Slide 3: Presentation overview. While there can be other systems that consume significant amounts of
energy (e.g., supplemental lighting, refrigeration, ventilation), this presentation focuses on
energy issues as they relate to heating.

Slide 4: Heat exchange can occur through different modes: conduction, convection, and radiation. For
conduction to occur, materials have to be in direct contact with each other. Convection involves
the movement of a fluid (e.g., air or water), and radiation occurs between objects with different
surface temperatures. In this image, conduction is represented by black arrows, convection by
red arrows and radiation by purple arrows. Finally, air movement is represented by green
arrows. The image shows a hypothetical greenhouse with multiple systems that are typically not
all utilized in the same growing area.

Slide 5: In order to determine the maximum heat loss (which is needed to determine the maximum
capacity of the heating system), all the modes of heat loss need to be calculated and summed
including structural heat loss, infiltration heat loss, and perimeter heat loss. For greenhouses
located at windy sites and/or for greenhouses that maintain a relatively large temperature
difference between the inside set point temperature and the outside temperature, adjustments
are needed to calculate maximum heat loss. Before selecting a particular heating system, the
fuel conversion efficiency needs to be considered so that the heating system is properly sized.

Slide 6: Structural heat loss can be determined using a straightforward equation. The U-value is material
specific and is typically found in supplier documentation and/or engineering tables (a table with
some values is shown in slide 7). The (surface) area of the greenhouse can be determined from
field measurements or calculated from information found in construction drawings. The inside
temperature is the inside (nighttime) temperature set point (we use the nighttime set point
because that’s when the coldest outdoor temperature are typically occurring). The 99% outdoor
design temperature can be determined from engineering tables (some interpolation may be
needed if the greenhouse site is some distance away from the locations listed in the table).

Slide 7: We use the 99% outdoor design temperature instead of the 100% outdoor design temperature
(i.e., the coldest temperature recorded for the site) as a compromise: This allows for a more
reasonably sized heating system. For the number of hours per year that the outside temperature drops below the 99% design temperature, a grower has two options: 1. Provide additional heating capacity (e.g., by operating standby kerosene heaters), or 2. Allow the inside temperature to drop a little. The latter approach is typically used and works well as long as the lower inside temperature does not have a lasting negative impact on plant growth and development.

Slide 8: A table with U-values for common greenhouse materials as well as a few common construction materials for comparison.

Slide 9: The infiltration heat loss can be determined using a simple equation. The greenhouse volume can be determined from field measurements or calculated from information found in construction drawings. The number of air exchanges (i.e., the leakiness) can be determined from the data provided in the table. A conservative approach would be to select the largest value for parameter C.

Slide 10: In an attempt to reduce infiltration heat losses through the louvered openings associated with (mechanical) ventilation systems, this grower installed roll-up vent louvers that create a much better seal between the inside and outside environment. Standard louvers are notoriously leaky.

Slide 11: The perimeter heat loss can be determined using the equation shown. The greenhouse perimeter can be determined from field measurements or calculated from information found in construction drawings. The perimeter heat loss factor can be determined from information found in the data provided in the table. In case heat loss to the soil underneath the greenhouse floor is of concern: When the local water table is high, it is likely that the soil underneath the greenhouse floor is (periodically) wet. Wet soil conducts heat readily, so in that case a layer of insulation underneath the entire floor may be warranted. However, if the water table is low and the soil underneath the floor remains dry, the cost of adding a layer of insulation may not outweigh the heat loss (estimated to be as much as 10% of the total heat requirement) to the soil underneath the greenhouse floor.

Slide 12: To reduce the perimeter heat loss, knee walls (or curtain walls) are often extended one to two feet below grade. Often insulation materials (such as expanded polystyrene boards) are used for this purpose. Gaps between the insulation material and the structural components should be avoided as much as possible.

Slide 13: To reduce heat loss through the side walls, this grower installed bubble wrap on the inside of the glazing. This increases the insulating properties of the wall, but still lets light through that is needed for photosynthesis.

Slide 14: For greenhouses located at windy sites, total heat loss calculations need to be adjusted (the windier the location, the more heat is lost through infiltration). The calculation procedure explained in the slide results in a multiplication factor that is incorporated into the final overall heat loss calculation. Similarly, if the temperature difference between the inside set point temperature and the outside temperature is large (e.g., when a crop requires high nighttime temperatures), adjustments to the total heat loss calculations are needed. An example in the slide shows how the multiplication factor can be determined.
Slide 15: Overview of the most common heating systems installed in greenhouses.

Slide 16: Addresses the main differences between hot-air and hot-water heating systems. As subset of hot-water systems include the root zone heating systems (both bench and floor heating systems). Root zone heating has additional advantages that are listed in the slide.

Slide 17: Images of root-zone heating systems.

Slide 18: Radiant heating systems have also been used in greenhouses. This slide list lists some of the advantages and challenges of radiant heating systems for greenhouse applications.

Slide 19: Energy (and shade) curtains have been used to reduce the (radiant) heat loss at night and during the colder part of the year. Such curtains have been reported to reduce heat loss by as much as 30%, making the payback period on the required investment relatively short (sometimes the investment will pay for itself in a single heating season). In addition to energy conservation, energy curtains are often used to reduce solar radiation during the summer months. As a result, the design selected often represents a compromise between the two different functions. More control and better energy savings can be realized with multiple (layers of) curtains that are each optimized for a single function. This design increases the installed cost.

Slide 20: Energy efficiency can also be improved by using insulated storage hot-water tanks (incorporated in water heating systems). Because heating systems operate at maximum efficiency when they run for long periods of time (in lieu of cycling on and off which reduces efficiency), storage can improve the efficiency of the heating system.

Slide 21: Proper control system and strategies are also an important component of greenhouse energy management. Sophisticated computer control systems are available to maintain the greenhouse at optimum growing conditions, while minimizing energy consumption. Control systems rely on accurate input data. Therefore, take care when selecting (temperature) sensors and placing them at representative locations.

Slide 22: Growers have a variety of options when selecting the most appropriate fuel source for their operation. Price and availability are important considerations. The table shows data on cost per unit of energy generated (1 million Btu in this case). The data, published by the U.S. Energy Information Administration (EIA) in June 2014, shows that coal, natural gas, and wood are the cheapest options. But this comparison does not include issues such as ease of handling and environmental impact (especially through the generation of greenhouse gases). Finally, the table includes typical conversion efficiency information that is necessary to determine the size of a greenhouse heating system. Conversion efficiency is incorporated into the calculation for required boiler/heater capacity after the total heat loss for the greenhouse is determined.

Slide 23: This slide list several energy saving strategies as well as typical savings that can be expected (in parentheses).

Slide 24: Summary.

Slide 25: Questions.