Energy-Efficient in Greenhouse Crop Production

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This narrative is a supplement for the presentation entitled Energy-Efficient in Greenhouse Crop Production. It was developed as part of a North Central Region SARE Professional Development grant.

Slide 1 - This presentation will review greenhouse production strategies that can be used to reduce energy costs for heating. It was developed by Erik Runkle and Matthew Blanchard from Michigan State University.

Slide 2 – A majority of heated greenhouses are used to produce bedding plants from January to May. In the northern U.S., energy costs fro heating can be 10-15% of total greenhouse production costs.

Slide 3 - The cost of natural gas continues to increase in the United States. Here is the price of natural gas since 1985 adjusted for inflation. From 1999 to 2009, the price has increased by 82%.

Slide 4 – Increases and fluctuations in fuel prices have threatened the profitability of greenhouse operations in the upper Midwest. One strategy to cope with higher energy prices is to improve production efficiency and minimize energy inputs.

Slide 5 - Greenhouse growers often produce hundreds of different crops. These crops can have different temperature and light requirements and scheduling and producing these crops can be a challenge.

Slide 6 - There are many strategies that greenhouse growers can use to reduce energy inputs for heating. In this presentation, we will cover production aspects that will improve efficiency and consume less energy for heating. Those include using supplemental lighting, controlling photoperiod to promote rapid flowering and temperature strategies to reduce energy inputs during finishing. The main objective of many of these energy-efficient production strategies is to optimize the greenhouse environment so crops are finished in the shortest time with the fewest energy inputs.

Slide 7 - Let’s first learn how we can accelerate crop time by lighting plugs and transplants. Many crops are first grown in plug trays and then transplanted into a finish pot for flowering. The greenhouse environment that these plugs are grown can influence subsequent flowering during the finished stage.

Slide 8 - Solar radiation (light) consists of three dimensions: quantity, quality, and duration.

Slide 9 - Growth and yield of most crops is determined by the cumulative amount of light received over time, not the instantaneous light level. We use the term **daily light integral** to describe this cumulative amount of light. Daily light integral or DLI is normally described in units of mol per square meter and day.
Plant growth and crop yield are related to the total number of photons received in a day, a term we call daily light integral.
By adding the instantaneous values over the course of the day, one can calculate the daily light integral in mol m-2 d-1

Slide 10 - Light that is used for photosynthesis is in the visible region from 400 to 700 nm. Daily light integral quantifies how many photons of light are delivered in a square meter during the day. This would be analogous to measuring total rainfall during a day.

Slide 11 - Values from sunlight in Wisconsin vary from 1 to about 50 mol m-2 day-1. In a greenhouse, values seldom exceed 25 mol m-2day-1 because of shading. “Good” plant growth in greenhouses generally requires 10 mol m-2 day-1 or more.

Here is a map of the U.S. showing the average outside daily light integral at different locations. The daily light integral is influenced by latitude, elevation, and cloud cover. The highest daily light integrals are generally in the southwest.

Slide 12 - Greenhouse glazing materials do not transmit all of the light. Here is an example of what the daily light integral would be in a greenhouse that transmitted 60%.

Slide 13 - The variation in DLI is due to season of the year (sun’s angle), cloud cover, and day length. Days are shorter in the winter, combined with low sun angles and cloud cover, result in very low light levels.

Slide 14 - The greenhouse structure can intercept light and decrease the DLI delivered to a crop

Slide 15 - Overhead plant material such as hanging baskets can also decrease the DLI on the crop below.

Slide 16 - This is the DLI in Madison, WI inside a greenhouse assuming 65% light transmission, which is a relatively high value. Some greenhouses may have a light transmission percentage of 50% or even less if hanging baskets are overhead. DLI varies with time of the year from 5.8 to 29.2 mol m-2 d-1. For most floriculture crops, plant quality decreases rapidly as daily light integral decreases below 10 mol per day.

In Wisconsin, daily light integral in the greenhouse falls below 10 mol per day for three months a year, November, December, and January. Exceptions include low-light foliage plants and some flowering plants like African Violet. African violets flower normally with 4 mol per day.

When the DLI is low, many grows use supplemental lighting to increase the DLI.

Slide 17 - For many plants, increasing DLI increases plant quality and accelerates flowering: smaller & thicker leaves, more and larger flowers, faster time to flower, increased branching, increased stem diameter, increased root growth.

Slide 18 - During propagation, cuttings rooted under a low DLI will take longer to develop roots. Production time during the plug stage can be reduced for some crops by increasing the DLI. Misting frequency during propagation may need to be increased at higher light intensities.

Slide 19 - As mentioned earlier, many crops are first grown as plugs or liners before they are transplanted into larger finish pots. The daily light integral during the plug stage can influence flowering and plant quality during the finish stage. In this photo, French marigold and celosia plugs grown under a DLI of 14 mols have thicker stems and better rooting than plugs grown under 4 mols. Plugs grown under a higher DLI will also be ready to transplant earlier than those grown under a low DLI.

Slide 20 - The daily light integral during the plug stage can influence flowering and plant quality during the finish stage. In this graph, time to flower of celosia decreased as the DLI during the plug stage increased. After transplant, plants were all grown in the same finish environment.

Slide 21 - Some plants flower fast under a higher DLI because they develop fewer leaves before flowering (development is accelerated).

Slide 22 - This is a summary of the advantages of lighting during the seedling stage: increased dry mass, greater root mass, increased rate of development and reduced finish time. The effects of supplemental lighting will carryover after transplanting. Many growers use high-pressure sodium lamps to increase the DLI. Using supplemental light during the plug stage is less expensive than during the finish stage because more plants can be lighted per square foot and the cost per plant is cheaper.

Slide 23 - Here are a few general recommendations when using supplemental lighting during the plugs stage. The instantaneous light intensity and lighting duration are both important. The high-pressure sodium (HPS) lamp is the most efficient lamp type. Goal is to provide 300 to 600 foot-candles of supplemental lighting at plant level (400 to 500 foot-candles is typical).

Slide 24 - Let's now discuss how we can manipulate photoperiod to reduce crop time and improve production efficiency.

Slide 25 - Before talking about photoperiod/day-length, we need to define what they are. Day length is defined as the duration from sunrise to sunset.

However, plants perceive light at as low as 0.1 - 0.25 µmol·m-2·s-1 (0.5 - 1.25 foot-candle). Therefore, photoperiod or biological day-lengths are 30 to 50 minutes longer than day-lengths. That is, from sunrise to sunset + civil twilight. The duration from twilight to sunrise or from sunset to twilight depends on weather conditions.

Flowering in many greenhouse crops is controlled by the duration of photoperiod. By providing a photoperiod that induces flowering, we can reduce the time a crop is in the greenhouse.

Slide 26 - Plants are classified as short-day, long-day and day-neutral according to their photoperiodic flowering responses. Photoperiodic control of flowering is one of the most important practical applications of light control in the current greenhouse industry. Let's look at some examples of photoperiodic responses.

Slide 27 - Obligate short-day plants are those that will only flower under a short photoperiod (typically 12 hours or less). One example of a SD plant is the holiday poinsettia.

Slide 28 - Many pot chrysanthemum varieties are considered obligate SD plants because they required short day lengths for flower development.

Slide 29 - Facultative short-day plants will flower under a photoperiod, but flowering is faster under short day lengths.

Slide 30 - Dahlias are an example of a facultative short-day plant. Plants will flower earlier under short days compared with long days. In dahlia, the development of underground storage structures (tubers) is promoted under short days.

Slide 31 - Dahlias are an example of a facultative short-day plant. Plants will flower earlier under short days compared with long days. Plants will also flower faster as the daily light integral increases. We can increase the daily light integral by adding different intensities of supplemental light from high-pressure sodium lamps (380 to 1140 footcandles).

Slide 32 - Here are some examples of facultative and obligate short-day bedding plants. African Marigold, Cosmos, Dahlia, Morning Glory, Salvia, Zinnia

Slide 33 - Day-neutral plants are those in which flowering is not regulated by photoperiod. In these crops, flowering may be controlled by other environmental factors.

Slide 34 - Bedding impatiens are and example of a day-neutral plant because flowering is not controlled by photoperiod. However, we can accelerate flowering by increasing the daily light integral. The daily light integral can be increased by adding different intensities of supplemental light from high-pressure sodium lamps (380 to 1140 footcandles).

Slide 35 - *Scabiosa* (pincushion plant) is and example of a day-neutral plant because flowering is not controlled by photoperiod.

Slide 36 - Here are some examples of day neutral, and facultative and obligate short-day plants. Cleome, French Marigold, Geranium, Impatiens, N.G. Impatiens, Thunbergia, Tomato, Vinca, Wax Begonia, Zinnia

Slide 37 - Obligate long-day plants are those that will only flower under a long photoperiod (typically 14 hours or more).

Slide 38 - *Rudbeckia* (Black-eyed Susan) is an example of an obligate long-day plant. Plants do not flower if grown under a critical photoperiod of 14 hours.
We define critical photoperiod in LD plants as the photoperiod that, when met or exceeded, elicits an identical population of plants to flower completely, rapidly, and uniformly.

The critical photoperiod differs among species, and can even differ among cultivars within a species.

Plants grown under photoperiod shorter than critical photoperiod can still flower but flower later, less uniformly, or only partially.

Slide 39 - Petunia 'Wave Purple' is an example of an obligate long-day plant. Not all petunia varieties require long-days for flowering, but all flower earlier under long day lengths.

Slide 40 - Facultative long-day plants will flower under a photoperiod, but flowering is faster under long day lengths. There are many examples of facultative long-day plants.

Slide 41 - *Viola* (pansy) is an example of a facultative long-day plant

Slide 42 - Here are some examples of day neutral, and facultative and obligate short-day and long-day plants. Ageratum, Blue Salvia, Dianthus, Fuchsia, Gazania, Labelia, Pansy, petunia, Rudbeckia, Snapdragon, Strawflower, Sunflower, Tuberous Begonia, Verbena.

Slide 43 - For a more comprehensive list of the photoperiodic requirements of bedding plants and herbaceous perennials, please visit the Michigan State University website for Greenhouse Energy Cost Reduction Strategies.

Slide 44 - Let's discuss some strategies that can be used to manipulate photoperiod in the greenhouse.

Slide 45 - To determine the variation in natural photoperiod at your location, first determine the latitude.

Slide 46 - This shows the natural (biological) photoperiod for locations from 30 to 50 degrees latitude during the year. In Wisconsin, the longest days are around 15 ½ hours long, and the shortest days are about 9 ½ hours long. If we consider a long day to be 14 hours, then growers would need to provide lighting from early September to mid-April. Note however that for a handful of crops, a 15-hour photoperiod (or longer) is needed for rapid flowering.

Slide 47 - If a short day is 12 hours long, then artificial short days would need to be provided from early March through early October.

Slide 48 - There are several strategies that can be used to create long days in the greenhouse. Interrupting the night or extending the day with incandescent lamps is most common. This can be done using supplemental high-pressure sodium lamps or plants that are very sensitive to light can be controlled using cyclic lighting

Slide 49 - A photoperiodic response is actually determined by the duration of darkness. Therefore, a long-day plant is also a short night plant. By interrupting a long dark night, flowering can be promoted in long-day crops. Plants can sense low levels of light so it doesn’t necessarily require a high light level.

Slide 50 - This photo shows the effectiveness of different night-interruption (NI) treatments for flowering of *Campanula carpatica*. Flowering was delayed under night breaks of less than 2 hours or less.

Also, two cyclic lighting programs, lighting plants for 10 percent or 20 percent of the 4-hour night break, were tested. The 10 percent lighting program (lights on for 6 minutes, off for 54 minutes) was not effective for flower induction. Under the 20 percent lighting program (lights on for 6 minutes, off for 24 minutes), all plants eventually bloomed, but flowering was delayed and not uniform.

For rapid and uniform flowering, night breaks should be 4 hours long, and the lights should be on the entire 4 hours.

Slide 51 - The advantages of incandescent lights are compact light source, low initial installation cost, light output is not affected by ambient temperature, and bulb life is not affected by the number of starts.

Incandescent lamps are widely used for photoperiodic response control.

Slide 52 - Its disadvantages are low light output per input watt of electricity (they are not energy efficient) and their high far-red light causes stem elongation.

Slide 53 - Example of a simple installation of incandescent lamps for photoperiodic lighting.

Light intensity - for photoperiodic control, a light intensity of 7-10 footcandles is adequate for all greenhouse species.

For example: For a standard bench, every 4 -5 feet a 60-W bulb, with a reflector, is sufficient.

Slide 54 - During cyclic lighting, lamps are turned on and off at specific times during the night interruption. Flowering of short-day plants can be prevented by growing plants under cyclic lighting.
Cyclic lighting can be used to save electrical costs or to reduce the load on the electrical system.

Incandescent lamps are used for cyclic lighting because lamp life is not influenced by the number of starts. Compact fluorescent lamps (CFLs) or high-pressure sodium lamps should not be cycled ON and OFF because the life of the lamp and ballast is reduced.

Slide 55 - Night interruption can be delivered continuously or cyclically for 4 hours. A common cyclic lighting strategy is 6 minutes on and 24 minutes off for 4 hours. Cyclic lighting is effective at preventing flowering in short-day crops.

Incandescent lamps are used for cyclic lighting because lamp life is not influenced by the number of starts.

Compact fluorescent lamps (CFLs) or high-pressure sodium lamps should not be cycled ON and OFF because the life of the lamp and ballast is reduced.

Slide 56 - During cyclic lighting, lamps are turned on and off at specific times during the night interruption For example, night-breaks lamps can be cycled on for 6 minutes and off for 24 minutes to reduce energy costs. Flowering of short-day plants can be inhibited by growing plants under cyclic lighting. Continous night-break lighting is usually used for long-day plants as insurance for a strong response.

Slide 57 - High-pressure sodium lamps can also be used for night interruption lighting or

Slide 58 - High-pressure sodium lamps can be mounted on a moving irrigation boom. The boom will move across the crop during the night interruption. Not much research has been done on this, but growers report it works for most (but not all) crops to regulate flowering.

Slide 59 - Another option for long-day lighting is to use a cyclic high-pressure sodium lamp. The lamp is sold as the “Beamflicker” by ParSource Lighting. The lamp is stationary with an oscillating parabolic reflector that rotates 180° to provide an intermittent beam of light over a relatively large growing area.

Slide 60 - Example of how the Beamflicker can provide an intermittent beam of light across the grower area.

Slide 61 - As the distance from the Beamflicker increased, the light intensity decreased and flowering of some crops is delayed or, at large distances, incomplete.

Slide 62 - Here are some guidelines for providing long-day lighting for rapid flowering of finish plants. Provide at least 10 foot-candles to bedding plants and perennials that are long-day plants. Light until around April 15, when the days become naturally long. In general, provide long days to plugs during the last two weeks, and to finish plants until flower buds are visible (or longer for obligate long-day plants)

Slide 63 - Now we will discuss how temperature can be managed for greenhouse energy efficiency

Slide 64 - Time to flower of greenhouse crops can be influenced by plant maturity (age), photoperiod (day-length), vernalization (a low temperature period required for flowering in some species, average daily temperature, and daily light integral.

Slide 65 - The rate of plant development (time to flower or the production of roots) is primarily influenced by the average daily temperature. The average daily temperature is the mathematical average temperature over a series of 24-hour periods and can be calculated as:
Average daily temperature = [(day temperature × hours) + (night temperature × hours)] ÷ 24

The average daily temperature is important to calculate because it determines the rate of plant development. Generally, the warmer the average daily temperature, the faster a plant grows. It's analogous to how fast you drive your automobile to get to work. The faster you drive, the earlier you arrive at work. Similarly, the warmer your crops are grown, the quicker they will grow and become ready for market.

The relationship between average daily temperature and growth and development is linear between the base and optimum temperature**.** The *base temperature* is a cool temperature at which a plant stops growing. The base temperature can vary considerably from crop to crop.

The *optimum temperature* is the temperature at which plant development is most rapid. As temperature increases beyond the optimum value, growth slows as plants show symptoms of heat stress. Therefore, in most instances, crops are grown above the base temperature but not above the optimum temperature of the crop. The optimum temperature can be around 70 °F (21 °C) for cool-season crops such as pansy and alyssum, or as high as 90 °F (32 °C) for warm-season crops such as vinca and hibiscus. Note that the optimum temperature for plants is not based on plant quality attributes, and thus the optimum temperature is not necessarily the most desirable growing temperature.

Slide 66 - Crops with a low base temperature are considered cold-tolerant (e.g., French marigold and petunia). Crops with a high base temperature are considered cold-sensitive (e.g., New Guinea impatiens and vinca). Cold-tolerant and cold sensitive crops should be grown separately.

Experienced growers can often predict which crops have a low base temperature because they are usually grown cooler than plants that have a high base temperature. During the winter and spring, floriculture crops are often grown about 20 to 30 °F (11 to 17 °C) higher than their base temperatures.

We rarely want to grow plants at or near the base temperature because plant development is too slow. One of the few times when a growing temperature near the base temperature is desirable is when plants need to be held because the markets are not available to receive plants, which can occur when sales are slow following an extended period of rainy weather.

Slide 67 - French marigold is an example of a cold-tolerant crop with a low base temperature. At 41 °F, plants will flower, but considerably later than at a 77 or 86 °F.

Slide 68 - *Angelonia* (Summer snapdragon) is an example of a cold-sensitive crop with a high base temperature. At 50 °F or lower, plants will die from cold injury.

Slide 69 - As discussed earlier, the average daily temperature of the greenhouse can be adjusted to speed up or slow down the development of a crop. However, the effects of changing the average daily temperature depends on the species, the magnitude of the change, and the original temperature setpoint. For example, the effect of changing the average daily temperature on crop timing of a cold-sensitive crop (Vinca) is shown here.

The effect of lowering the temperature can have a more dramatic effect on cold-tolerant crops. For example, lowering the temperature from 65 to 60 °F increases time to flower of vinca (from a plug) by about 26 days – much longer than the delay in petunia (13 days) or French marigold (6 days) with the same temperature decrease.

Slide 70 - We now add a cold-tolerant crop, wave petunia. The effect of lowering the temperature can have a more dramatic effect on cold-tolerant crops. For example, lowering the temperature from 65 to 60 °F increases time to flower of vinca (from a plug) by about 26 days – much longer than the delay in petunia (13 days) or French marigold (6 days) with the same temperature decrease.

Slide 71 - Here is the addition of French marigold, which is relatively insensitive to temperature.

Slide 72 - Examples of some cold-tolerant and cold-sensitive crops based on estimated base temperatures. Generally, cold-sensitive crops should be grown warm (e.g., >70 degrees F) whereas cold-tolerant can be grown warm or cool (depending on time of year, light conditions, desired plant quality, etc.)

Slide 73 - Although the average daily temperature is what primarily controls crop timing, the daily light integral can also affect crop timing, as well as crop quality.

Slide 74 - For most crops, as temperature decreases and daily light integral increases, time to flower decreases. The number of flowers at first flowering increases as daily light integral increases and temperature decreases.

Crops grown cool take longer to flower, and thus they have a longer period of time to harvest light. Because of this, many plants (especially cold-tolerant crops) are of higher quality when grown at moderately cool temperatures.

Slide 75 - Here's another example, for African marigold.

Slide 76 - And an example for petunia

Slide 77 - A user-friendly software program to predict greenhouse energy consumption, *Virtual Grower,* has been developed by Jonathan Frantz and colleagues at the USDA-ARS Greenhouse Production Research Group in Toledo, Ohio. This software provides the ability for growers to predict heating costs based on user-defined inputs such as growing temperature, greenhouse location and structure, time of year, fuel type, fuel cost, etc.

Slide 78 - Virtual Grower software can be used to design a "virtual" greenhouse according your specific greenhouse characteristics.

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Slide 80 - The user can select temperature set points and the heating schedule.

Slide 81 - The user can select temperature set points and the heating schedule.

Slide 82 - The user can select temperature set points and the heating schedule.

Slide 83 - Heating costs are predicted according to user-defined inputs such as growing temperature, greenhouse location and structure, time of year, fuel type, fuel cost, etc.

Slide 84 - Let's use Virtual Grower to predict the heating costs for a petunia crop grown in Madison, Wisconsin. These are the greenhouse characteristics we will use to design our "virtual" greenhouse.

Slide 85 - Before we can estimate heating costs to produce a crop at different temperatures, we need to design a schedule for when the plants will be grown in the greenhouse. If we would like the crop to finish in flower on April 1, plants grown under a daily light integral of 10 mol·m–2·d–1 with a 16-hour photoperiod and at 58, 63, 68, 73, 79 °F, would need to be transplanted on 26 January, 13 February, 23 February, 1 March, or 6 March, respectively. Let's determine which production strategy will require the least energy for heating the crop. Is it more energy efficient to grow at 58 °F and transplant early or grow at 79 °F and transplant later?

Slide 86 - According to our heating predictions from Virtual Grower, less energy would be consumed to produce a Petunia 'Wave Purple' crop in Madison, WI for **April 1** if grown at a warm versus a cool temperature. These heating costs will vary by crop, finish date, and location in the U.S. For example, in San Francisco, CA, energy consumption is cheaper at 58 °F (0.11) versus 73 °F ($0.21). The most energy-efficient production temperature varies by greenhouse location because heating requirements are dependent on outside weather conditions..

Slide 87 - Heating costs vary with finish date. As outside temperatures increase later in the spring, less heat is required to maintain a desirable greenhouse temperature set point. According to our heating predictions from Virtual Grower, the least energy would be consumed to produce a Petunia 'Wave Purple' crop in Madison, WI for **May 15** if grown at 68 or 73 °F.

Slide 88 - We have focused on delivering a particular average daily temperature over a period of time. However, the way temperature is delivered during a 24-hour period can also influence energy consumption.

The concept of "temperature integration" describes how plants respond to temperature over a period of time. Simply put, the rate of plant development is dependant upon the average daily temperature from the time you plant the crop. What is the implication of temperature integration? If your day and night are each 12 hours long, and if you lower your night temperature without increasing your day temperature the same amount, your average daily temperature will decrease. Thus, cooler nights without warmer days will increase the time it takes for your crop to become shippable or transplantable. If your night temperature settings are longer than 12 hours, then you need to offset the shorter day temperature set point even more so that your 24-hour average temperature stays the same.

Slide 89 - By using the strategy of temperature integration, greenhouse heating costs can be lowered. Approximately 75% to 80% of heating occurs at night
Therefore, a cooler night and a warmer day can consume less energy while still realizing the same average daily temperature
However, this strategy (warm day and cool night) creates a positive day and night temperature fluctuation (+DIF), which promotes stem extension in many greenhouse crops.

Slide 90 - The difference between the day and night temperature can influence plant height of many plants. Stem elongation increases as the day temperatures progressively become warmer than the night temperatures.

A negative DIF (-DIF) is created when the day is cooler than the night. In contrast, a positive DIF (+DIF) exists when the day is warmer than the night.

A positive DIF will result in tall plants. Plants grown under equal day and night temperatures (zero DIF) will be shorter, and plants grown under a negative DIF will be even shorter.

This concept is well illustrated by Easter lily. Plants on the left were grown at a large negative DIF and plants on the right were grown under a large positive DIF.

Slide 91 - Using Virtual grower, we can predict the heating costs to heat a greenhouse in Madison, Wisconsin with different temperature set points. All of these temperature strategies (+DIF, 70 °F-day 60 °F-night; (0 DIF, 65 °F-day 65 °F-night; -DIF, 60 °F-day 70 °F-night) achieve the same average daily temperature, so crops will flower at the same time. However, plant height will be different at flowering.

In all of these examples, heating costs decreased from January to April. In January and February, there is little difference in heating costs between temperature strategies. In March and April, 4 to 15% more energy would be required to heat a greenhouse at a constant 65 °F versus +10 °F DIF (70 °F-day 60 °F-night).

Slide 92 - When energy costs were cheaper, many grower used a –DIF to maintain short plants with less growth regulating chemicals. However, this strategy is no longer economical. In this example, energy costs for March and April would increase by 10 to 32% at a –DIF versus +DIF.

Slide 93 - The yellow boxes remind you what the day and night temperatures are (if each is 12 hours long) to obtain the same average temperature of 65 F.

Slide 94 - For more information on strategies to improve greenhouse production efficiency and reduce heating costs, please visit the Michigan State University website for Greenhouse Energy Cost Reduction Strategies.

Thank you for your attention.