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GREENHOUSE
Energy Conservation Strategies

By Erik Runkle, Department of Horticulture, Michigan State University and
A. J. Both, BioEnvironmental Engineering, Department of Environmental Sciences,
Rutgers, The State University of New Jersey

After labor expenses, energy is typically the largest overhead cost in the production of greenhouse crops in temperate climates. Of the total energy consumed, roughly 65 to 85 percent is for heating, and the remainder is for electricity and transportation. In an industry with declining profit margins and an increased desire for sustainable production, greater emphasis is being placed on producing greenhouse crops in an energy-efficient and environmentally friendly manner. This document presents 13 production strategies and technologies that greenhouse growers can use to reduce energy consumption and improve greenhouse production efficiency. Although many of these concepts can apply to virtually any greenhouse-grown crop, the focus is on the production of floriculture crops in controlled greenhouse environments located in temperate climates.

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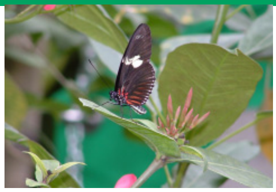

Install efficient photoperiodic lighting when growing long-day plants

When the natural day length (photoperiod) is short, many bedding plants and herbaceous perennials flower earlier when provided with artificial long days. Many long-day plants flower faster when provided with a night length of less than 10 hours (when the day is at least 13 to 14 hours long). Therefore, in North America, photoperiodic lighting can be useful from around mid-September to early April.

Photoperiodic lighting is effective when delivered to extend the natural day or during the middle of the night (Figure 1). Day-extension lighting typically begins around sunset and ends once the total desired photoperiod is achieved. For example, if sunrise is at 7 a.m. and sunset is at 6 p.m., then a 15-hour photoperiod can be achieved when the lamps operate from 6 p.m. until 10 p.m. Night-interruption or night-break lighting is equally effective and is usually delivered by turning lamps on from 10 p.m. to 2 a.m. If the supply of electricity is limited, then half of the crop could be provided with day-extension lighting from 6 p.m. to 10 p.m., and the other half with night-interruption lighting from 10 p.m. to 2 a.m. Regardless of lighting strategy, the minimum recommended light intensity is 2 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (10 footcandles, which equals around 100 lux) at plant height.

Figure 1. As with many bedding plants and herbaceous perennials, petunia 'Fantasy Pink Morn' flowers earlier when low-intensity lighting is used to shorten the long night period (also called "night break"). Here, the natural day length was 9 hours long and during the long-day treatment (right), low-intensity lighting was provided near the middle of the night for 4 hours. Image courtesy of Ryan Warner, Michigan State University.

You can save a substantial amount of energy by replacing incandescent lamps with more efficient photoperiodic lighting strategies. Here are some options:

> For more specific information on greenhouse lighting of floriculture crops, visit **http://flor.hrt.msu.edu/lighting.**

- Replace incandescent lamps with compact fluorescent lamps (CFLs). CFLs consume about one fourth of the energy compared to incandescent lamps. There are a few crops, such as petunia and pansy, in which flowering of some varieties is delayed under light from CFLs, especially when used as night-interruption lighting. Therefore, you may wish to only replace every other incandescent lamp with a CFL, at least for these two crops.
- Provide cyclic lighting, where light is delivered to plants on an intermittent basis during the night. There are three common techniques to deliver cyclic lighting:
    1. Turn incandescent lamps on for 6 to 10 minutes every half hour during the desired lighting period. This can reduce energy costs by two thirds or more, and is effective on most crops.
    2. Install high-intensity discharge lamps on a moving boom that runs back and forth above crops for at least four hours during the night. Some growers have used this method with success, although little scientific information is available to support this specific recommendation.
    3. Install high-intensity discharge lamps that have a rotating reflector (such as the Beamflicker from PARsource[1]) above crops. Operate these lamps for at least 4 hours during the night. Based on Michigan State University (MSU) research, one 600-watt lamp is recommended for every 1,500 square feet (140 square meters) of growing area.

[1] Mention of product names or companies does not constitute an endorsement. Other manufacturers may have similar products available with comparable features.

A long list of floriculture crops flower earlier when provided long days, and some crops even require long days to flower. Common long-day crops include ageratum, blue lobelia, blue salvia, campanula, coreopsis, dianthus, gazania, hibiscus, leucanthemum, pansy, perennial garden phlox, petunia, rudbeckia, snapdragon, tuberous begonia and verbena, but there are many others.

For most species, once a plant is induced to flower, the flowers will develop even under a natural photoperiod. Therefore, once flower buds are visible (often about 3 to 4 weeks after the start of long days), you can turn off lamps and long-day plants will proceed to flower. Long-day lighting is recommended until shipping or early April, whichever occurs first, for a few crops, such as 'Wave Purple Classic' petunia and butterfly weed.

Plants that require short days to induce flowering (African marigold, some chrysanthemums and poinsettia) will not flower if exposed to long-day lighting. Some of these short-day plants can detect light levels of 0.1 $\mu mol{\cdot}m^2{\cdot}s^1$ (0.5 footcandles) or even lower, so be aware of light "pollution." Plants that flower earlier when grown under short days (cosmos, dahlia and morning glory) will have delayed flowering if exposed to long days. Long-day lighting provided to day-neutral plants (e.g., aquilegia, delphinium, French marigold, geranium, impatiens, nepeta, thunbergia, vinca, wax begonia and others) has no beneficial or detrimental effect.

Provide high-intensity lighting when growing young plants

Use high-intensity lighting as a supplement to increase photosynthesis. The objective is to increase the photosynthetic daily light integral (DLI) to increase plant growth. The DLI is the cumulative number of photons of photosynthetic light delivered to a plant canopy each day. The common DLI unit is moles per square meter per day ($mol{\cdot}m^{-2}{\cdot}d^{-1}$), and since it is a value that accumulates, it cannot be determined instantaneously. The DLI is particularly important in greenhouse crop production because plant biomass (e.g., roots, stems, flowers and fruit) is generally a function of the amount of light available to plants: the higher the DLI, the greater the plant growth. In temperate climates, the DLI inside greenhouses can be a limiting factor from late autumn to early spring.

During the year, the average DLI in a greenhouse can range from low values (5 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) to high values (25 $mol{\cdot}m^{-2}{\cdot}d^{-1}$), due to factors such as the seasonal angle of the sun, cloud cover, day length, use of shade curtains and light transmission of the greenhouse structure. When producing crops during winter in the northern United States, the DLI in the greenhouse is often below 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, and supplemental lighting is beneficial to maintain plant quality and crop schedules. Remember that the greenhouse structure, glazing material, overhead equipment, etc. can also reduce the DLI inside the greenhouse. If you place hanging baskets overhead, you can reduce the amount of light reaching the crop below considerably, possibly causing poor plant quality, especially in early spring.

In contrast to photoperiodic lighting, lighting to enhance photosynthesis requires a much higher intensity and lamps usually operate for a longer period (up to 20 hours) each day. A typical lighting installation delivers 60 to 80 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ (450 to 600 footcandles) at plant height, although even higher intensities (up to 200 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) are provided for some vegetable crops. The high-pressure sodium (HPS) lamp is presently the most widely used light source for supplemental lighting in greenhouses (Figure

Figure 2. The high-pressure sodium lamp is still the most economical lamp type for most greenhouse supplemental lighting applications. Photo courtesy of Erik Runkle, Michigan State University.

2). On a relative basis, it is moderately efficient, has a long bulb life and emits light that is rich in orange light. Two added benefits to using HPS lamps are: (1) a significant amount of heat is emitted from these lamps, which can save on heating fuel, and (2) the radiation emitted by the lamps can increase plant temperature, thereby accelerating crop growth and development. Much less commonly used is the metal halide lamp, which is slightly less efficient at converting electricity into photosynthetic light, but has a shorter bulb life than HPS lamps. Although numerous light-emitting diode (LED) products are marketed for plant applications, in most cases, they are not yet cost effective. However, as the efficiency of LEDs increases and costs decrease, they will become more economical for greenhouse operations.

Because of the substantial delay in flowering when plants are grown cool, more energy may be consumed by growing a crop at cooler temperatures than growing it warmer with a shorter finish time.

Adding supplemental lighting to a greenhouse is a relatively expensive investment and operational costs can be high, approaching or surpassing the cost of heating in some applications. One of the most economical uses of supplemental lighting is on plugs and liners. Adding supplemental light during this stage is especially important in the northern United States because a majority of plugs and liners are produced late in the winter and in early spring, when the natural DLI is low. Providing supplemental light to young plants has many advantages including faster growth, shorter internodes, thicker stems, increased root development and improved quality (Figure 3). The cost of lighting during the young plants stage is low on a per-plant basis since they are grown at a high density. The reduced production time from using supplemental lighting during the plug stage provides the opportunity for increased revenue because more crop turns are possible. In most situations, supplemental lighting of floriculture crops during the finish stage is not economical because of their lower density and per-container cost.

To minimize operational costs and save on electrical energy, only provide supplemental lighting when irradiance is low, such as at night and on cloudy days. Computers that control the greenhouse environment can be configured so lights only turn on when ambient light levels outside or inside are below a minimum value and for a specific time period (to avoid equipment cycling), e.g., for at least 15 minutes below 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (1,500 footcandles).

Manage greenhouse temperature based on the crop and finish date

Floriculture crops are grown under a wide variety of environmental conditions. One principle that applies to all crops is that their developmental rate (such as the rate of leaf unfolding or rate of flowering) decreases as temperature decreases. As temperature decreases, plants develop progressively slower and, at some point, they stop growing. The cool temperature at which plant development stops is referred to as the base temperature. The base temperature varies among species, although for most floriculture crops, estimated values range from 32 to 50 °F (0 to 10 °C).

As temperature increases above the base temperature, the rate of development increases, until some temperature at which the plant develops as fast as it can. The temperature at which development is maximal can be called the optimum temperature. Again, the optimum temperature varies from one plant species to the next. The optimum temperature is not necessarily the best temperature to grow a crop; under light-limiting conditions, plants can be of moderate or even poor quality if grown at a crop's optimum temperature.

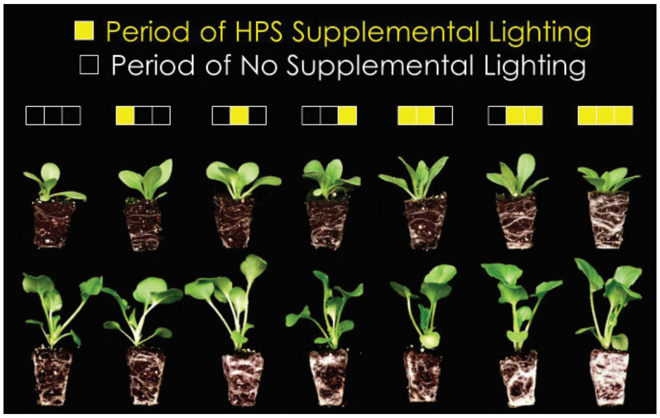

Figure 3. Supplemental lighting from high-pressure sodium (HPS) lamps during three stages of plug production of petunia 'Madness Red' (top) and pansy 'Delta Premium Yellow' (bottom). Each stage was 9 days (for petunia) or 11 days (for pansy) long. For example, indicates that supplemental lighting was provided only during the middle third of production (days 10–17 for petunia and 12–21 for pansy). Shoot and root growth increased as the lighting period increased, especially toward the later stages. Image courtesy of Wook Oh, Michigan State University.

Researchers at Michigan State University, the University of Minnesota and the University of Florida have recently been quantifying how temperature controls floriculture crop timing. You can download a spreadsheet that helps growers determine the impact of changing temperature on crop timing at **http://floriculturealliance.org**. Click on the "Grower Resources" tab. Using "FlowersOnTime: A Computer Decision-Support Tool for Floriculture Crop Producers," a grower selects a crop then specifies the finish crop time at a particular temperature, based on past experience, growing conditions, starting plant material size and finished crop specifications. The effect of increasing or decreasing the average daily temperature at 2 °F (1.1 °C) intervals on flowering time is then predicted.

Virtual Grower, a free computer program developed by the U.S. Department of Agriculture – Agricultural Research Service (USDA–ARS) and available at **www.virtualgrower.net**, has enabled growers throughout the United States to predict heating costs for their greenhouses. You can use the program to help make decisions on growing temperature set points, use of alternative fuels and energy-saving investments. One of the significant uses of the program is the ability to predict the amount of energy needed to maintain a desired temperature at different times of the year. When combined with information on temperature's effects on crop timing, you can identify the most energy-efficient growing temperatures.

For example, ageratum grown in 288-cell plug trays under a 16-hour long day and then transplanted and grown under long days takes approximately 61 days to flower at 58 °F (14 °C), 43 days at 63 °F (17 °C), 33 days at 68 °F (20 °C), and 27 days at 73 °F (23 °C). With this information, growers can determine transplant dates so plants are in flower for predetermined market dates when grown at different temperatures. For example, for ageratum to flower on April 5, plugs need to be transplanted on Feb. 3 if grown at an average daily temperature of 58 °F or on March 3 if grown at an average of 68 °F. Because of the substantial delay in flowering when grown cool, more energy may be consumed by growing a crop at cooler temperatures compared to when grown warmer with a shorter finish time.

Figure 4 presents the estimated relative greenhouse heating cost for growing ageratum using Virtual Grower. The costs are based on a per-crop basis and are relative to

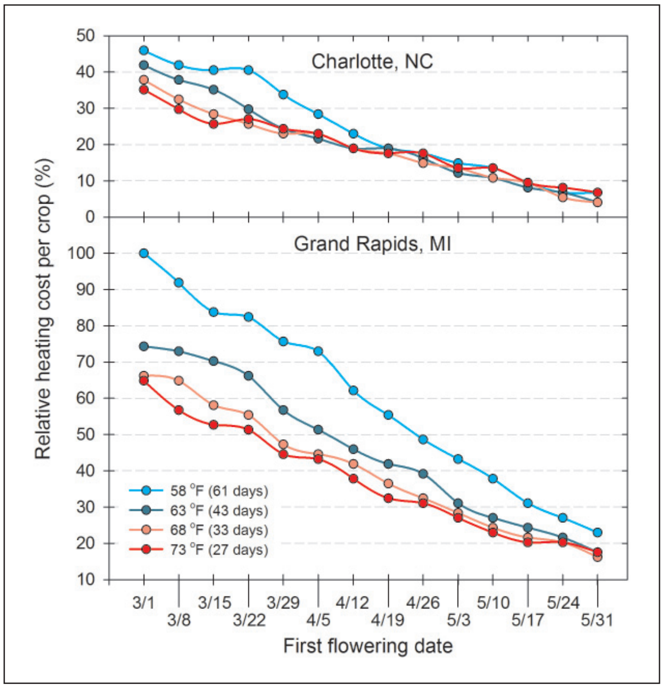

Figure 4. The relative cost to heat a crop of ageratum, from transplant of a 288-cell plug to first flowering, was determined for two locations at four different temperatures using Virtual Grower. The production time under a 16-hour long day is also provided for each temperature. Graph courtesy of Erik Runkle, Michigan State University.

the most expensive finish date and growing temperature. Estimates are for two locations for finish dates in March, April and May. In Grand Rapids, Mich., more energy was consumed per crop when ageratum was grown cool throughout the spring season. In the winter, when daily heating costs are highest, it was cheaper to produce the crop warm to finish it in a shorter period of time. As the finish date ran into May, there were fewer differences in heating costs at different finish temperatures, but it was always more expensive growing ageratum at 58 °F. Lower temperatures increasingly delayed crop development and increased total crop-heating costs.

Using the same approach – but for a greenhouse in Charlotte, N.C. – growing ageratum at 58 °F was more expensive on a per-crop basis until mid-April. For most dates, the total energy consumed to grow the crop at 63 to 73 °F was similar. However, growing warmer allows growers to turn crops more quickly, which opens space for another crop. This can be particularly beneficial for operations that have space constraints. You can review articles with more examples of the uses of Virtual Grower with specific bedding plant crops at **http://flor.hrt.msu.edu/annuals**.

So why doesn't every grower turn up the heat and produce crops more quickly? First, the information generated from Virtual Grower depends on the location, greenhouse characteristics and crop. That's why using Virtual Grower for your own greenhouse is so important: results vary from one greenhouse to the next so the program's utility hinges on spending a little more time to generate the most meaningful results. Second, under light-limiting conditions in the early spring, growing some species warm can produce low-quality plants. Therefore, plants that are typically grown cool, such as petunia, ageratum and snapdragon, should generally not be grown warmer than the low 70s until light conditions are higher (beginning in March in the northern U.S.).

Use temperature integration strategies

Research has shown that plants develop and flower in response to the average daily temperature. Therefore, you can adjust greenhouse temperatures on an hourly or daily basis in response to outdoor conditions without influencing time to flower as long as the target average temperature is provided. One method of managing greenhouse heating costs is dynamic temperature control in which heating set points are lowered when the greenhouse energy loss factor is high (i.e., outside temperature and incoming solar radiation are low) and increased when the energy-loss factor is low. This strategy maintains a target average temperature over a period of several days. A research greenhouse in Denmark using this strategy consumed substantially less fuel for heating compared to using typical day/night temperature set points. To utilize dynamic temperature control, a greenhouse environmental control computer with sophisticated software is required.

However, not all greenhouses use environmental control computers, and of those that do, very few in the U.S. use dynamic temperature control. An alternative and simple energy-saving approach is to use a warmer day than night temperature regimen in which the difference between the day and night temperature is positive (+DIF). With a +DIF, the heating set point is lowered during the night, when energy consumption for heating is highest. A low night temperature is compensated by increasing the day temperature so that the target average daily temperature is achieved. A negative consequence of using a +DIF is that stem elongation is promoted in many crops. Many growers actually use a cooler day than night temperature (–DIF), which inhibits stem extension but also consumes more energy for heating.

For more information on greenhouse temperature management, visit **http://flor.hrt.msu.edu/temperature**

The potential energy savings that can be obtained using a +DIF can be estimated using Virtual Grower. Again, predicted heating cost savings depend on the specific situation, especially the time of year, greenhouse location and crop grown. Energy cost simulations were performed to grow a French marigold crop, from transplant to first flowering, at two locations in the United States: Charlotte, N.C. and Grand Rapids, Mich. Of the six greenhouse temperature regimens evaluated, the most energy was consumed for heating a greenhouse in Charlotte by growing French marigold 'Janie Flame' for first flowering on March 15 at a 16-hour day/8-hour night of 68/79 °F (20/26 °C) (Table 1). Growing the crop at the same average daily temperature at a constant 72 °F (22 °C) would save 6 percent in heating costs, and using a warmer day than night temperature [75 and 64 °F (24 and 18 °C), respectively] would save 14 percent. Energy savings on a

Table 1. Predicted decrease in greenhouse heating costs relative to the temperature regimen and finish date that consumed the most energy to grow marigold 'Janie Flame' from transplant of a seedling to first flowering. Heating inputs were estimated using Virtual Grower for two locations and three flowering dates with a 16-hour day and 8-hour night. Percentages are relative to each location only.

Average daily temperature (ºF)	Day/night temperature set point (°F)	Desired first flowering date		
		15 Mar.	15 Apr.	15 May
		Charlotte, NC		
64	61/72	12%	42%	65%
	64/64	24%	57%	82%
	68/61	32%	65%	89%
72	68/79	0%	33%	60%
	72/72	6%	40%	70%
	75/64	14%	51%	82%
		Grand Rapids, MI		
64	61/72	0%	35%	61%
	64/64	3%	40%	68%
	68/61	5%	43%	73%
72	68/79	4%	35%	60%
	72/72	5%	37%	64%
	75/64	8%	41%	70%

percentage basis were even greater when the average daily temperature was lower (64 °F) and when the finish dates were later (April 15 and May 15).

Regardless of the temperature set points, energy can be saved by increasing the dead band of the environmental control computer settings. The dead band is a range of temperatures in which neither heating nor venting occur. By setting a fairly wide dead band (5 to 7 °F, or 3 to 4 °C), overheating or excessive ventilation is less likely to occur and thus, avoids cycling of temperatures and unnecessary energy inputs. However, increasing the size of the dead band reduces the system's ability to maintain the greenhouse temperature at or near the desired set point.

Transplant larger plugs and liners to shorten finish crop time

In the production of ornamentals, most growers produce crops in two distinct phases: the young plant (plug and liner) stage and the finish plant (transplant to flowering) stage. During the young plant stage, plants are grown at a high density and thus, the heating costs per plant are relatively low (Table 2). After transplant, the heating costs per plant increase dramatically because plants are grown at a much lower density.

Table 2. An example of heating costs per 10,000 units (plug/liner cells or finish containers) based on $0.117 per square foot, which is an estimated value for a constant 65 °F (18 °C) greenhouse in Grand Rapids, Mich., in March with natural gas heating at $0.90 per therm, a 70-percent efficient boiler, double-poly greenhouse without an energy curtain and a 12-hour day/night.

Container	Units per square foot	Heating cost per 10,000 units per week
288-cell tray	197	$ 8.85
72-cell tray	49	$ 35.85
10-cell strip	46	$ 28.10
606 flat	26	$ 67.50
4” pot	9	$ 195.00
6” pot	4	$ 438.75
12” basket	1	$ 1755.00

For example, let's make a set of assumptions for a greenhouse grower in Michigan (specific situations will vary among growers) who wants to produce 10,000 4-inch bedding plants. Let's assume it takes 4 weeks to produce a 288-cell plug and 6 weeks to produce a 72-cell plug. Using the assumptions in Table 2, the estimated heating costs to produce 10,000 plants are:

Situation 1: Heating cost to produce 288-cell plugs:
4 weeks × $8.85/week = $35.40

Situation 2: Heating cost to produce 72-cell plugs:
6 weeks × $35.85/week = $215.10

If time from seeding to first flowering is constant (which is often the case), then finish time starting with a 72-cell plug would be reduced by 2 weeks compared to starting with a 288-cell plug. Therefore, the heating cost savings by shortening the finish time for a crop grown in 4-inch pots by 2 weeks can be estimated as:

2 weeks × $195.00/week = $390.00.

The $390.00 heating cost savings by the shorter finish time more than offsets the $179.70 ($215.10 – $35.40) higher cost of heating a 72-cell plug. Of course, other factors would need to be considered, but in many situations when heating costs are high and greenhouse space is limiting, using a more mature transplant can reduce total heating inputs necessary for producing the crop.

Reduce air leaks

It is quite common to find areas where the warm greenhouse air is escaping to the cold outdoors. Air can escape in many different places. Some energy auditors use an infrared (IR) sensor to identify where air is escaping. However, you can identify many air leaks simply by closely inspecting the greenhouse glazing, walls, doors, fans, vents and other areas. Pay special attention to where the covering material attaches to the foundation, side and walls, and around fans and vents. Here are some of the primary areas on which to focus:

- Patch holes in the plastic covering and side walls, or replace cracked or missing glass panes.
- Keep the doors closed, and make sure they close completely.
- Weather-strip doors, vents and fan openings.
- Ensure louvers are sufficiently lubricated so that they close tightly.
- Shut off some of your exhaust fans from late fall through early spring; then cover openings with insulation or plastic to reduce air infiltration.

If you have a double poly greenhouse, it is also important that the space between the two layers is properly inflated (Figure 5). Always use outside air to inflate the two layers of plastic film. The value of having two layers of plastic becomes almost nonexistent if the fan that maintains the air gap fails to operate. Jonathan Frantz of the USDA-ARS was contacted by a grower who had raccoons tear into his outer layer and nest repeatedly between the layers. Frustrated, the grower finally gave up and allowed the double layer to deflate, effectively giving him a single layer plastic greenhouse. Frantz did an energy audit for the grower in that section, and his energy losses were so high that the grower could pay someone round the clock to prevent the raccoons from deflating the double-layer plastic and the grower would still make money. Thus, especially during the winter, routinely check to make sure the inflation fan is blowing air into the gap between the two layers of plastic.

Figure 5. Since the air space between two layers of polyethylene provides insulation, the fans that keep the layers inflated should be routinely checked to ensure they are operating properly. Note that this fan is installed improperly: it should be pulling in air from the outside instead of from the inside of the greenhouse to reduce the potential for humid air causing condensation between layers. Photo courtesy of A. J. Both, Rutgers University.

Insulate side and end walls

A greenhouse structure loses heat (energy) at night or during the winter months through physical processes called conduction, convection and radiation.

- Conduction is the process of heat transfer through a material. When you put a metal pot over a fire, eventually the handle will get hot too. Thus, as long as there is a temperature difference between the inside and the outside of the greenhouse, energy will flow through the structural materials from the warm side to the cold side.
- Convection is the process of heat transfer by the movement of a fluid (e.g., air or water). A heating pipe heats the air surrounding it and this warmer air rises and moves away from the pipe. The warmed air is replaced by colder air that is not yet warmer by the pipe, starting a continuous process.
- Radiation is the process of heat transfer resulting from the temperature difference between surfaces that are in the line of sight from each other. Standing next to a hot fire (or standing outside on a hot sunny day), you can feel radiation heating the surface of your skin. Similarly, in a greenhouse hot water pipes radiate energy to their surroundings, including the plants.

Greenhouses are designed for maximum light transmission, and as a result, often have limited insulating properties. Some portions of the side walls and end walls can be modified to improve their insulating capacity with very little impact on light transmission. These portions are called the knee wall or curtain wall, and are sections of the wall that are often constructed of brick or concrete block and typically rise from the foundation to the first two or three feet. Additional insulation can be attached or incorporated into these wall sections to reduce the overall heat loss through the above-ground greenhouse structure. These wall sections are often used to attach perimeter heat pipes, and the higher the insulating value of these wall sections, the more of that heat stays in the greenhouse.

In the past, some growers opted to add temporary insulating boards to the entire north-facing side wall in an attempt to reduce greenhouse heat loss during the winter when the sun entered the greenhouse at low angles (northern hemisphere). However, the winter period is often relatively dark with many overcast days. During cloudy days, the remaining sunlight is highly diffuse, and as a result, also enters the greenhouse through the north-facing side wall. Therefore, a better option might be to increase the insulating value of the north-facing side wall with little impact on light transmission. One solution is to cover the inside of a glass clad north-facing side wall with plastic bubble wrap (Figure 6).

Energy can be saved by increasing the insulating value of the north-facing side wall with little impact on light transmission.


Figure 6. Plastic bubble wrap installed on the inside of the north-facing sidewall. The bubble wrap adds insulation but allows some light to enter the greenhouse through this sidewall. Photo courtesy of A. J. Both, Rutgers University.

In addition to insulating opaque sections of greenhouse walls as best as possible, it is also important to consider the potential heat loss that occurs at ground level along the perimeter of the greenhouse. Wet soil is a good conductor of heat. When the soil immediately outside the greenhouse perimeter is wet and in direct contact with the soil or concrete floor inside the greenhouse, a conduit is created for heat to flow from the inside to the outside of the greenhouse. To reduce heat from escaping through this route, an insulating barrier can be installed. For example, a two-inch thick polystyrene board extending vertically down for two feet can significantly reduce heat loss at ground level along the perimeter of the greenhouse.

Install and maintain retractable curtains

With the many greenhouse designs in use, there are many ways to install and operate retractable curtains. In gutter-connected greenhouses, growers typically install retractable curtains inside and horizontally above the trusses. Retractable curtains serve two purposes: they create some amount of shading for the crops underneath, and they block some amount of heat radiation to the outside environment. Shading is useful during sunny days from spring through autumn when the plants may become stressed from excessive solar radiation. Blocking heat radiation is useful at night, particularly during the winter, when heat is needed to maintain the temperature set point. Growers have reported significant seasonal energy savings of up to 30 percent, often resulting in a quick return on investment. In most installations, the curtain serves these two purposes and, as a result, a compromise is made between the effectiveness of either control strategy. In some cases, growers install multiple curtains to increase the level of light and energy control (e.g., multiple curtains allow access to two different levels of shading).

Depending on greenhouse orientation, design and grower preferences, you can install curtain systems to operate from gutter to gutter or from truss to truss. The mechanisms used to deploy the curtains include various push-rod systems or systems that use cables that are rolled up on a metal post. These mechanisms are operated by motors attached to gear boxes that ensure slow but steady deployment or retraction of the curtain. A computer system that evaluates light conditions at plant level (for shading purposes) and outside weather conditions (for energy conservation purposes) often controls the motors. Curtain motors often operate several curtains (through mechanical arrangements to distribute power take-off) at the same time and generate significant amounts of torque to do so. Therefore, it is important to set the physical limit switches on these motors correctly to prevent damage to the curtain system or even the greenhouse structure. Install stationary skirts around the outer edges of the curtains to prevent unwanted openings.

Growers have reported significant seasonal energy savings of up to 30 percent with the installation of energy curtains, often resulting in a quick return on investment.

In shading mode, curtains are sometimes operated in stages, i.e., deployed or retracted at a certain percentage of full deployment. However, this practice can result in distinct shadow bands on the crop below, depending on whether the plants were shaded or not. For some crops, these shadow bands, if relatively stationary during the day, can result in uneven plant growth. In energy savings mode, curtains are either retracted or fully deployed, except for early in the morning, when curtains are often cracked open a little to allow the cold air that accumulated above the curtain to mix with the warmer greenhouse air before reaching the plants. Once installed, curtain systems should operate satisfactorily for many years provided regular checking and maintenance is performed. Curtain materials are available in many different configurations, including fire-retarding fabrics that significantly reduce the risk of a rapidly spreading fire. It is highly recommended to have a retractable curtain installed by a professional installer.

Install infrared anti-condensate polyethylene film

Plastic film has been used to cover greenhouses for almost 50 years. Different plastics are used to cover greenhouses, each with its own physical properties and cost. The plastic most often used is clear polyethylene with a film thickness of six mils (0.15 mm). To reduce heat loss, install two layers of polyethylene and keep them apart by a layer of air provided by a small squirrel cage fan that uses outside air for the inflation. Using this method, growers have reported significant energy savings from the relatively high insulating value of the stagnant inflation air. The cost of operating the small inflation fan continuously is very minor compared to the potential energy savings that can be realized. You can accomplish similar or even higher energy savings by covering the greenhouse with rigid twin- or triple-walled plastic panels made from polycarbonate or acrylic. These rigid panels do not require an inflation fan.

Using polyethylene film to cover greenhouses has several advantages: it is a relatively inexpensive cladding material that's relatively easy to install, and it diffuses incoming solar radiation, resulting in enhanced penetration of light into the plant canopy. Obviously, using a double-layer cladding material reduces the amount of light reaching the crop compared to a single layer design. Polyethylene film as a greenhouse cladding material has a life expectancy of 3 or 4 years because of the degrading of the plastic due to the ultraviolet component of sunlight, the inevitable rubbing of the film against the greenhouse structural elements, and the high temperatures of contact surfaces between the film and the greenhouse structure on sunny days.

In one Minnesota study[2], use of a double-layer poly with infrared blocking had a simple payback period of 1 to 2 months.

[2] Eugene A. Scales & Associates. (2003). *Energy conservation opportunities for greenhouse structures*. Roseville, MN: Author. Prepared for Minnesota Department of Commerce Energy Office, St. Paul, MN.

Over the years, several improvements have been incorporated into polyethylene films used as greenhouse cladding material.

1. Films are now manufactured in a tube shape allowing for easier installation in the double layer configuration. These tubes come in various widths that match most common greenhouse roof dimensions, whether freestanding or gutter connected.
2. Films were developed that block some of the IR (heat) radiation. As a result, during the day, less of the heat component of solar radiation enters the greenhouse and thus reduces the need for ventilation; during the night, less of the greenhouse heat provided by the heating system escapes to the outdoor environment. This IR blocking feature dramatically reduces greenhouse energy consumption. For example, a Minnesota study estimated that the return on investment for installing an IR double poly plastic was less than 2 months, even when production was seasonal[2]. When films are manufactured in tubes, both the top and bottom film will have the IR blocking feature. When films are installed as two separate layers, some growers opt to install a film with the IR blocking feature only as the bottom layer, which is done to reduce installation cost.
3. To prevent beading of water droplets on the surface of double layer polyethylene film installations (particularly on the inside of the greenhouse), the film surface was given a treatment so that water droplets run off (the so-called anti-condensate treatment). Water droplets on the inside film surface reflect some of the incoming sunlight, which is undesirable in many situations.

Therefore, when plastic covering needs to be replaced, energy can be saved if at least the inside layer of a double poly glazing blocks IR and has an anti-condensate treatment.

Properly maintain heating equipment

Greenhouses can be heated with a variety of heating systems and fuel sources. Price and availability are the two most important factors that determine the choice of fuel source. As a result of high energy prices, there has been a lot of interest recently in alternative fuel sources, and biomass in particular. While biomass can be an attractive fuel source for greenhouse heating, you will need to consider several issues before switching to an alternative fuel source. These issues include, but are not limited to: reliability and quality of the fuel supply, handling and storage, possible modifications to or replacement of current heating equipment, air quality permits, maintenance demands and waste disposal.

Common greenhouse heating systems include hot-air, hot-water and IR systems. Hot-air heating systems produce hot air (typically as point sources) that has to be evenly distributed throughout a greenhouse. Non-uniform heat distribution results in non-uniform plant growth and development. You can distribute heat using a fan-jet (poly tube) system, horizontal airflow fans or both. Hot air-heating systems are often less expensive compared to hot-water systems and offer a degree of redundancy since multiple heating units are typically installed to provide heat to the greenhouse (Figure 7).

Hot-water heating systems produce hot water that is distributed through a plumbing system that is installed throughout the greenhouse environment. As a result, hot-water systems often provide better uniformity of the heat distribution and can be placed closer to the plants through methods such as bench or floor heating systems. However, as heat gets delivered closer to the plants, the maximum allowable water temperature needs to be reduced so that plants are not damaged. In that case, additional heating capacity such as overhead heating, perimeter heating or both is needed to maintain acceptable greenhouse temperatures. On the other hand, by providing heat closer to the plants, the air temperature of the greenhouse could be maintained at a lower set point, resulting in potential energy savings. Hot-water heating systems often have a certain buffering capacity, extending the time between a malfunction of the heating system and catastrophic crop failure.

Figure 7. Gas-fired unit heater installed in a greenhouse to deliver hot air. Photo courtesy of A. J. Both, Rutgers University.

IR heating systems distribute heat by radiation (and some convection from heated surfaces). Radiators are placed above the crop and any part of the canopy with a direct line of sight to the radiator will receive heat depending on the radiator surface temperature and the temperature of the plant surface. Plant surfaces that are shaded from the radiator, including lower layers of leaves, will not receive the radiation, which can result in uneven heating. IR heating systems can deliver heat very quickly once units are turned on. In older greenhouses, it is not always possible to install the radiators at sufficient distances above the crop to sufficiently cover large enough growing areas.

Heating greenhouses is relatively expensive because greenhouses are designed for maximum light transmission and not for maximum insulating properties. As a result, it is important to regularly inspect and maintain heating equipment, including the operation calibration of the temperature sensor(s) and the environment control system. For growers that do not have a service contract with a licensed heating contractor, we recommend training a dedicated employee and maintaining an adequate supply of spare parts. Growers can effectively use computer control systems to monitor and troubleshoot heating systems, and to send out warnings by phone, e-mail or both to alert growers of potential problems.

Replace an inefficient heating system with a more efficient one

It is almost inevitable that some of the heat contained in the fuel is expelled from the greenhouse with the exhaust gasses. However, the goal is to keep these losses to a minimum. Several reasons why a heating system becomes less efficient over time include:

- The unit is not properly maintained or adjusted.
- Deposits have formed on components of the combustion chamber.
- A heat exchanger is dirty.

- A fan distributing hot air or a pump distributing hot water is not working properly.
- The combustion process is not receiving enough oxygen.

To obtain the highest efficiency from a heating system, a regular check and maintenance schedule is essential (Figure 8). In addition, new developments in the design and construction of heating systems may have resulted in models that have a higher efficiency compared to the ones that were available many years ago. Therefore, compare new model specifications with the specs of the unit(s) that are already installed in the greenhouse. Finally, you can implement control strategies that are better adapted at minimizing energy consumption. Many environmental control companies regularly update their programs, and implementing these updates in a timely fashion can result in significant savings.

Figure 8. Regular boiler maintenance ensures proper operation and increases reliability of the heating system. Photo courtesy A. J. Both, Rutgers University.

Some newer heating system designs are worth considering when retrofitting or installing a new greenhouse:

1. Condensing boiler technology. When fuels combust, water vapor is a by-product of the combustion process. Because it took energy to convert (liquid) water to water vapor, the conversion energy can be recaptured by allowing the water vapor to condense back to water. These boilers are made with stainless steel components to allow for corrosion-resistant condensation. Condensing boilers have a higher efficiency compared with conventional boilers and can be operated on demand (i.e., they have no stand-by losses, like the much larger conventional boilers that constantly keep some water volume at a predetermined set point temperature).
2. Direct-fire unit heaters. These heaters do not have a heat exchanger and thus, have very high efficiencies. However, they need to burn very clean to prevent any contamination of the greenhouse environment from unwanted by-products of the combustion process. An added advantage of these units is that the carbon dioxide produced during the combustion process can be released into the greenhouse environment, which can increase plant growth.

Some newer heating system designs are worth considering when retrofitting or installing a new greenhouse.

3. Combined heat and power systems. These systems generate electricity to run greenhouse equipment and to export to the local grid when there is excess and capture (often by using heat exchangers) the heat contained in the combustion gasses for heating purposes. By using the original fuel for two purposes (the simultaneous production of electricity and heat), the overall system efficiency is much improved. Growers in northern Europe routinely use these systems, but their use in the Unites States is very limited for various reasons, including the inability to sell excess electricity back to the power grid at a reasonable price and challenges obtaining permits.
4. Heat pumps. A heat pump is a refrigerator that can also be operated as a heater. By reversing the flow of the refrigerant in a refrigeration cycle, the same unit can operate as a heater. Thus, one system can be operated as a heater or cooler (air conditioner). Ground-source heat pumps, which are systems that extract heat from the ground during the winter and dump excess heat into the ground during the summer, are especially attractive for greenhouse operations. Their overall system efficiency can be further enhanced by incorporating energy storage (e.g., insulated water tanks).

Install and maintain horizontal air flow fans

Horizontal airflow fans (HAFs, Figure 9) are installed in greenhouses to help mix the air. Air mixing is sometimes necessary to improve the uniformity of temperature, humidity and carbon dioxide. Loss of uniformity of these parameters often results in non-uniform plant growth and development. The risk of non-uniform conditions is particularly high when little or no ventilation is needed to maintain temperature, humidity set points or both, such as during the winter.

HAFs are typically installed in so-called raceways and direct the air in horizontal jets. In each greenhouse section or bay, fans point in one (longitudinal) direction on one side and in the opposite direction on the other. The length of the section or bay determines the number of fans on each side. The recommended fan capacity is approximately 3 ft^3 per minute per ft^2 (3 m^3 per minute per m^2) of growing area. The airflow capacity of HAFs is very small compared to the capacity of ventilation fans. HAFs are typically mounted just below the trusses, but high enough to keep them out of the way for people and equipment

Figure 9. Horizontal airflow fans (HAFs) installed in a greenhouse to increase the uniformity of growing conditions. Photo courtesy of A. J. Both, Rutgers University.

moving through the greenhouse. HAFs should be shielded with a screen for safety reasons and some designs include a shroud for improved efficiency. Fan motors should be rated for continuous operation and have thermal overload protection, especially when the HAFs are mounted in close proximity to retractable curtains. Use a sturdy mount to prevent rocking during operation. Do not use chains.

HAFs provide benefits when the air would otherwise be still. When there is air movement in the greenhouse from other causes such as ventilation fans or open roof vents, HAFs have little or no utility. Therefore, you can save energy if the HAFs are automatically turned off when the greenhouse is being vented.

Utility Rebates

Many gas and electric utility companies offer rebates on new and retrofit equipment, systems and controls that save energy. Contact your utility companies for more information. Examples include:

- T5, T8 and compact fluorescent lamps
- IR polyethylene film
- High-efficiency heating systems such as power-vented unit heaters and condensing boilers
- High efficiency unit heaters
- Automated systems that turn off equipment when not needed
- Thermal screens
- Perimeter and wall insulation

In addition, state and federal grant and loan programs can provide additional support for energy-efficient investments.

Operate ventilation systems for maximum efficiency

To maintain optimum growing conditions, warm and humid greenhouse air needs to be replaced with cooler and typically drier outside air. To accomplish this, greenhouses use either mechanical or natural ventilation. While air conditioning of greenhouses is certainly technically feasible, the installation and operating costs are typically prohibitively high. Mechanical ventilation requires inlet openings, exhaust fans and electricity to operate the fans. When designed properly, mechanical ventilation is able to provide adequate cooling under a wide variety of weather conditions. Typical designs specify a maximum mechanical ventilation capacity of 10 ft^3 per minute per ft^2 (10 m^3 per minute per m^2) of floor area for greenhouses with a shade curtain and 12 cfm per ft^2 for those without a shade curtain. Below are some highlights of energy-efficient ventilation systems:

- Multiple and staged fans can provide different ventilation rates based on environmental conditions. Variable speed fan motors allow for more precise ventilation rate control and can reduce overall electricity consumption.
- Natural ventilation works based on two physical phenomena: thermal buoyancy (warm air is less dense and rises) and the so-called wind effect (wind blowing outside the greenhouse creates small pressure differences between the windward and leeward side of the greenhouse, causing air to move towards the leeward side). All you need are strategically placed inlet and outlet openings, vent window motors and electricity to operate the vent motors. Compared to mechanical ventilation systems, electrically operated natural ventilation systems use a lot less electricity.
- Ultimate natural ventilation systems include the open-roof greenhouse design (Figure 10), where the very large ventilation opening allows for the indoor temperature to almost never exceed the outdoor temperature.

Figure 10. Open-roof greenhouse with a fall chrysanthemum crop. Note the shadow bands on the crop caused by the cover material (double poly) on the greenhouse roof. Photo courtesy of A. J. Both, Rutgers University.

Conclusions and resources for more information

This document is meant to provide an overview of the major ways in which energy costs can be reduced during greenhouse production of floriculture crops. Not all strategies may be applicable and some may not deliver a favorable economic return on investment. You may wish to consult with an energy auditor with commercial greenhouse experience. You can download a two-page fact sheet about what a greenhouse energy audit entails at **http://flor.hrt.msu.edu/energy-audits**. This webpage also lists MSU-certified greenhouse energy auditors.

Keep in mind that floriculture companies are in the business of growing plants, which require a favorable growing environment. Some energy-saving strategies may reduce energy costs, but they may also create a less favorable environment for plant growth and development. For example, adding a third layer of plastic to a double poly greenhouse will reduce heat loss, but it will also reduce light transmission. During production in the winter and early spring, that reduction in light transmission can delay rooting of cuttings, reduce branching and stem thickness, and delay flowering time.

For expanded and more detailed information on many of these topics, check out the following websites and books:

Books

- *Energy Conservation for Commercial Greenhouses* by John W. Bartok Jr., Extension professor emeritus and agricultural engineer, University of Connecticut. For ordering information, visit **www.nraes.org**.
- *Greenhouse Engineering* by Robert A. Aldrich and John W. Bartok Jr. For ordering information, visit **www.nraes.org**.
- *Lighting Up Profits, Understanding Greenhouse Lighting*, edited by Paul Fisher, University of Florida, and Erik Runkle, Michigan State University. For ordering information, visit **http://meistermedia.com/store/books.html**.

Websites

- *Energy Conservation* resources at the University of Wisconsin Extension Learning Store: **http://learningstore.uwex.edu/Energy-Conservation-C29.aspx**
- *Floriculture Crop Production Information* by the Michigan State University Extension Floriculture Team: **http://flor.hrt.msu.edu/production-info**.
- *Greenhouse Energy Cost Reduction Strategies* developed by Matthew Blanchard and Erik Runkle, Michigan State University: **http://hrt.msu.edu/Energy/Notebook.htm**
- *High Tunnels and Greenhouses*, part of the Vegetable Crops Online Resource Center of Rutgers University: **http://njveg.rutgers.edu/html/gc-4high-tunnels.html**
- *Horticultural Engineering* at Rutgers University: **http://aesop.rutgers.edu/~horteng**

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