sanford

With energy costs representing more than 10% of greenhouse growers' sales, now is an optimal time to consider ways to reduce greenhouse energy consumption.

Energy costs are the third highest cost for most greenhouse growers, behind labor and plant materials (U.S. Department of Agriculture, *2009 Census of Horticultural Specialties,* Table 33). Energy costs represented 5.9% of sales in 2003, but that number has grown to over 10% because of increasing energy costs and downward pressure on retail prices (Brumfield, Both, and Wulster, *How Are Greenhouse Growers Coping with Rising Energy Costs?*, 2009). Heating energy represents 70 to 80% of a typical greenhouse grower's total energy consumption, while electricity represents 10 to 15% and transportation fuel (for trucks, tractors, and other vehicles) makes up the rest.

This publication covers key aspects of heating and cooling a greenhouse that you should consider—preferably before the greenhouse is built. Topics include the effects of glazing materials on heat loss and light transmission, ways to reduce infiltration and nighttime heating losses, types of greenhouse heating units, the effect of heat distribution on heating costs, ways to maximize space utilization, using efficient circulation and ventilation fans, how supplemental lighting can reduce energy requirements, and more. This publication also refers to several additional resources, the details of which can be found in the **Resources** section at the end.

As you consider ways to reduce energy consumption in a greenhouse, it's important to recognize that there are trade-offs between the agronomic needs of the plants and the economic savings offered by the various energy-efficiency options. For example, using more layers of glazing materials (greenhouse coverings) reduces heat loss, but it also reduces the amount of light transmitted into the greenhouse, in turn reducing plant growth. Therefore, if you're considering adding a layer of glazing material, you must weigh the energy savings against the longer plant-growth cycles. On the other hand, you could use glass glazing to maximize light transmission, but doing so would require a larger capital cost because the weight of the glass would require a stronger structure. The operation costs would also be higher due to higher heat-loss rates of single-pane glass glazing. Energy-related greenhouse management factors, such as set-point temperatures and relative humidity, can also affect plant growth rates and disease and require trade-offs. For example, keeping the greenhouse at a lower temperature reduces daily heat losses, but keeping it below plants' optimal range can extend growing times and increase production costs.

Basics of heat loss and gain

The heat losses and gains in greenhouses occur in four ways: **conduction, convection, infiltration,** and **radiation** (figure 1). All of these heat loss and gain pathways exist in all buildings and greenhouses, regardless of the building type or size. All four pathways affect the temperature whether you are heating or cooling a greenhouse, but in northern climates, they are typically examined in terms of heat loss because heating represents the majority of energy costs.

Conduction heat loss is the transfer or flow of heat through a material, such as greenhouse glazing. The energy flow rate is called the heat transfer coefficient, or U-value, and is measured in British thermal units per square foot per degree Fahrenheit per hour (Btu/ft^2-°F-hr). You may be more familiar with R-value, or thermal resistance, which is used to rate building materials. The R-value of a material is the inverse of the U-value (R = 1/U). The smaller the U-value or the larger the R-value, the lower the rate of heat loss through a material.

Convection heat loss is the exchange of heat between a moving fluid, such as air in a greenhouse, and a solid surface. As air is heated in a greenhouse, it rises to the roof and loses some of its heat to the roof glazing materials. Then the cooler, heavier air sinks towards the floor until it is warmed by the heater or by warmer floors and benches.

Infiltration is the exchange or leakage of air through small openings in the greenhouse envelope (figure 2). In winter, the air entering the greenhouse will need to be heated to bring it to the greenhouse set-point temperature. In summer, the air entering will need to be cooled.

Figure 2. Infiltration heat loss occurs when cold air enters and heated air escapes the greenhouse through cracks and small openings, such as those around the sill board, doors, and joints.

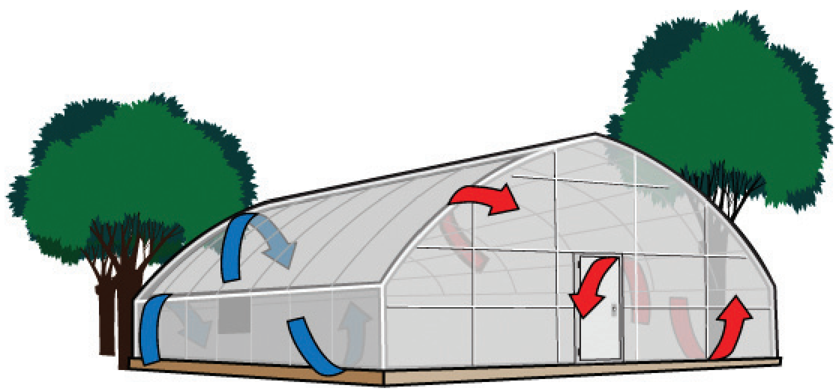
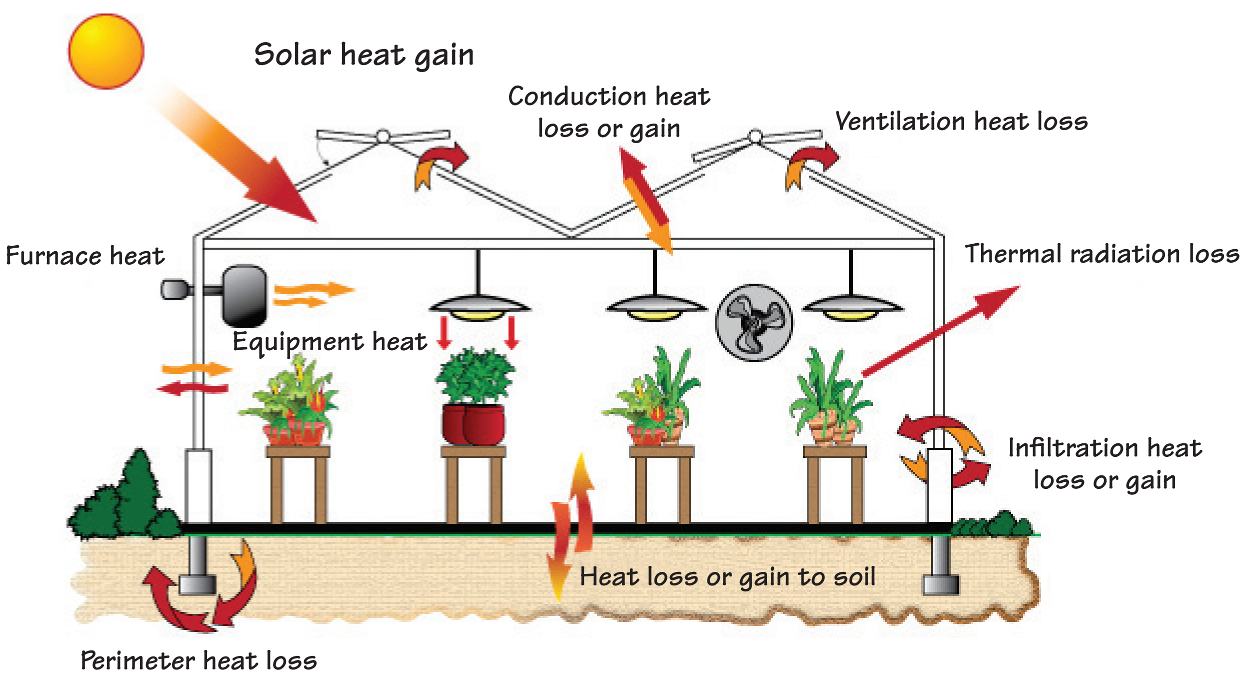
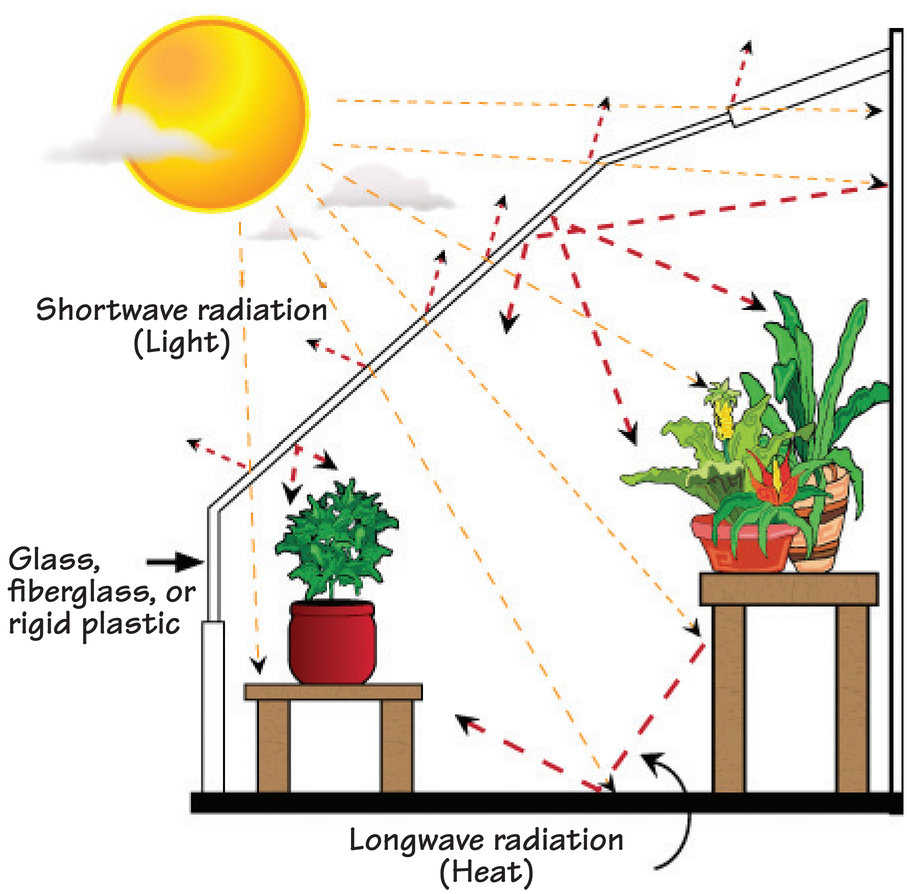


Figure 1. Greenhouse heat loss and gain pathways.



Radiation is heat transfer between two bodies without direct contact or a transport medium. There are two types of radiation that affect greenhouses: solar, or **shortwave** radiation and longwave, or **infrared (IR)** radiation. Radiation can result in heat loss or heat gain, depending on conditions. Sunlight is an example of radiation heating: Shortwave radiation from the sun passes through the glazing and heats the greenhouse plants, soil, and structures even when it is below freezing outside. Radiation cooling is most noticeable on clear winter nights. As the plants, soil, and greenhouse structures become warmer than the surrounding temperature, they emit heat in the form of IR radiation. The radiated heat travels toward the glazing, and some is reflected back into the greenhouse while some passes through and out to the night sky (figure 3).

Figure 3. Shortwave radiation from the sun heats objects inside the greenhouse, which then re-radiate the heat. Some of that longwave radiation is reflected back into the greenhouse, while the rest passes through the glazing materials and out into the air.



Structural considerations

If you are planning new greenhouses, be sure to consider how the type, shape, orientation, and glazing materials will affect energy consumption.

Greenhouse type

A gutter-connected greenhouse covering a half-acre has 15 to 20% less surface area and therefore less heat loss than several freestanding greenhouses covering the same area. Stand-alone greenhouses have a surface area–to–floor area ratio of 1.7 to 1.8, while gutter-connected greenhouses have a ratio of about 1.5 or less.

Space can be used more effectively in a gutter-connected greenhouse, leading to higher labor efficiency, but the entire greenhouse shares the same environmental conditions unless you divide it with walls and set up the heating and ventilation systems in zones. Dividing the greenhouse into zones allows you to heat only a portion of the greenhouse when starting up, reducing energy costs. Many growers create zones using vertical roll-up curtains along a post line.

Freestanding greenhouses provide isolated growing conditions, which can help control diseases and pests and allow for different environmental conditions to meet the needs of specific crops. Stand-alone greenhouses are also narrower, which makes them easier to ventilate naturally with roll-up sidewalls, and they can be heated as they are filled.

An example illustrates the potential energy savings: Two growers are considering new greenhouses in Madison, Wisconsin. Grower A plans to buy freestanding greenhouses while Grower B plans to buy a gutter-connected greenhouse. Both growers plan to grow spring bedding plants. All of the greenhouses will have a double layer of polyethylene film with IR treatment on the inside layer. Each grower will have 24,000 square feet of covered floor area, and the greenhouses will be heated from February 15 to May 31 with LP gas power-vented unit heaters with a seasonal efficiency of 78%.

Grower A plans to buy eight 30- x 100-foot greenhouses with 3-foot sidewalls and 15-foot peaks. According to a heat-loss model, each greenhouse will use an estimated 1,793 gallons of LP gas over the 4-month period, for a total of 14,344 gallons of fuel. Grower B plans to buy one five-bay gutter-connected greenhouse that measures 150 x 160 feet (30-foot-wide bays) and has 10-foot sidewalls and a 15-foot peak. The heat-loss model estimates that the gutter-connected greenhouse will use 11,929 gallons of LP gas over the 4-month period. In this example, the gutter-connected greenhouse will use 2,415 gallons less LP gas than the eight freestanding greenhouses and expend 18% less energy.

You may be thinking: But I'm just a small grower! If there's a possibility you might want to expand, be sure to plan for growth and expansion from the beginning. Consider starting with a small one- or two-bay gutter-connected greenhouse that will allow you to add bays or extend the length as your business grows. The initial cost for the greenhouse will be higher, but you'll see the payback as you grow.

Shape

Which geometric shape has the smallest surface area for a given covered area? A hemisphere (half of a sphere). For commercial greenhouses, a hemisphere may not be practical, but a cube is and has the second smallest surface area for a given covered area. So the closer your greenhouse footprint is to a square, the less heat loss and lower heating bills you can expect. Notice that in the example above, the 150- x 160-foot gutter-connected greenhouse is very close to a square.

Orientation

Generally, it's best to orient single-span greenhouses so the length runs east–west. This orientation maximizes winter sunlight and heat gain in the greenhouse (figure 4). Orient gutter-connected greenhouses with the length running north–south so that the shadow cast by the gutters moves during the day. If a gutter-connected greenhouse is oriented east–west, the shadow of the gutter will move very little, creating a location with less direct sunlight and possibly slower plant growth.

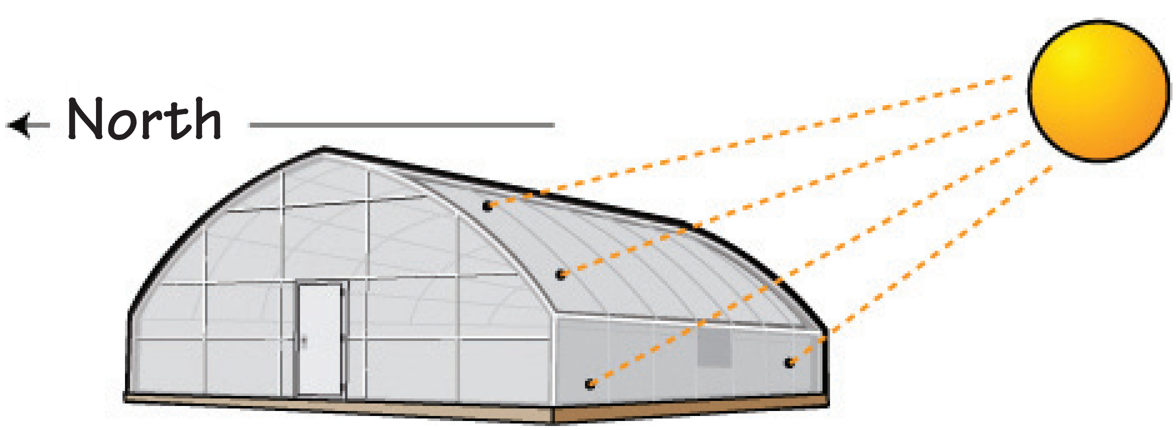
Glazing materials

Common glazing materials for greenhouses include glass, acrylic, polycarbonate, polyethylene film (often called poly film), and fiberglass. These materials can be used as a single layer or multiple layers; using two layers is most common. Glass is the original greenhouse covering, while most new greenhouses use a double layer of poly film glazing. Fiberglass was popular in the past but is no longer used in commercial greenhouses because it degrades (yellows) rapidly, reducing light transmission faster than other similarly priced glazing materials.

Glass is typically used as a single layer and therefore has the disadvantage of high heat loss, but it also has the highest light transmittance, which is important because light equals plant growth. Glass lasts a long time, often outlasting the structure that supports it, but it is also heavy and requires a more expensive structure to support the weight.

A double-layer poly film glazing loses heat at half the rate of single-paned glass but has a 3- to 4- year life, the shortest of any of the glazing materials, and transmits about 10% less light than glass. Poly film is cheap, and its light weight allows for a lower-cost structure.

Figure 4. Orienting a single-span greenhouse so the length runs east–west maximizes winter sunlight and heat gain.



However, despite the different properties of glazing materials, all single-walled glazing materials transmit about 90% of sunlight, regardless of the type of material (table 1). A second layer of glazing reduces the light transmission about 10%, to about 80%.

The conduction heat-loss rate of single-pane glass is approximately the same as other single-walled materials; all single-walled materials have a U-value of 1.1 to 1.2 Btu/ft^2-°F-hr. Double-walled glazing materials are roughly equal also; their U-values range from approximately 0.5 to 0.7 Btu/ft^2-°F-hr.

Glazing materials with shorter life expectancies usually fail or need to be replaced because UV radiation degrades the glazing, reducing light transmission. Many insurance companies require glazing and exposed insulation to be made of materials with low flammability.

Traditionally, triple-wall polycarbonate is used for walls but is not recommended for the roof, because the three layers allow less light to get to the plants. It can be used for roofing, but it transmits about 4 to 5% less light than double-wall materials (about 75% light transmission). Supplemental lighting can be used to compensate for the lower light levels, allowing growers to use triple-wall glazing without slowing plant growth. However, installing a thermal curtain system would allow you to use a glazing material with higher light transmittance and save substantially more energy, so a curtain system is generally recommended over triple-wall glazing.

Thermal transmission is the ability of IR radiation (heat) to travel through material and is particularly an issue in greenhouses on cloudless winter nights. Glass and rigid plastic glazing have the potential to keep thermal transmission to less than 3%, while regular poly films lose about 50% of the radiant heat. If condensation has collected on the glazing, less IR radiation will leave the greenhouse, but less sunlight will enter the greenhouse.

Poly film manufacturers have developed films with an IR radiation additive, which reduces the loss of IR radiation through the films. These special IR films typically reduce losses by up to 30% and cost about 1.5¢ more per square foot than a standard film (about $10 per year for a 30- x 96-foot greenhouse). A greenhouse with double-layer poly film glazing would have the IR film as the inside layer only and would have a standard film as the outside layer. IR films have the same light transmittance as regular poly films; in fact, they help to diffuse the light entering the greenhouse, which is helpful for growing some crops. The payback on IR film versus a standard film is about 2 to 3 months in the northern climates.

Table 1. Comparison of glazing material properties

Material	% light transmission	U-value[1]	% thermal transmission[2]	Life expectancy (years)	Flammability[3]
Glass					
Single	88–93	1.1	3	25+	none
Double	75–80	0.7	< 3	25+	none
Acrylic					
Single	90	1.13	< 5	30+	medium
Double	84	0.49–0.56	< 3	30+	medium
Polycarbonate					
Single	90	1.1	< 3	10–15	low
Double (6–10 mm thick)	78–82	0.53–0.63	< 3	10–20	low
Triple (8–16 mm thick)	74–76	0.42–0.53	< 3	10–20	low
Polyethylene film					
Single	87	1.2	50	3–4	varies
Double	78	0.7	50	3–4	varies
Double, with IR	78	0.5	< 20	3–4	varies

Sources: *Energy Conservation for Commercial Greenhouses* (NRAES-3) and product literature.

[1] The lower the U-value, the less heat lost through a given material.

[2] Refers to the amount of infrared radiation (heat) that travels through the material and out of the greenhouse.

[3] Reflects the likelihood of the material being easily ignited if directly exposed to a flame.

Most film manufacturers make only one or two IR products, and the IR additive is often combined with an anti-condensate additive to reduce condensate beading on the film. Product names that contain "IR" indicate that the product has additives for blocking IR radiation. "AC" indicates the presence of an anti-condensate additive (see table 2).

Most new greenhouses use a double poly film or, for structured walls, a double-wall polycarbonate glazing. Acrylic, an alternative to polycarbonate, has superior UV and weather resistance, which is reflected in the longer expected life of 30 years or more. Double-walled acrylic also has about 3% higher light transmittance than double- or triple-walled polycarbonate and 6 to 8% higher light transmittance than poly films, which means faster plant growth. The disadvantages of acrylic are that it scratches easily and costs more. In a double-walled polycarbonate or acrylic greenhouse, the wider the air gap, the lower the conduction heat-loss.

Air space between poly film layers

If you use a double poly film glazing, you must inflate and maintain the air space between the two layers of film to reduce heat loss. This is commonly done using a small electric blower. Growers are strongly encouraged to locate the blower inside the greenhouse but draw air from outside, because the colder outside air will have lower humidity and result in less condensation between the sheets (figure 5).

The poly film layers may touch where the film is stretched over the roof peak or transitions from the roof to the sidewalls, restricting air movement and leading to underinflated sections. If the film is too loose, it can move against the frame and wear, leading to holes. You can eliminate both of these problems by adding jumper hoses between roof and wall sections. If there is a leak in the outside layer (from a hole or improper sealing), it may result in excessive condensation on the inside layer. Finding and fixing the leak should reduce the amount of condensation.

Recycling plastic glazing materials

The expected life span of plastic glazing materials can range from 1 to 4 years for plastic films to 10 to 15 years for polycarbonate, on up to 30 years or more for acrylic. Eventually, all plastic glazing materials degrade and must be replaced. All plastic glazing materials are recyclable if kept clean, and recycling them saves energy because they are petroleum based. Contact your local plastic recycling company or local recycling coordinator for recycling locations.

Sealing the greenhouse envelope

Infiltration rates in greenhouses are measured by the number of air exchanges per hour and are proportional to the number of joints in the greenhouse glazing and other openings such as louvers, doors, and fans. Glass greenhouses have the highest infiltration rates while double poly film–covered greenhouses have the lowest—typically half the rate of a glass greenhouse (table 3).

Table 2. Major manufacturers of polyethylene films with IR additives

Company	Trade name
AT Films Inc.	Dura-Film 4 Thermal AC
	Dura-Film 4 Thermal AC Plus
Berry Plastics Corp.	Tufflite Infrared
Ginegar Plastic Products Ltd.	Sun Saver 4 (EVA)
	Sun Selector AD-IR
	Suntherm
Green-Tek Inc.	GT-IR/AC
Klerks Hyplast Inc.	K3 IR/AC
	K50 IR/AC

Table 3. Infiltration rates for greenhouses

Type of greenhouse	Air exchanges per hour
New construction	
Double-layer poly film	0.5–1.0
Polycarbonate, acrylic	0.75–1.25
Glass	1.0–1.5
Old construction	
Good condition	1.0–2.0
Poor condition	2.0–4.0

Sources: Adapted from *Energy Conservation for Commercial Greenhouses* (NRAES-3) & the National Greenhouse Manufacturers Association's heat-loss standard.

Figure 5. An outside air kit helps minimize condensation by pulling air from outside the greenhouse to inflate the space between sheets of poly film.

Locating and plugging holes in the greenhouse envelope generally reduces infiltration heat losses by 3 to 10%. Follow this checklist to find and seal the most common gaps:

- Make sure roof and wall vents close properly and that gaskets are in good condition and seal tightly.
- Check that the glazing is fastened tightly and that lap joint seals are in good condition.
- Repair any holes in the glazing.
- Add or replace weather stripping around doors and install doorsills as needed.
- Seal corrugated roll-up doors for winter; they tend to have significant air leaks along the sides and across the top and are difficult to seal. Installing a plastic film over unused doors is the best way to seal them.
- Seal roll-up or curtain sidewalls for the winter. Use a piece of poly film and a wiggle-wire channel on the inside, or use a wiggle-wire channel to fasten curtains to the sill board and ends.
- Fill in gaps around the sill board so the earth comes up halfway on the inside and outside.
- In winter, cover unneeded fan and vent louvers with foam boards and plastic. Make sure the power is disconnected. Also, ensure that fan and vent louvers needed during the winter close tightly. If louvers need to be lubricated, use a dry lubricant, such as graphite, which won't attract dirt. Consider using a nighttime cover for louvers to reduce infiltration losses.
- Cover leaky glass greenhouses with a single or double layer of poly film to reduce infiltration losses by as much as 40%.

Figure 6. A slope-flat-slope layout is one type of thermal and shade curtain system that can significantly reduce nighttime heat loss.

Windbreaks

Wind speed greatly affects infiltration rates; 15 mile-per-hour winds can double heat loss in a greenhouse. Well-designed windbreaks can reduce wind speeds by 50%, reducing heat losses by 5 to 10% compared to an open area. They can also reduce snow accumulation on roofs. A windbreak can be a fence-like structure or it can be 4 to 5 rows of mixed coniferous and deciduous trees. Using a mix of species and both fast- and slow-growing trees reduces the risk of disease or pests affecting the entire windbreak. Hybrid poplar and white pine are generally good choices for fast-growing trees. The windbreak should be located upwind of the prevailing wind direction at a distance of 4 to 6 times the mature height of the trees planted.

Insulation

In general, as much of the greenhouse envelope as possible should be translucent materials to let in the sunlight, but some areas can be insulated to reduce conduction heat loss without reducing light. If your plants sit on benches, you can insulate the area from the sill board to the bench top because it doesn't affect the amount of light that reaches the plants. In new construction, you can fabricate the wall by conventional construction methods and use 1 or 2 inches of foam board for insulation. In an existing greenhouse, you can fasten a piece of foam board against the glazing. The foam board needs to be rigidly held in place and sealed on all sides to provide insulation value. Foam board loosely set along the sidewalls provides little insulation.

Foam is flammable and should be kept away from heat sources. It's a good idea to use foam board faced with aluminum foil because it increases flame resistance, reflects heat back into the greenhouse, and reduces the rate at which UV radiation degrades the foam board.

You can also insulate all opaque surfaces on the north walls of greenhouses, although many growers have found that there is enough indirect light from the clouds and snow cover that using translucent coverings helps contribute to plant light levels.

In new construction, installing perimeter insulation is recommended. This is commonly done by installing a 1- or 2-inch foam board to a depth of 24 inches or more around the perimeter, on either the inside or outside of the sill board. Perimeter insulation not only reduces heat loss but also keeps the ground or floor near the walls warmer—an important factor when plants are sitting on the floor, as cold roots slow growth.

Thermal and shade curtains

About 80% of greenhouse heating occurs at night, so increasing the resistance to nighttime heat loss has a large impact on reducing heating costs. Thermal curtains, or screens, as they are sometimes called, can reduce nighttime heat loss of the covered surfaces by about 50% (figure 6). They can also be used for summer shading to reduce cooling costs. Thermal curtains are fabrics that are pulled across the roof and are sometimes used to cover sidewalls. The curtains retain heat by serving as a thermal barrier between the plants and the roof and, in some cases, they reduce the volume of heated space in the greenhouse. The curtain can travel from gutter to gutter (or side to side), between trusses at the level of the bottom chord (the lowest brace on a rafter), or following the pitch of the roof. Curtain materials vary from plastic film (not recommended) to aluminized woven fabrics that reflect heat back into the greenhouse.

Thermal curtains can be controlled automatically or manually. They can be automated to open and close according to available sunlight, temperature, or time, or, in smaller greenhouses, they can be operated manually with a crank to reduce initial costs. Some growers install two curtains to fulfill different purposes, such as shading and blackout, and use them together in winter to minimize nighttime heat loss. For more detailed information on thermal curtains, see the publication *Using Curtains to Reduce Greenhouse Heating and Cooling Costs* (A3907-03).

Greenhouse heating

Effective greenhouse heating requires that you consider not only the type of heating system and maintenance needed but also the location of the heat distribution.

Unit heaters

Unit heaters have been the heater of choice for many growers because of their low capital and installation costs, reliability, and ease of staging. There are five types of unit heaters available for greenhouse application: gravity-vented, power-vented, separated-combustion, high-efficiency condensing (figure 7), and unvented. The efficiencies, placement, and economics of these types of heaters are discussed in detail in the publication *Greenhouse Unit Heaters* (A3907-02).

Figure 7. A high-efficiency condensing heater.

Using multiple heaters is highly recommended for all greenhouses to reduce the chance of a no-heat situation. If one heater fails, the remaining heater(s) must be able to keep the greenhouse warm enough to prevent plants from being damaged or killed.

For large greenhouses, a central hot water boiler is a popular choice. The heat can be distributed into the greenhouse through a heated floor, radiant heat pipes, or water-to-air heat exchangers. Selecting an efficient boiler and keeping it well maintained is key to keeping energy costs under control.

Heated air distribution

The heat distribution location in a greenhouse can decrease total energy usage and increase growth and yields at the same time. Often, greenhouses are heated with one or two forced-air unit heaters that discharge the heated air above crop level. If two unit heaters are used, they are typically placed in opposite corners on opposite ends of the greenhouse to create a circular airflow pattern. Heaters are often placed high in the greenhouse to allow more room for benches or walkways. Heat rises, so to maintain the desired temperature at the crop level, the entire volume of the greenhouse must be heated.

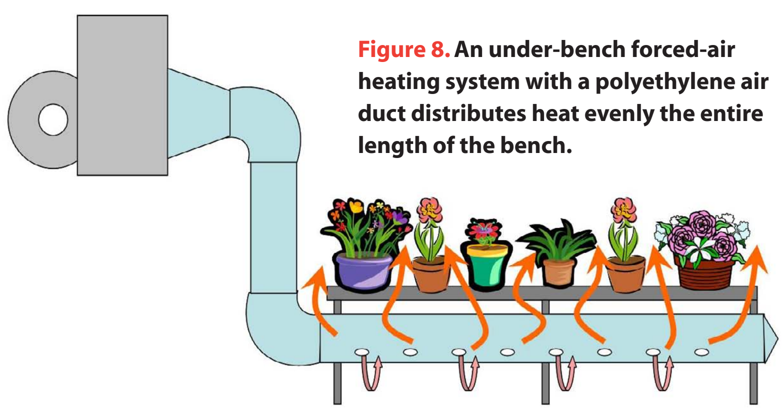
Many growers use stirring fans to reduce air stratification (the tendency of hot and cold air to separate, with hot air rising and cold air sinking) and equalize the air temperature. This system is effective, but it is not the most energy-efficient option because it heats air that does not necessarily benefit plant growth.

Distributing the heat in the floor, under the bench, or on the bench creates a microclimate, warming the plants and immediate surroundings—but not the entire greenhouse—to the desired growing temperature. This production method, known as root-zone heating, saves approximately as much energy as turning down the thermostat 5 to 10°F.

In-floor heating typically uses a hydronic, or hot water, heating system. Heat pipes are usually distributed about 12 inches apart in the floor, and the heat warms the floor and transfers to pots sitting on the floor and to the surrounding air. A boiler provides the heat or, in small- and medium-sized greenhouses, a hot water heater will work. If you plan to use hydronic floor heating, you'll still need a unit heater or air–heat exchanger during cold spells because the heated floor will not transfer heat rapidly enough to maintain the desired growing temperature around the plants.

Under-bench heating can use either a forced-air system or a hydronic system. A forced-air system can consist of a unit heater with a blower-type fan connected to ductwork that distributes the heated air under the bench. A polyethylene air duct is inexpensive and distributes the heated air evenly the entire length of the bench (figure 8). However, the polyethylene tube will get wet from watering and may be a place for algae and bugs to grow.

Figure 8. An under-bench forced-air heating system with a polyethylene air duct distributes heat evenly the entire length of the bench.



An under-bench hydronic system uses a low-output finned tube (such as Delta Fin™ TF or DuoFin) or a standard pipe to provide heat under the plants (figure 9). (Delta Fin is a trademark of Delta T Solutions in San Marcos, and DuoFin is a product of TrueLeaf Technologies in Petaluma, California.) Placing a skirt around the bench will help keep the heat under the bench and allow cooler air temperatures in the rest of the greenhouse. Bench-top hydronic heating systems distribute the heat via a mat or tubing placed on the bench.

Research at Rutgers University indicates that root-zone heating requires about 20 Btu per square foot of bench area. It may also require more watering, depending on the water-holding capacity of the soil mix being used.

High-efficiency and radiant heating systems

There are several types of high-efficiency (HE) heating systems that can be used in greenhouses. Some unit heaters have efficiencies in the range of 90 to 93%, and some HE hot water boilers for hydronic systems have efficiencies up to 98%. These HE boilers can operate as stand-alone boilers or be added to an existing boiler system (figure 10). When used with an existing boiler system, the HE boiler is set up as the primary boiler and the existing boiler fires only when the heating demand exceeds the HE boiler's capacity. Add-on HE boilers are often sized at 80% or less of the design capacity to reduce capital costs and provide a faster return on investment.

Overhead radiant heating systems can also be used in greenhouses. These systems radiate heat that heats the plants but not the air directly. Radiant heaters are not widely used in greenhouses because there is a risk of burning the plant leaves. They are best used in loading docks, head houses, or work areas of warehouses.

Heating system maintenance

Heating systems are critical to the operation of a greenhouse. If a heater fails, it could result in substantial crop loss, and if it is operating inefficiently, it will increase production costs. Having the heating system inspected and serviced once a year will usually pay for itself in fuel savings and reduce expensive emergency service calls. Each year, the heat exchangers, burners, and steam traps (if used) should be cleaned and inspected, and the thermostats should be calibrated. Soot on boiler heat exchangers or fire tubes can increase fuel consumption by 10%. If you have a central heating system, you can also conserve energy by insulating pipes and ductwork in the head house where heat is not needed. Proper heating system maintenance can reduce fuel costs by up to 20%.

It's also important to evaluate air intakes for unit heater and boiler combustion air to maintain proper combustion. If you smell combustion gases in the greenhouse on a cold night when all of the heaters are running, the heating system isn't vented properly or doesn't have enough air intakes for proper combustion.

Figure 9. An under-bench hydronic heating system can use a low-output finned tube or a standard pipe to provide heat under the plants.

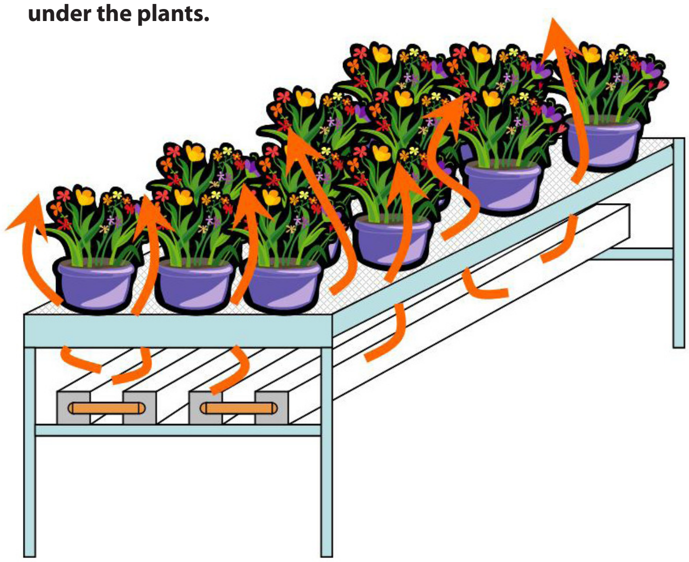


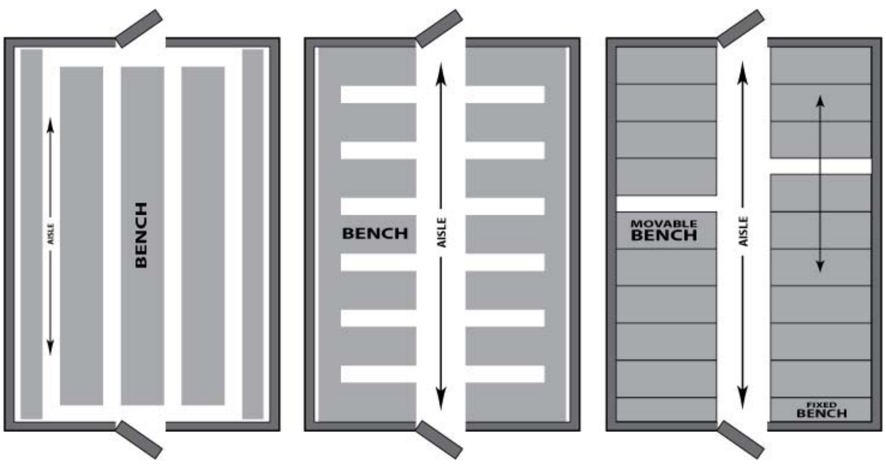
Figure 10. High-efficiency hot water boilers can operate as stand-alone boilers (shown) or be added to an existing boiler system.

Space utilization

You may not think of effective space utilization as a way to conserve energy, but the more plants you can fit into a greenhouse, the lower the energy per unit produced will be. A traditional, longitudinal layout with benches running lengthwise in a 30- x 96-foot greenhouse provides a growing area of 64% of the total floor area (figure 11). A peninsular layout provides 70% of the space as growing area. Movable benches can increase the growing space to 84%. You can use the longitudinal layout for retail as well as growing, while the movable benches are strictly for growing unless they are on wheels and you can remove some of them from the greenhouse for the retail season. The peninsular layout can be used for retail space depending on the aisle width between benches. To reach 70% space utilization, you'll have 18-inch aisles, which aren't suitable for retail.

Racking systems and overhead hanging baskets also increase the amount that you can produce in a greenhouse. Plants that require more light can be hung overhead or stacked on the tops of racks with shade-loving plants below. However, growing plants with high light requirements below hanging baskets may increase the production time and affect the plant quality, so it's important to consider plant types. Growing on the floor is also an excellent way to increase space utilization, although it may require an irrigation boom, depending on the layout.

Figure 11. Bench layout affects the amount of available growing space. Growing area percentages in a 30- x 96-foot greenhouse: longitudinal layout—64% (left), peninsular—70% (middle), movable—84% (right).



Fans

Fans play a key roll in controlling the greenhouse environment, and using energy-efficient fans that are properly sized can help reduce energy costs.

Circulation fans

The air in a greenhouse must be mixed to prevent air stratification. Mixing the air also reduces heating needs and lowers fungal disease incidence by promoting faster drying of foliage. There are three types of fans used for this purpose: paddle, jet, and basket fans. Paddle and jet fans are mounted overhead and mix air in a vertical pattern. They are more effective than basket fans at preventing stratification, but they can't be used when some types of thermal or shade curtains are closed and they move air within only a small diameter under the fan.

Baskets fans are the most common and energy-efficient type of circulation fan (figure 12). They are typically mounted on an interior wall, ¼ of the width of the greenhouse from the exterior wall, over the benches and above head-height so they are out of the way. Typically, several fans are placed throughout a greenhouse to create a circular horizontal airflow. Basket fans run continuously, moving the air horizontally around the greenhouse to promote drying, prevent condensation on leaf surfaces, distribute heat evenly, and prevent temperature stratification. During the day, horizontal airflow reduces carbon dioxide depletion at the leaf boundary and reduces the amount of radiant heat on the leaves, decreasing the likelihood of the leaves, flowers, or fruit getting burned. Once basket fans get the greenhouse air moving, they need to overcome only friction and turbulence losses to keep the air moving. A rough rule of thumb is to install enough horizontal airflow fans to supply 2 cubic feet per minute of airflow per square foot of floor area.

Figure 12. Basket, or stirring, fans are the most common and energy-efficient type of circulation fan.

Ventilation fans

Ventilation, or exhaust, fans aid in regulating the temperature and sometimes humidity in greenhouses. Ventilation fans are a substantial user of electricity in a greenhouse, so installing energy-efficient fans will reduce production costs. The efficiency of a ventilation fan is measured as cubic feet per minute per watt (cfm/W), or airflow per unit of energy. The higher the value, the more energy efficient a fan is. However, fan efficiencies can vary greatly. Similar models of 48-inch ventilation fans can have efficiencies that range from 12 to 27 cfm/W. Fortunately, the BESS Lab of the University of Illinois performs independent tests and makes the data available in a bulletin and online to help consumers select energy-efficient fans (see **Resources** section for web address).

In general, larger diameter fans are more efficient, and fans with diffuser cones may be up to 24% more efficient than fans without them. When purchasing ventilation fans, look for fans with efficiency ratings of 20 cfm/W or greater at a static water pressure of 0.05 inch for fans that are 36 inches and larger.

Motors used in greenhouse fans should have totally enclosed housings in accordance with the National Electric Code to keep moisture and dust out. Buying fans with variable speed controllers allows you to purchase larger and more efficient fans and program them to work like a group of smaller fans. The fan can be used at a low speed for winter ventilation and be programmed to speed up as the temperature increases in the greenhouse in spring and summer. A fan running at half speed uses only 15% of the energy used at full speed.

Maintenance

Fan maintenance is often neglected. The two most common maintenance issues are louvers that don't open or close properly and loose belts. Louvers that don't open can reduce airflow by up to 40%, while loose belts that slip can reduce airflow by 30%. At the start of the ventilation season (April), check the louvers for free operation and lubricate pivot points with a dry lubricant such as graphite. Do not use oil or grease, as they will attract dirt faster and cause the louvers to malfunction sooner. Objects in front of the fan outlet, such as trees and shrubs, will impede airflow and should be removed to a distance of 10 times the diameter of the fan.

Check the condition and tension of belts several times during the growing season. If you are buying new fans, you can eliminate a maintenance chore by making sure they have automatic belt tensioners. If you have retrofitted your existing fans with automatic tensioners, checking the belt condition and tension once a season will be sufficient.

If you use insect screens, inspect them regularly and clean them as necessary. Uninspected screens can become dirty or torn, restricting airflow or admitting insects. When using insect screens, select exhaust fans that can overcome pressure drops across the screen and still provide adequate airflow.

Summer temperature control

There are several other tools that you can use to beat the summer heat and save energy. As previously discussed, thermal or shade curtains can help block sun and reduce the temperature in the greenhouse. Shade curtains can lower air temperatures under the curtains by 10°F. Other options for controlling greenhouse temperatures during the summer include evaporative cooling, or misting, and natural ventilation, which can be facilitated with roll-up sidewalls and roof vents or open-roof designs.

Open-roof greenhouse designs can often control the greenhouse temperature sufficiently without exhaust fans. Natural ventilation works primarily on the principle that wind blowing across a roof vent will create a low-pressure zone that will suck the air out of the greenhouse while letting air in the side vents (figure 13). A secondary principle in effect to a significantly lesser degree is thermal buoyancy—the fact that hot air rises. Thermal buoyancy dominates only on hot, still days. In greenhouses with open sidewall vents and open roof vents or an open-roof design, the cooler air enters the greenhouse through the sidewall vents and replaces the hot air that has exited through the roof vents, creating convective airflow. To maximize ventilation and its benefits, the sidewall vents should face the prevailing wind direction and the air inlets should be low enough so the air entering the greenhouse moves through the plants.

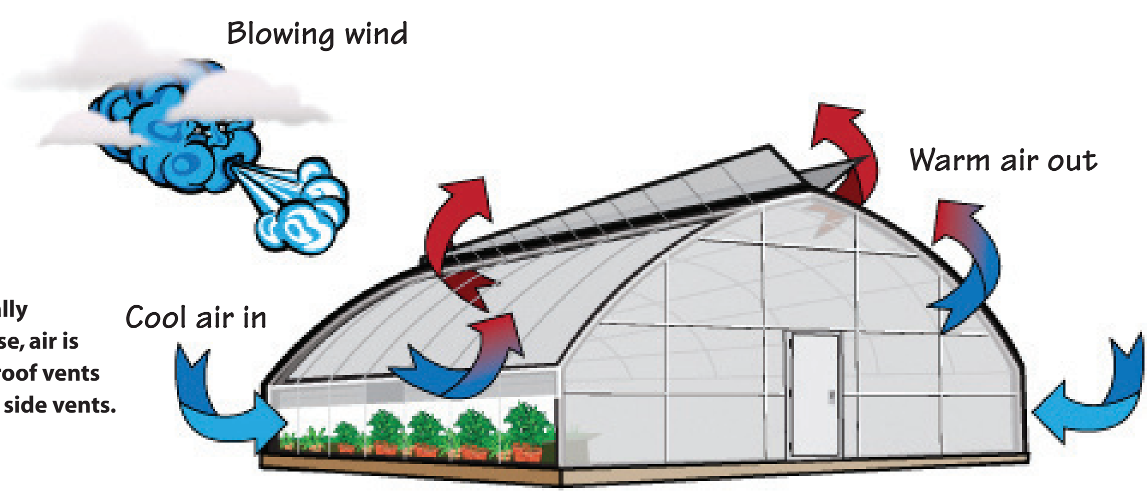


Figure 13. In a naturally ventilated greenhouse, air is sucked out through roof vents and flows in through side vents.

Roll-up and curtain sidewalls work especially well for summer ventilation in freestanding single-span greenhouses, but their loose fit leads to high infiltration rates and increased winter heating. Curtain sidewalls are often made from single-layer glazing materials, resulting in high conduction losses as well. To help reduce winter heat loss, cover the roll-up sidewall opening from the inside with a sheet of poly film and install a poly film fastening system to seal the roll-up curtain to the sill plate and sides.

Supplemental lighting

Using supplemental lighting allows you to better predict and shorten time to market and to produce higher-quality plants that flower earlier. The ability to shorten time to market might also allow you to delay starting plants, resulting in less heating. There are several types of lamps used for supplemental lighting. T8 fluorescent lamps are recommended for growing chambers, while high-intensity discharge (HID) lamps are recommended for greenhouses (figure 14). Two types of HID lamps are used in greenhouses: high-pressure sodium (HPS) and pulse-start metal halide lamps. HPS lamps are the more energy-efficient option and emit a yellowish-orange light. Pulse-start metal halide lamps emit a bluish-white light. Most growers use HPS lamps or a 50-50 mix of HPS and metal halide lamps.

To reduce energy consumption, control lamps with timers. Or better yet, use a light integral controller. This type of controller measures the sunlight entering the greenhouse daily and controls the lights to provide just enough supplemental light to reach a minimum daily light integral, thus controlling the plant growth rate.

Supplemental lighting can provide at-plant light levels ranging from about 400 to 1,000 foot-candles. The lamp wattage you need depends on your desired light intensity and the lamp spacing. Typically, fixtures have 400- to 1,000-watt lamps.

Lamp placement is important to ensure uniform light distribution. Greenhouse lighting fixture manufacturers have modeling programs that can help you determine the best wattage and placement of lamps for your particular crop. Different crops have different responses to light, so it's important to make sure you understand the lighting needs of the plants you are growing before you start. Refer to the book *Lighting Up Profits* by Paul Fisher and Erik Runkle for more information.

Figure 14. A high-intensity discharge (HID) fixture provides supplemental lighting. Fixture manufacturers have programs to help you determine your lighting needs.

Environmental controls

There are many environmental parameters that need to be controlled in a greenhouse—most significantly air temperature, humidity, CO_2 levels, lighting, and irrigation. Air temperature and humidity can be controlled with heaters, fans, and louvers. CO_2 can be added using bottled CO_2 or a CO_2 generator, or by increasing the amount of outside air entering the greenhouse. Lighting can be supplemented with lights or decreased using a shade curtain.

In an effort to control energy costs, there are some environmental control interactions to avoid, such as running exhaust fans when the heater is on, cycling heaters and fans on and off, and operating fans while adding CO_2. If you use individual controls, some of these interactions cannot be prevented, but if you use a central controller, you can optimize the system to prevent conflicts. A basic controller usually controls heaters and fans and allows the heater to have day and night set points (figure 15). If the greenhouse fans are staged, a basic controller may also increase the number of fans operating as the greenhouse temperature increases.

A more sophisticated controller may have outputs to control heaters, fans, louvers, CO_2 enrichment, lights, thermal or shade curtains, and irrigation, and it may have inputs for temperatures, humidity, CO_2 levels, daily light integral, soil moisture, and a weather station. Proper measurement techniques are important for getting accurate temperature and relative humidity values. Use a shielded, aspirated box to help ensure that the air temperature is measured accurately.

Figure 15. A basic environmental controller usually controls heaters and fans and allows for day and night set points.

Advanced controllers can make adjustments based on indoor and outdoor conditions. For example, when the sunlight level drops due to a bank of clouds, a basic controller waits for the greenhouse temperature to drop below the set point before closing the vents. The advanced controller is likely to predict that since the light level has decreased, the temperature will be dropping and, if the vents are open, close them immediately to conserve heat and reduce heating needs.

Every greenhouse should have a minimum of a day–night programmable heating system controller to take advantage of DIF, the day–night temperature differential. Plants respond to the average daily temperature, not necessarily the daily maximum or minimum temperatures, although there are some limits. So having a temperature set point of 75°F daytime and 65°F nighttime is the same as a continuous 70°F to plants. This plant trait allows you to reduce energy costs by decreasing the nighttime set point, which reduces heating requirements, and increasing the daytime set point, when you have sunlight to help with heating. A 10°F day–night temperature differential can save 5% in heating energy use.

Passive solar greenhouses

All greenhouses use passive solar energy, but some greenhouses are designed and constructed to minimize the supplemental heating that is needed. Passive solar greenhouses are optimized for a particular time of year, usually wintertime, when the most heating is required (figure 16). Winter-optimized passive solar greenhouses are well insulated on the north wall and roof and at least a portion of the east and west walls to minimize heat loss. The south roof face is glazed and pitched at an angle (usually equal to the latitude) to maximize the amount of winter sunlight that enters the greenhouse. On a sunny day, even during the winter, the solar energy entering the greenhouse may exceed the heating needs of the greenhouse. Instead of being vented, the excess heat can be collected and stored in various forms of thermal mass such as water, rock, brick, concrete, and sand. The collection system can be as simple as a wall of black-painted, water-filled barrels that sit in the back of the growing space or under benches and heat up as the sun hits them. Or the system can be more complex, such as a system that blows hot air from the peak of the greenhouse through pipes that are buried under the floor in sand, where the excess heat is stored. Another option is to use a heat pump to extract the excess heat from a greenhouse and store it in a water storage tank. Active solar thermal systems can also be used to supplement heating needs.

Research at Cornell University found that 25% of heating needs can be offset by establishing rock beds under growing benches and blowing air from near the roof through ducts in the rocks. With this type of system, the transference of heat into the thermal mass during the day and out at night causes the air temperature to vary. The variance may be wider than is normally recommended for some crops and may require supplemental heating. If that is the case, it's important to consider that the thermal mass inside the growing space will act as a heat sink, thus requiring a longer time and more energy to increase the greenhouse temperature. Phototropism, plants' tendency to grow towards light, can be a problem in passive solar greenhouses but can be overcome by mounting reflective materials on the walls and roof and using supplemental lighting.

A passive solar greenhouse in the northern hemisphere should face south, and the south roof face can be covered with any type of double-walled glazing. The south wall should be tall enough so the snow that accumulates on the ground doesn't obstruct the snow sliding off the roof. During the winter, the sun is low in the southern sky and the light will reach the back, or north wall, of the greenhouse and heat any thermal mass located there. During the summer, the sun is high in the sky and won't reach the back of the greenhouse, reducing the amount of heat going into thermal storage and heat loading in the greenhouse.

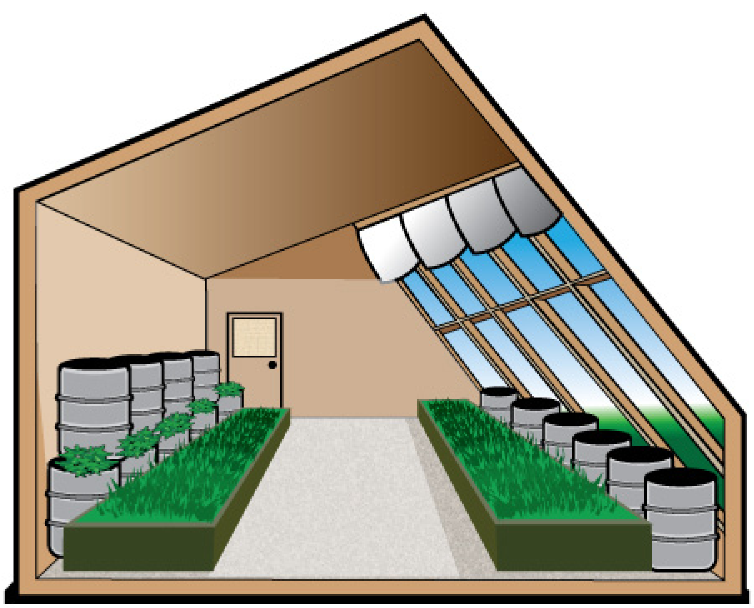


Figure 16. A typical passive solar greenhouse has well-insulated opaque surfaces, a glazed south wall pitched at an angle equal to the latitude, and water-filled barrels to collect heat.

Energy audits

Estimating your baseline energy use is a great first step toward improving the energy efficiency of your greenhouse. There are several web-based tools available for this purpose. One is an Energy Self Assessment tool developed by the University of Wisconsin for the USDA–Natural Resources Conservation Service. The tool helps assess your current greenhouse energy use and then estimates the heating energy that would be saved with different types of equipment and management practices. A second tool is Virtual Grower, a program developed by USDA–Agricultural Research Service that can be downloaded to run on your computer. Virtual Grower can help you predict greenhouse energy use and the growing times of different crops for different lighting and temperature profiles. Using the information in this publication and the USDA modeling tools along with an energy audit will help you quantify the most economic options for reducing energy use in your greenhouse operation.

Resources

For more information, see the following resources, some of which were used in the preparation of this publication:

Energy Efficiency in Greenhouses series, by Scott Sanford. Available online at learningstore.uwex.edu.

- *Greenhouse Unit Heaters: Types, Placement, and Efficiency* (A3907-02)
- *Using Curtains to Reduce Greenhouse Heating and Cooling Costs* (A3907-03)
- *Biomass Energy for Heating Greenhouses* (A3907-04)
- *Biomass Heating in Greenhouses: Case Studies* (A3907-05)

BESS Laboratory website. University of Illinois at Urbana-Champaign. bess.illinois.edu/.

Energy Conservation for Commercial Greenhouses (NRAES-3), J.W. Bartok, Jr. Ithaca, NY: Natural Resource, Agriculture and Engineering Service, 2001. (Available at www.nraes.org.)

Greenhouse Energy website. Michigan State University. www.hrt.msu.edu/Energy.

Greenhouse Engineering (NRAES-33). R.A. Aldrich and J.W. Bartok, Jr. Ithaca, NY: Natural Resource, Agriculture and Engineering Service, 1994. (Available at www.nraes.org.)

"Grower 101: Exploring Underbench Heating Options." John Bartok, Jr. *Grower Product News,* Vol. 18, No. 10, Oct. 2006. (Available at www.hrt.msu.edu/energy/Notebook/pdf/Sec3/Exploring_Underbench_Heating_Systems_by_Bartok.pdf.)

How Are Greenhouse Growers Coping with Rising Energy Costs? R.G. Brumfield, A.J. Both, and G. Wulster. New Brunswick, NJ: Rutgers, April 2009. (Available at aesop.rutgers.edu/~farmmgmt/newsletters/newsletter2a.pdf.)

Lighting Up Profits: Understanding Greenhouse Lighting. Paul Fisher and Erik Runkle. Willoughby, OH: Meister Publishing, 2004.

Tools

Energy Self Assessment–Greenhouse Self Assessment Tool. Available at www.ruralenergy.wisc.edu. Provides baseline energy use estimates and recommends energy-efficiency measures.

Virtual Grower Software. Available for download from USDA–Agricultural Research Service. www.ars.usda.gov/services/software/software.htm. Determines energy use and potential savings for energy efficiency measures.

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