ENERGY-RELATED AGRICULTURAL BEST PRACTICES

Guidebook

For Greenhouses

NEW YORK STATE | NYSERDA

December 2022

Greenhouse Energy Best Practices Guidebook

Energy-efficient technologies, processes, and practices create opportunities to optimize farm-energy use and lower operating costs. This best practices guidebook provides energy-related information to provide farms with a better understanding of farm-energy use, energy-efficient technologies, alternate modes of operation, and practices that optimize energy use to assist in making sound investment decisions and incorporate energy efficiency into daily practices.

Brought to you by:

NEW YORK STATE | NYSERDA

New York State Energy Research and Development Authority (NYSERDA)

NYSERDA, a public benefit corporation, offers objective information and analysis, innovative programs, technical expertise, and support to help New Yorkers increase energy efficiency, save money, use renewable energy, and reduce reliance on fossil fuels.

EnSave

Energy Solutions for the Modern Farm

EnSave is an agricultural energy services company committed to helping its clients achieve their resource conservation goals. Over its 30-year history, EnSave has designed and implemented energy and greenhouse gas reduction programs for energy utility companies, federal agencies, state governments, and agricultural cooperatives.

Table of Contents

Introduction

A grower can save a substantial amount of energy by implementing steps to reduce heat loss in the greenhouse. Greenhouse energy savings can also be found by upgrading lighting, motors, refrigeration, and ventilation. An energy audit or audit pre-consultation can better determine which actions are most cost effective for your unique situation.

Energy-Use Basics

The energy pyramid provides a useful way to consider energy management in your greenhouse. Starting at the base, the pyramid begins with the easiest and most cost-effective options.

A Cost-Effective Approach to Reducing Energy Costs

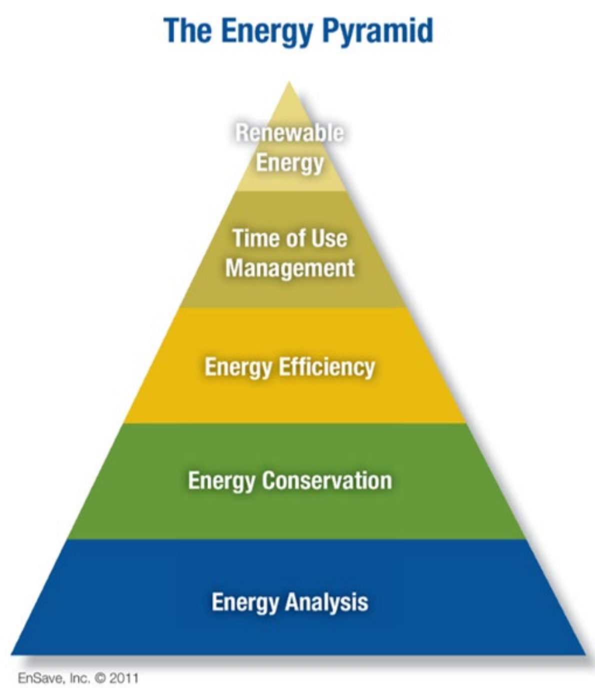
Greenhouse producers who are seeking to cost-effectively minimize their energy expenses should follow the energy pyramid when identifying opportunities for energy-cost savings.

An initial energy analysis or audit is used to evaluate greenhouse-energy use and cost-saving opportunities before making any investments. The goal of this analysis is to identify energy conservation and energy efficiency projects that will be most effective in reducing the overall energy needed in the greenhouse.

Once energy use has been minimized, time-of-use management can sometimes be utilized to reduce the cost of power from the electric utility. This can be determined with a review of the utility rate categories along with greenhouse equipment operating times and energy use.

Finally, once the energy usage and cost have been minimized, a renewable energy assessment can be performed to determine the feasibility, size, and cost-effectiveness of renewable energy systems.

There are many well-established practices that reduce overall energy use for greenhouses. This guide focuses on the fundamental three bottom tiers of the energy pyramid, with steps and information for the top two once completed.

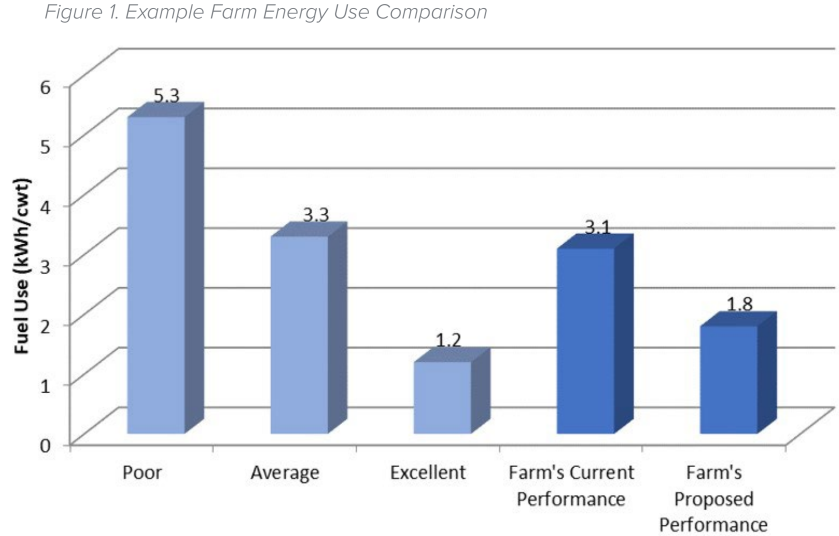


Energy-Use Analysis and Audits

Energy use in a greenhouse can be thought of in terms of how much energy is used per unit of product produced (for example, flowering potted plants or pounds of tomatoes). Greenhouses of similar type and size in comparable climates should have similar energy use. Collectively they can be evaluated to determine what the typical energy use and cost savings are, once best practices are implemented. Figure 1 – Example Farm Energy Use Comparison shows a comparison between total electrical energy used (kWh) per unit of produce for greenhouses of similar types. In a real comparison the units could be pounds, baskets, or whatever makes sense for the crop type. The goal of an energy analysis is to determine how each greenhouse can go from poor or average energy use to use that is as efficient as possible for their size and type of operation. The kWh/unit metric can be used for that comparison.

Every greenhouse is different, and each has different opportunities for energy savings. An energy audit is the first step to understanding your greenhouse's unique energy and cost saving possibilities, which is essential to reducing energy usage.

Figure 1. Example Farm Energy Use Comparison



Energy Conservation

Energy conservation is a change of processes or equipment that results in less energy use. Most energy conservation measures are simple actions you can take with your existing setup to reduce energy usage. Each system that uses energy has different opportunities for conservation. For example, in facility lighting and heating systems, turning off the lights or turning down the thermostat when not needed is an excellent and easy way to save energy. Using timers and motion sensors to do the same thing automatically are examples of energy conservation actions as well. Generally, these activities are low or no-cost, but may not save as much energy as energy-efficient equipment.

For greenhouses, an important example of energy conservation is the use of light sensors in a supplemental lighting control system to determine if the crops have appropriate sunlight exposure. The lighting controller then automatically dims or turns off the supplemental lights accordingly, saving considerable energy over schedule- or timer-based systems.

Energy Conservation

Process Improvements: Sometimes energy can be conserved by changing the order or method for how work is done. For example, utilizing natural sunlight and ventilation will save on energy costs associated with lighting and cooling. Or using waste heat from one process to add heat to another process.

Reducing Equipment Run-Hours: Anything that is plugged in or turned on uses energy. Turning that equipment off and only running it when needed reduces equipment running hours and saves energy.

Use of Switches, Timers, and Sensor-Based Controls: Timers and sensors are great for energy conservation and are often small investments that can save money without having to remember to do things differently. Anything that is using power when idle is an opportunity for automatic shutoffs. Anything that can be controlled with light, dark, motion, temperature, fluid levels, and other environmental conditions may be an opportunity for automatic controls. For example, motion sensors, dimmers, and timers can be used in areas of the greenhouse that are only used during certain times of day or for brief periods such as entrances, hallways, and storage areas. Heating and cooling systems present opportunities for temperature and schedule-based controls. Controls for crop supplemental lighting systems based on sunlight sensors can offer significant energy reductions. Remote control options are also available for some equipment, such as lights and thermostats, and can be turned on, off, or adjusted from a smartphone or computer.

Maintenance: Performing regular service and maintenance of structures and equipment is the best case for efficient operation and long lifespan. This includes various motors, pumps, and heating equipment, as well as non-mechanical components, such as glazing, weather sealing, and lighting.

Energy Efficiency

Energy efficiency refers to using less energy by changing equipment or system design to more efficient options. Each greenhouse system has different opportunities for energy efficiency. Replacing the lights or furnace with a more efficient model, reconfiguring a system to do the same task with less energy, or changing to a more efficient fuel source are all examples of reducing energy use without reducing the quantity or quality of the crops produced. This guide contains many recommendations for energy efficiency upgrades. Generally, energy efficiency measures have a cost, but the cost is worthwhile due to higher energy savings, creating a quick return on investment, and often providing other benefits such as improved working conditions.

Energy Efficiency

Equipment Upgrades: Technology is changing and improving continuously and there are many options to reduce energy costs by installing these new technologies. Often this is done when equipment reaches the end of its life, but depending on the age and type of equipment, it may be worthwhile to make the investment to change the equipment before it fails because the energy cost savings are high. The time it takes for energy savings to payback the cost of the equipment is known as the payback period. After the payback period has been reached, all the energy savings go to the farm’s bottom line.

Fuel Switching: Changing to a fuel source that operates equipment more efficiently or is a more cost-effective fuel can offer significant savings. Actual savings vary by regional energy source availability and by the cost of connecting to the new fuel source but should be considered when upgrading equipment. Examples of fuel switching include switching from oil to natural gas or propane, or from any fossil fuel to electricity.

Energy Use in Greenhouses

There are a diversity of greenhouse-energy uses that can benefit from conservation and efficiency projects. Opportunities for energy savings vary significantly between greenhouse operations based on factors that include the greenhouse dimensions, construction style, use of supplemental lighting, and crop environmental needs. Heating fuel is typically responsible for most of the energy use in greenhouses, particularly if the greenhouse does not have significant electrical loads such as supplemental lighting or cold storage.

Greenhouse-Energy Conservation Opportunities

In New York State, greenhouses have several key opportunities for energy improvements. Figure 2 – Primary Greenhouse-energy Uses shows the main categories of energy use by greenhouses, each of which presents opportunities for reducing operational costs and improving profitability.

Figure 2. Primary Greenhouse-energy Uses

Lighting | **Heating** | **Ventilation**

Cooling | **Refrigeration** | **Irrigation**

Table 1 – Summary of Recommended Energy Conservation and Efficiency Best Practices provides a summary of energy best practices and their typical payback periods for New York State greenhouses in each energy-use category. The payback period ranges for each technology were derived primarily from a combination of data obtained from NYSERDA-funded greenhouse energy audits, equipment price and savings data published by equipment manufacturers and vendors, and personal communications with subject matter experts, including greenhouse consultants. Payback periods are highly variable depending on the baseline conditions of the greenhouse, the specifications of the installed equipment, and the energy costs paid by the greenhouse, both currently and over the useful life of the equipment.

The typical savings percentage values in Table 1 provide an estimated range of annual greenhouse energy-cost reduction achieved by completing the recommended improvement. This percentage is the reduction in energy costs associated with the relevant energy end use, not from total greenhouse energy cost. For example, a 20% energy cost reduction associated with upgrading to high-efficiency fans means that the energy usage associated with those fans would be reduced by 20%, not the total greenhouse energy or electricity usage. Additionally, some energy efficiency improvements are interactive, and the savings cannot be added. For example, if new high-efficiency heaters are installed in the greenhouse and at the same time, better insulation is added, the energy savings of the new setup is based on how the two changes work together, not by adding the individual energy reduction estimates of each.

The payback period for an efficiency upgrade refers to the years of energy savings required to pay for the initial investment necessary to make the improvement. After that period, the annual energy savings go directly to the business bottom line. It is important to note that the typical payback periods provided in this guide only account for energy cost savings and do not include savings from reductions in other inputs such as water, fertilizer, maintenance, or labor. Additionally, equipment updates made to improve crop yield or production, such as adding a supplemental lighting system, where one did not previously exist, may increase overall energy use. In that case, crop yield per energy unit used is a better metric of greenhouse efficiency. For example, weight or number of crops produced per kilowatt-hour of electricity used, which could be determined by dividing the annual production by annual kilowatt-hour usage.

Each energy improvement list in Table 1 is described in detail in this guide, including system design and equipment recommendations. For all greenhouse-energy use categories, low-cost and maintenance best practices are also provided. Working with an equipment dealer or manufacturer is recommended for equipment sizing and installation guidance; however, the efficiency rating resources provided in this guide can be used to compare models and makes of various equipment to determine which will achieve more energy savings. The back of this guide includes additional resources for process and technical support, funding opportunities, and more.

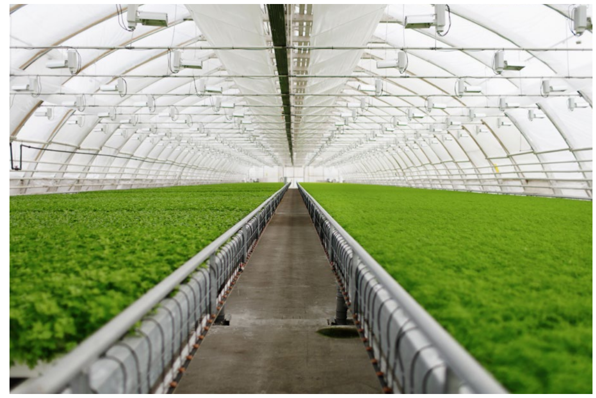
Table 1. Summary of Recommended Energy Conservation and Efficiency Best Practices

Description	Potential Improvements	Typical Savings (% energy cost reduction)*	Typical Payback (years)*
Horticultural Lighting	Upgrade from single-ended to double-ended HPS fixtures	40%–50%	1–3
	Upgrade from double-ended HPS to LED fixtures	40%–55%	5–10
	Install adaptive lighting controls	15%–30%	1–3
Heating and Cooling	Install high-efficiency glazing on greenhouse walls and ceilings	15%–25%	1–4
	Install greenhouse and perimeter insulation and air sealing	5%–15%	1–2
	Install root zone heating	15%–30%	1–4
	Install thermal curtains	20%–60%	1–3
	Upgrade to high-efficiency heater (condensing unit or condensing boiler)	10%–30%	2–5
	Install and program temperature controllers and schedules	5%–15%	3 – 7
	Install high-pressure fogging system	10%–20%	3–8
Ventilation	Install natural ventilation system (sidewall and ridge)	50%–100%	4–10
	Upgrade circulation fans to high-efficiency fans	20%–35%	8–12
	Upgrade exhaust fans to high-efficiency fans	15%–25%	8–12
	Install exhaust fan variable frequency drive (VFD) controller	10%–20%	1–3
Irrigation	Install precision irrigation system	25%–75%	2–4
Environmental Control Systems	Install greenhouse environmental control system	5%–10%	1–5
Miscellaneous Motors, Pumps, and Fans	Upgrade AC induction motors to NEMA Premium®® motors	2%–5%	8–15
	Upgrade small motors to ECM models	65%–75%	3–5
	Install motor controls for uses with varying motor loads	50%–80%	3–5
	Convert internal combustion engines to electric motors	20%–50%	4–6
	Install timer on internal combustion engine block heaters	65%–90%	3–5
Refrigeration	Replace degraded cooler and freezer gaskets	5%–15%	1–3
	Upgrade refrigeration compressor to high-efficiency type	20%–30%	5–10
	Install strip curtains	15%–30%	1–2
Water Heaters	Install pipe insulation	3%–4%	1–2
	Upgrade to high-efficiency water heaters	10%–20%	8–12

**See Typical Savings and Payback explanations in section narrative.*

New York State Greenhouse Case Study

The following is a real-life example of typical small-sized greenhouse in New York State that will save an estimated $2,400 per year in energy costs by investing in energy improvements. While an initial investment of $16,290 is needed to realize these savings, this investment will pay for itself in less than seven years through the reduced energy costs. After 10 years, the greenhouse business will have realized a net gain of about $7,700 and will continue to add approximately $2,400 to its bottom line each year thereafter over the lifespan of the new equipment.



This greenhouse operation grows vegetables and herbs year round in a 30 x 72-foot gable style greenhouse. The sidewalls and roof consist of inflated double-layer polyethylene film. The end walls are a triple-wall polycarbonate material. The sidewalls roll up in summer to take advantage of natural ventilation for cooling, and in the winter (December through April), an oil-fired furnace is used to maintain an approximate temperature of 66°F. The furnace used approximately 1,411 gallons of fuel oil to maintain the setpoint temperature throughout the winter.

A key energy savings opportunity at this greenhouse is to replace the roof and sidewall glazing with thermal infrared anti-condensate (IRAC) greenhouse film for the inner poly covering. Though condensation between the currently installed poly layers can reduce thermal radiation losses it also reduces thermal radiation gain from the sun. Condensation between the poly layers can result in other problems like material deterioration and mold. By using a poly layer that has an IRAC coated inner layer, the condensation is eliminated, and the thermal radiation losses are reduced by up to 20%. The cost difference for an IRAC film-coated poly covering over a standard covering is about $0.02 per square foot.

Another energy savings opportunity for this greenhouse is to install a thermal energy curtain. This technology saves energy by retaining heat in the greenhouse at night or on cloudy cold days. The amount of heat that is retained depends on the type of curtain material used, but commonly results in savings of 30% to 60% when compared to a greenhouse with no curtain. The thermal curtain conserves heat in the greenhouse in three ways. First, it creates an insulating layer of air between the curtain and the roof. Second, it reduces the volume of air in the greenhouse that needs to be heated. Lastly, it reflects the radiated heat back into the greenhouse instead of outside. The cost for installing a thermal energy curtain varies depending on the greenhouse style and curtain material; however, for this analysis an estimate of $2.50 per square foot was used.

This operation uses an oil-fired furnace to provide heat to the greenhouse. Replacing this equipment with a wood pellet boiler would allow the greenhouse to be heated by a renewable energy source and would result in energy savings as well.

This greenhouse analysis identified multiple energy and cost savings measures with equipment investment recommendations that will reduce operating costs and update the systems. Table 2 – Example Recommendations for New York State Greenhouse provides a summary of audit recommendations, estimated investment costs, and annual savings. Other efficiency opportunities, such as supplemental lighting, ventilation, dehumidification, and cooling were evaluated but found not to be cost effective for this greenhouse, so no recommendations were made. In this case, the recommendations are all for greenhouse heating efficiency. This means they are interactive and if all are implemented together, saving may be less than estimated. Installing better glazing and thermal curtains reduces the amount of fuel needed to warm the greenhouse, which means the furnace would run and cost less to use. The audit calculation is for the savings that corresponds with individual recommendations because a producer may choose to implement only one. In this case, the producer may choose to implement only the first two recommendations because they have the best pay back, while the third is marginal and requires the most initial investment.

Technologies and recommendations are discussed in detail in following sections. Each greenhouse is unique and must be analyzed on a case-by-case basis, which is exactly what an energy audit delivers.

Table 2. Example Recommendations for New York State Greenhouse

	Improvement Recommendation	Estimated Annual Electric Savings (kWh)	Estimated Annual Cost Savings ($)	Estimated Cost to Install ($)	Estimated Payback (Years)
1	Replace greenhouse walls and roof with double polyethylene film that has IRAC coating on inner layer	130	$290	$890	3.1
2	Install a thermal curtain inside the roof of the greenhouse	700	$1,550	$5,400	3.5
3	Replace oil furnace with pellet boiler	1,410*	$560	$10,000	18.0
TOTALS: yearly cost savings, total installed cost, and combined improvement payback period		2,240	$2,400	$16,290	6.8

** With furnace fuel switching there would be an increase of 12.3 tons of pellets to heating costs. This cost is subtracted from the total cost savings from the fuel oil.*

Energy Conservation and Efficiency Projects

Lighting

Greenhouse lighting falls into two main categories: lighting used to supplement sunlight for crop growth (horticultural lighting), and human lighting used for illuminating all other areas (non-horticultural lighting). This section focuses on horticultural lighting because it represents a significantly larger opportunity for energy savings in greenhouses that have supplemental lighting systems. For non-horticultural lighting, switching to light emitting diode (LED) technology is an almost universal recommendation.

Figure 3. LED Lighting for Cucumbers

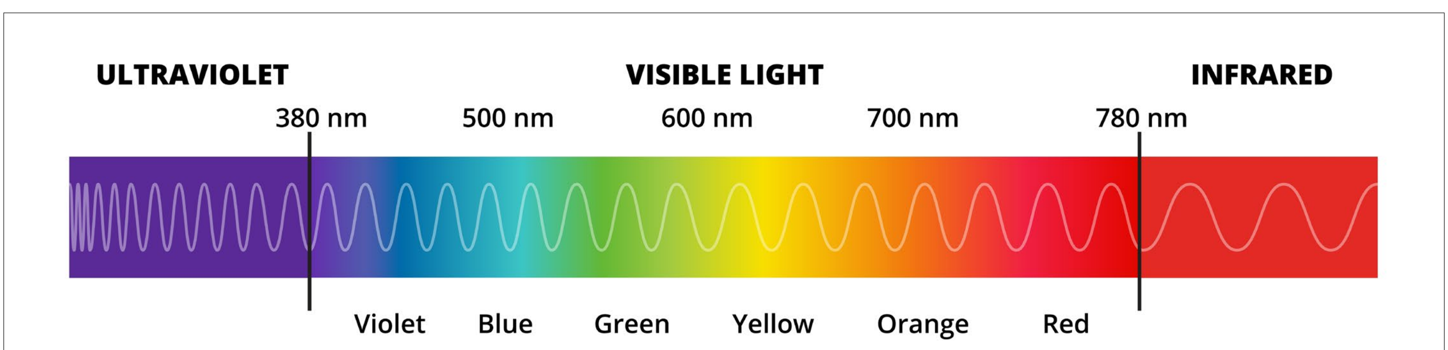
While sunlight should be used as much as possible, greenhouse supplemental lighting can enhance crop growth, quality, and yield and allow for year-round production. LED technology offers an increasingly cost-effective alternative to the high-intensity discharge (HID) lighting commonly used in greenhouses and can result in up to 55% in energy savings. Figure 3 shows a LED supplemental lighting system for cucumbers. LEDs are available in many shapes and sizes and can replace older technologies for most applications. While it may seem practical to replace light fixtures only as they burn out over time, the light output of older technology fixtures, such as high-intensity discharge (HID) fixtures can degrade substantially over time meaning the same amount of energy is used but light output is much lower than when new. In many cases it is less expensive to make a proactive investment and upgrade to more efficient technology up front. The Design Lights Consortium (DLC) has recently created a standard for horticultural lighting, enabling producers to see which models are most energy efficient and offer the best value based on lifespan and manufacturer warranties. In addition to LEDs, installing double-ended HID fixtures with electronic ballasts can result in significant energy savings in greenhouses over using legacy single-ended HID technology with magnetic ballasts.

In greenhouse supplemental lighting systems, the most critical specifications are the light quantity (intensity) and light quality (spectrum), which should be selected to optimize crop performance.

Figure 4 – Spectral Distribution of PAR Light Wavelengths Used by Plants shows the spectra of light wavelengths that are utilized by plants for photosynthesis, known as the Photosynthetic Active Radiation (PAR) range. Wavelengths outside of the PAR range may influence additional aspects of plant biology, such as flowering and nutritional quality, but the PAR range has proven to be effective for most crops, and lighting within this output range is widely available in horticultural lighting systems.

The intensity of light within the PAR spectrum is measured in µmoles of light photons. Instantaneous PAR spectrum output of a light source is described in µmoles/sec and known as Photosynthetic Photon Flux (PPF). The PAR spectrum output in a one meter by one meter area is the Photosynthetic Photon Flux Density (PPFD), measured in µmoles/sec/m2. Specifications for PAR and PPFD should be considered when selecting supplemental lighting, with attention to the distance away from the fixture at which the manufacturer measured the PPFD value. Different PAR intensity and spectrum values are appropriate for different crops and growth phases, and horticultural lights, whether LED or high-intensity discharge (HID), produce different PAR spectrum and intensity depending on the light design.

Figure 4. Spectral Distribution of PAR Light Wavelengths Used by Plants



LED lighting, in addition to being more energy efficient and longer lasting than traditional HID fixtures, such as high-pressure sodium (HPS) and metal halide (MH) technology, offer a much wider variety of lighting spectra, as shown in Figure 5 – Examples of Spectrum and Intensity of HPS and LED Lights. Importantly, LED technology is available with tunable spectra, which can be used to accomplish specific outcomes for plants, such as changing the growth habit, color, or amount of a specific compound produced by the plants. This feature can also be used to save energy. For some crops, with a sufficient balance of natural sunlight in addition to the supplemental lighting, broad spectrum supplemental lighting may not be required. Longer wavelength lighting (primarily reds) inherently uses less energy than shorter wavelength lighting (primarily blues and broad-spectrum lighting, which contains these wavelengths). If red lighting can be utilized without negatively impacting other aspects of crop production, it will reduce overall energy use.

Energy efficiency of a horticultural lighting system is measured in Photosynthetic Photon Efficacy (PPE), which is the light source PAR output capacity per Joule of electricity used in µmol/J. The higher this number, the more energy efficient the fixture.

Photoperiod (day length) and daily light levels are also important factors that impact crop performance and energy costs. Automatic lighting controls are a key opportunity to reduce energy use while potentially improving crop yield and quality. For crops that are influenced by photoperiod (day and night length) at various lifecycle stages, lighting controls provide a means to regulate lighting. The most basic greenhouse supplemental lighting system controls use timers to manage the operational schedule of lights. More advanced control systems, such as adaptive lighting controllers, utilize PAR sensors to dynamically adjust lighting system output based on available sunlight, and track the daily light integral (DLI), which is the measurement of accumulated photosynthetic light throughout the day. Each crop has an optimal DLI, after which additional light does not significantly improve productivity, and can even cause damage. Adaptive lighting controls enable the greenhouse to maximize the use of sunlight, minimize supplemental lighting and associated energy use, while achieving a consistent DLI. Figure 6 – Adaptive Lighting Control System provides an overview of the adaptive lighting control system.

Figure 5. Examples of Spectrum and Intensity of HPS and LED Lights

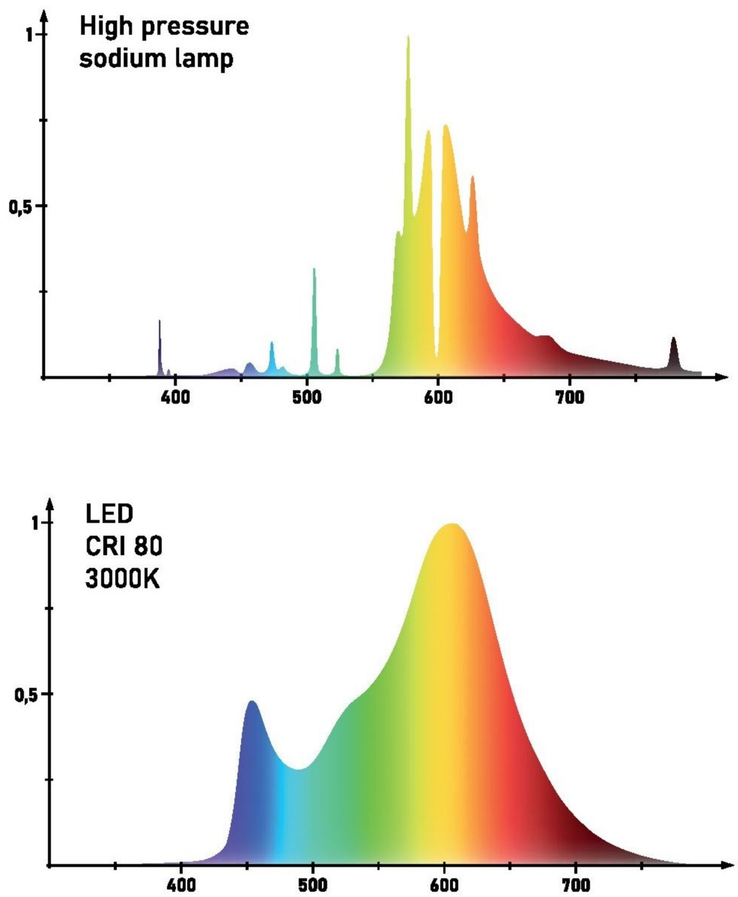
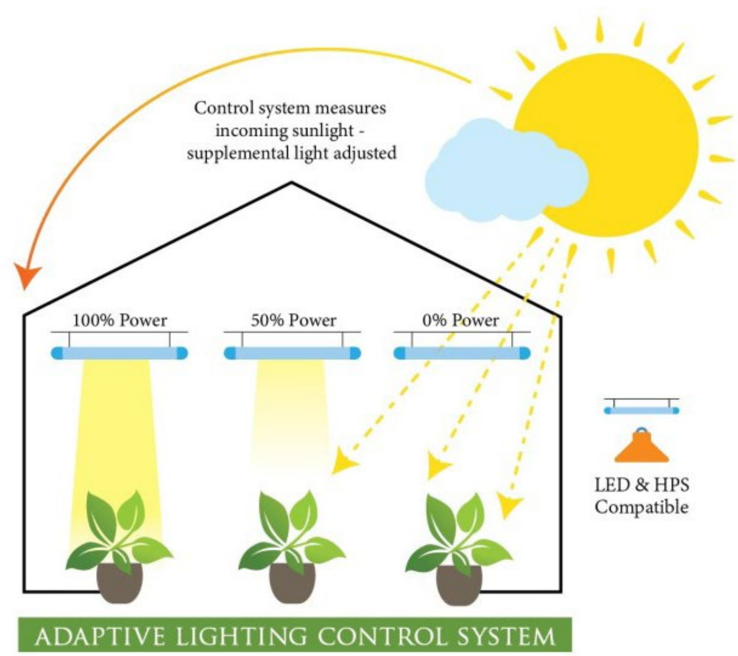


Figure 6. Adaptive Lighting Control System
Credit: https://candidus.us/how-it-works/



Lighting Equipment Upgrades – Key Considerations

Technology Options: The most energy-efficient horticultural lighting options are Light Emitting Diodes (LEDs). LED fixtures are available in many shapes and sizes and are designed to minimize shading. If LEDs are too expensive (or not used enough hours in a year to justify upgrading) and your greenhouse uses single-ended High-Pressure Sodium (HPS) fixtures, significant energy cost savings can still be achieved by switching to electronic ballast double-ended HPS.

Horticultural Lighting: Supplemental lighting to aid crop growth is the primary energy usage in greenhouse lighting systems. Lighting used for this purpose includes the following considerations.

- Light Spectrum: For specific crops and plant light-cycle phases, a target spectrum may be used; for example, to keep crops compact or to promote red pigmentation in red-leaf lettuce. Consider a lighting source with less than 30% blue light. Fixtures that are primarily red with 10-20% blue are the most energy efficient, although greenhouse workers appreciate full-spectrum lighting (such as white LEDs).
- Light Output: For horticultural lighting, the light output between 400 and 700 nm is considered with a unit of µmol/second. A fixture with 1200 µmol/s has twice the light output as a fixture listed as 600 µmol/s. Because horticultural LEDs are available in a range of shapes and sizes for different applications, it is important to understand the light output and work with the manufacturer on the plan for lighting installation. For example, bar-type LED fixtures may have a lower light output so more must be installed per unit area than a high-power HPS replacement fixture.
- Energy Efficiency: For horticultural lighting, the energy efficiency (or efficacy) of a fixture is described by Photosynthetic Photon Efficacy (PPE), which is the total light output (in µmol of light between 400 and 700 nm) per Joule of electricity used. PPE values for new HPS fixtures may be as high as 1.7 µmol/J, while LED fixtures range from 2.1 to 3.7 µmol/J, depending on the manufacturer. Refer to the Design Lights Consortium Horticultural Lighting Qualified Product List (QPL) for independent test results.

General Lighting: General purpose lighting used for purposes other than crop production also offer some opportunities for energy savings. These lights have different specifications and are selected accordingly.

- Brightness Rating: For general purpose (i.e., human) lighting other than crop supplemental lighting, the bulb brightness rated is provided by the light bulb manufacturer and is measured in lumens. Lumens are the actual amount of light the bulb produces regardless of the amount of energy (watts) it consumes to do so. The higher the lumens, the brighter the bulb. Because many people are used to older technologies and think of brightness in terms of watts, many LED manufacturers also provide an "incandescent equivalent watt rating." To conserve energy, use only the brightness required.
- Energy Efficiency: Lighting energy-use efficiency is rated in lumens per watt. The higher the lumens per watt, the more efficient the bulb. To qualify for rebates, many programs require light bulbs and fixtures to be EnergyStar® or DesignLights Consortium® (DLC) listed.

Automatic Lighting Controls: Sensor-based and adaptive lighting controls offer an excellent way to save energy and optimize crop growing environment and productivity at each lifecycle phase. These more sophisticated controllers can be used to control the whole greenhouse, or in sections used for different crop. Remote options are also available so lights can be adjusted from a smartphone or computer. Lighting controls can be used for any type of lighting.

Environmental Protection: Consider where the bulb will be located and if they should be in a sealed, waterproof housing, protected from dirt and dust, or something in between. Fixtures made for horticultural applications typically have protection from humid environments, although not necessarily for water spray. If fixtures are not available with protection ratings required, a protective enclosure may be added.

Figure 7. Use of Natural Lighting

Low/No-Cost Options

Natural Lighting: For all applications, utilize daylight when possible. Figure 7 shows an effective use of natural lighting with minimal obstructions to the crop canopy.

Low-Cost Lighting Controls: Light timers, dimmers, and simple sensor-based controls, such as motion, sunlight, and sensors, offer excellent and low-cost way to save energy. They are available for individual lights or as lighting control units for the whole facility.

Maintenance and Cleaning: Cleaning off light bulbs, reflectors, and light covers can dramatically improve light levels and reduce the bulb brightness rating required for a work area. Clean off every six months to a year.

Fixture Location: For any lighting, the closer the fixture is to the target, the more photons of light it will receive but the less area will be covered, as illustrated in Figure 8.

For horticulture lighting, fixtures should be installed to minimize light loss to aisles, perimeters, and other non-canopy areas. Because LED lights produce less heat than other technologies, these fixtures can be moved close to the crops without causing heat stress. Lowering fixtures increases the number of photons that reach a specific area, so lighting does not have to be on as long to reach target daily light integrals (DLI). This can be useful in shorter seasons. However, because lowering the fixture also reduces the spread of the light, more fixtures would be required to cover the same total area of crops. As a result, even with the reduced lighting time and potential benefits to production, it may not result in energy savings. Work with a lighting supplier to determine the lighting installation requirements to meet your crop needs.

For general purpose lighting, locating the fixtures for the best coverage of the workspace and task requirements, and then selecting the appropriate brightness rating is the simplest strategy.

Figure 8. Effect of Fixture Height on Crop Lighting

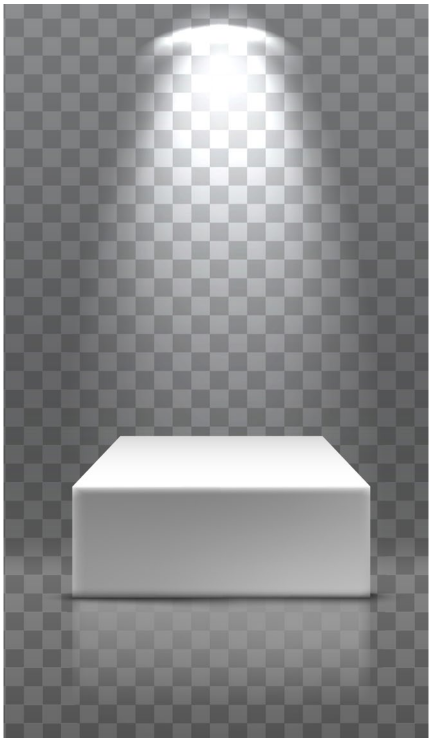


Table 3. Typical Energy Savings for Greenhouse Lighting Improvements

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Upgrade from Single-Ended to Double-Ended HPS Fixtures	40%–50%	$800–$1,500 / fixture	1–3
Upgrade from double-ended HPS to LED Fixtures*	40%–55%	$250–$500 / fixture	5–10
Install Adaptive Lighting Controls	15%–30%	$5,000–$8,000 per controller	1–3

**Fixture often must be DLC listed to qualify for utility rebate.*

Online Lighting Energy and Selection Guides

- https://www.designlights.org/horticultural-lighting/search/ (DLC qualified lights)
- https://www.energystar.gov/products (EnergyStar® listings and selection guide)
- https://www.epa.gov/cfl/recycling-and-disposal-cfls-and-other-bulbs-contain-mercury#other (old bulb recycling information)

Heating

Greenhouse heating is often the most significant use of energy for crop production, particularly in colder northern climates. However, heating also offers key opportunities for energy savings. Simple, low-cost efforts like in-ground perimeter insulation, sealing leaks and gaps, and installing automatic temperature controls can go a long way. The choice of greenhouse glazing, films, and curtains has big impact on heat retention. Use of localized heating of plant beds is a very effective way to reduce the amount of energy needed to keep plants at optimal temperatures. For heating target areas, or the whole greenhouse, there are many space heating system options to choose from. For all heating systems, existing fuel sources and heating mechanisms should be considered. In a greenhouse, it is often beneficial to use a combination of heating technologies, as each system is appropriate for different spaces and purposes.

Table 4. Greenhouse Heat Regulation Technologies and Uses

Technology	Fuel Types	Mechanism and Function	Where Used
Glass Glazing	N/A (passive)	Solar radiation, heat retention	Greenhouse walls and roof glazing
Multi-Layer Poly Film Glazing	N/A (passive)	Solar radiation, heat retention	Greenhouse walls and roof glazing
Infrared Anti-Condensation (IRAC) Film Inner Layer Glazing	N/A (passive)	Solar radiation, heat retention	Greenhouse walls and roof glazing
Thermal Curtains	N/A (passive)	Solar radiation, heat retention, heat reduction/shading	Greenhouse inner roof space
Root Zone Heating Pads	Electric	Conduction of heat through heating pads	Crop bench or floor (in/around)
Root Zone Radiant Heating Tubes	Electric, gas, biomass	Hot water pumped through pipes and heat is radiated into surrounding air	Crop bench or floor (in/around)
Radiant Tube Infrared Heater	Gas	Infrared radiation from heating element through the air	Space and surface heating
Condensing Unit Heater	Electric, gas, biomass	Fans blow air over heated metal elements to warm and distribute, sometimes through heating ducts	Space heating or central heating
Boiler	Electric, gas, biomass	Hot water pumped through pipes and heat radiated into surrounding air	Crop bench or floor heating and/or central heat systems

Heating System Equipment Upgrades – Key Considerations

Types of Heating Systems: In greenhouses there are several strategies for keeping crops at the right temperature. They are often used in combination to achieve the best energy efficiency.

- Passive Heat Systems: Passive heating systems are mechanisms used to retain heat in the greenhouse overnight and on colder days. They include wall and roof glazing options, thermal curtains, and more.
- Crop and Root Zone Heat Systems: Crop zone heaters are installed beneath the plants and include in-floor systems, systems at floor level, and systems installed in the plant benches. These options are the most efficient for keeping the plant root zone at optimal temperatures but are not indented to heat the whole greenhouse.
- Space Heating Units: Space heating units are installed to heat specific areas of the greenhouse. Depending on the size of the greenhouse, one or more units may be installed or added to heat the entire greenhouse. They are typically self-contained heating units and can be utilized as needed in a particular area, which makes them efficient and flexible as the growing cycles change.
- Central Heating Systems: Central heating systems are stationary units designed to heat the entire greenhouse by distributing heated air, steam, or water around the greenhouse in tubes or ducts. These units are typically the most expensive option to install but can also be the most energy and cost efficient to operate in larger spaces. These systems are most appropriate for general heating of larger greenhouses, and additional heat may still be required at the plant level.

Fuel Type: Heaters can run on fuel oil, gas, biomass, or electricity. Investing in a new heating system can be an opportunity to switch to a lower cost, cleaner energy source. Local energy costs and availability should be considered with fuel switching, as well as the cost for connecting the new fuel source to the equipment.

Heater Efficiency: Heater efficiency is typically rated as either a percent combustion efficiency or coefficient of performance (CP or CoP) specification. Combustion efficiency is the percentage of fuel used that is converted into heat and applies only to fuel-burning systems, such as natural gas or propane. CP is a similar rating but uses a ratio to compare the amount of heating (or cooling) achieved to the energy used. CP can be applied to any fuel type. Combustion efficiency is between 0 to 100%, while CP is between 0 and 1. In both cases, the higher the rating, the more efficient the system.

Heating System Controls: All heating systems should include thermostat controls to automatically turn off the units when the target temperature is reached. Thermostats with accurate temperature sensors (+/-1°F for digital thermostats) installed in the right location ensure crop appropriate and energy efficient temperature regulation. Schedule-based temperature settings and remote controls can also be utilized to reduce temperature targets as appropriate through the day and seasons. Passive heating systems, such as thermal shades, may be able to utilize electronic control of the mechanical mechanisms to make them easier to use or automatic. When using a combined heating and cooling system, set the heating and cooling targets several degrees apart so the unit does not run continuously. An integrated climate control system can also ensure that heating and cooling do not occur at the same time.

Passive Heating Upgrades – Key Considerations

Glazing Material: Glazing refers to the transparent material that is used to cover the walls and roof of a greenhouse, while allowing light to pass through and reach the plants. Glass, polyethylene film, and polycarbonate film are the most common choices. Heat retention capability of glazing material is rated either by R-value or U-value. The U-value is the inverse of the R-value (1/R), so the lower the U-value, or the higher the R-value, the better the heat retention. The most energy efficient glazing options are described here.

- Glass: While the glass itself has better heat retention than plastic, glass greenhouses typically have more gaps in their construction which allows for air infiltration and losses. Covering these gaps will lead to excellent heat retention, especially in colder months; however, this must be managed with proper ventilation for humidity control and air exchange. Glass installations are more permanent with a longer lifecycle and lower maintenance but are costly to install. Overall glass is a good choice but may not be appropriate for all operations. Glass can be purchased with various R-value ratings. The most effective are known as low-E glass.
- Multi-Layer Polyethylene Film: Plastics offer lower cost option, and the technology is continuously improving. Polyethylene film is a common choice due to its low cost and easy customization to fit the greenhouse frame; however, it has a very short lifespan of approximately four years. The R-value of a single layer of polyethylene film has an R-value of around 0.85, while a double layer is approximately 1.5 and can significantly increase fuel savings in the winter months. However, multiple layers do have a negative impact on sunlight transmission through the greenhouse.
- Multi-Layer Polycarbonate: Polycarbonate is more durable than polyethylene and is also easily customizable. Single layer polycarbonate has an R-value comparable to polyethylene, but double layers can boost heat retention to R-values as high as 2.5.
- Infrared Anti-Condensation (IRAC): Use of multi-layer greenhouse roof and sidewall film with IRAC film as the inner layer is the best option for energy savings. Standard double layer poly film reduces thermal radiation losses too, but it also reduces thermal radiation gain from the sun. Additionally, condensation between the poly layers can result in other problems like material deterioration and mold. IRAC coated film eliminates the condensation and reduces thermal radiation losses by up to 20% (Runkle 2008).

Thermal Curtains: Thermal curtains (also called energy screens or heat curtains) are a layer of material in the roof space of the greenhouse that can be used for either heat retention or shading to provide passive temperature regulation. For heating, thermal curtains work by creating an insulating layer between the cold roof and greenhouse space and reduces the volume of air in the greenhouse that needs to be heated. The degree of heat retention depends on the type and porosity of the material and is selected as appropriate for the climate and crops. Some materials are more reflective as well. Closing the curtains a couple hours before sundown will trap heat for overnight warmth.

Greenhouse with Thermal Curtains

Crop Bottom Heating with Hot Water Systems

Crop Bottom Heating with Electric Mats
Photo Credit: https://warmset.com/projects/greenhouse-heating

Root Zone Heating – Key Considerations

Technology Options: Root zone heat systems are the most efficient option for getting heat to the plant root zone, where it is needed most for crop production.

- Electric Heating Pads: Bench and floor mats with integrated heating elements are an effective way to uniformly radiate heat to plants trays. Use of electric heat is energy efficient, but cost effectiveness depends on the size of the operation and local electric rates. Electric heating pads come in various sizes and are portable so the pads can be used just in specific areas as needed, such as for plant propagation.
- Boiler-Based Hot Water Systems: Boiler-based root zone heating systems can utilize existing boiler equipment used for centralized heating or be a smaller stand-alone system. These systems use gas, oil, biomass (such as wood pellets), or electricity to heat water. The water is then circulated in tubes in or around the floor or benches, radiating and heating the air around the plants.

Greenhouses Heating Systems – Key Considerations

Technology Options: There are many options for space and centralized heating, utilizing various fuel types, heating mechanisms, and heat distribution systems. The following are the most energy efficient options for greenhouses. Greenhouse size, type, existing infrastructure, and crops will determine the best option.

- Condensing Unit Hot Air Heater: Condenser units utilize a powerful fan that blows air across a heated metal element and distributes it into the open spaces. The most energy efficient condenser units typically use natural gas or propane to heat the metal element. They also extract heat from the exhaust air and circulate it back into the system. With these features they achieve combustion efficiency of 93% or greater. Condenser units are typically modular and sized for the space to be heated. The number of units and placement depends on heating requirements and can effectively be used to heat some or all the facility.
- Radiant Tube Infrared (IR) Heaters: There are several types of IR heaters available for various applications. The variety that are most appropriate from greenhouses are the are low-intensity, saturating, radiant tube IR heaters that are installed overhead. They can be used for heating large areas of the greenhouse, entire canopy areas, or the whole greenhouse. This technology heats objects in the greenhouse, including plants, workers, the greenhouse, and other structures, which enables a lower greenhouse temperature without sacrificing comfort or productivity. The absorbed heat stays in the greenhouse longer than heated air. Radiant tube heaters currently available for greenhouses use natural gas or propane, but future models are in development that will operate on electricity.
- Centralized Boiler Systems: Central boiler systems are appropriate for closed spaces of any size. They use gas, oil, biomass (such as wood pellets), or electricity to heat water. The water is then circulated in tubes/fins around the building and the heat radiates into the air around them. A key opportunity for efficiency when utilizing a boiler system in a greenhouse is to include root zone heating in these heating loops. In this way the boiler will provide general greenhouse heating as well as plant-optimized heating. Keeping root-zone temperature at optimum often allows the air temperature to be cooler while maintaining crop growth. The boiler unit consists of a water heater, water circulation pump, and exhaust fan (gas/oil only). The most efficient greenhouse boiler systems are condensing boilers, which have rated thermal efficiencies of up to 99%.

High-Efficiency Gas Condensing Unit

Low/No-Cost Options

Greenhouse Site and Windbreaks: Ideally greenhouses are in protected areas out of the wind with good year-round solar exposure. For those that are not, installing windbreak structures facing the regional prevailing winds can reduce heat loss and energy costs. A temporary wind break can be a 10 to 12 foot snow fence located 40 to 60 feet away from the greenhouse. To create a permanent wind break, plant a mix of coniferous and deciduous trees about the same distance from the greenhouse.

Insulation and Sealing: Insulation and sealing is one of the simplest and most effective ways to save energy.

- Greenhouse: Sealing leaks around doors, shutters, vents, baseboards, and other openings is a simple way to reduce energy loss. For example, adding foam insulation board to the perimeter of the greenhouse can significantly reduce energy loss. This insulation should be installed 12 to 24 inches into the ground around the greenhouse. Also be sure to patch/repair any holes in the greenhouse glazing to reduce air infiltration.
- Boiler Water Heater: Insulating the boiler water heater with a water heater jacket and installing pipe insulation on hot water lines reduces heat loss and water heater energy use for a very low cost. At a minimum, pipe insulation should be installed on the first 20 feet of pipe from the water heater. Electric water heaters can be fully insulated, while gas and oil heaters should not be covered near the hot flue.

Settings and Controls: For a small investment, programmable thermostats offer a significant opportunity to save energy by allowing temperatures to be set on a schedule that makes sense for greenhouse operations and crop productivity. Turning the temperature down by just a few degrees can make a significant difference in energy use too, but it must be appropriate for the crop requirements. Utilizing a thermostat with an accurate temperature sensor (+/-1°F for digital thermostats) and placing it in a location that is most representative of crop temperature will achieve the best results consuming the least energy. A thermostat with a remote temperature probe will offer the most flexibility. Locate the temperature sensor (or thermostat unit) in a shaded area with good airflow as close to the crop production area as possible. Keep it away from heating and cooling equipment and ducting, and greenhouse walls and openings. For combined units that heat and cool, set a several degrees neutral zone between heating and cooling settings so the units do not run continuously.

System Maintenance: Regular equipment maintenance reduces energy costs and extends equipment life.

- Gas and Oil Heaters: Annual checkups for gas and oil heaters should include cleaning air filters and exchangers; a flame check or combustion test for burning efficiency; inspection and cleaning of fuel filters, nozzles, and valves; inspection, alignment, and lubrication of fan motor, belts, and bearings (as applicable). A blue flame indicates a clean burn and yellow indicates insufficient air.
- Thermostats: Metal contact on older style electromechanical thermostats can be off by many degrees and will perform better and more accurately if they are annually cleaned and recalibrated. Electronic thermostats do require cleaning.
- Boiler Water Heater: To reduce sediment buildup, which leads to inefficient operation, the boiler water tank should be emptied regularly. Install a valve on the tank drain. When the tank is at a low water level, drain the remaining water for daily general-purpose uses. Completely empty the tank at least twice a year. Inspect and repair leaks on fittings and faucets.

Table 5. Typical Energy Savings for Greenhouse Heating Improvements

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Install High-Efficiency Glazing on Greenhouse Roof and Walls	15%–25%	$0.015–$3.50 / SF	1–4
Install Greenhouse and Perimeter Insulation and Sealing	5%–15%	$1–$5 / LF	1–2
Install Thermal Curtains	20%–60%	$2–$5 / SF	1–3
Install Root Zone Heating	15%–30%	$2–$3 / SF	1–4
Install Condensing Unit Heaters or Condensing Boiler	10%–30%	$20–$36/kBtu	2–5
Install and Program Temperature Controls and Schedules	5%–15%	$500–$15,000+	3–7

Cooling

Generally, greenhouse cooling in colder regions such as New York State can be handled within the ventilation system. However, there are other approaches that can be considered to reduce ventilation costs and provide additional cooling when needed. The recommendations in this guide are the most effective options for cooler climate greenhouses that do not see extended cooling days for most of the year.

Cooling Equipment Upgrades – Key Considerations

Types of Cooling Systems: As with heating systems, greenhouse cooling technologies can generally be divided into passive and active cooling systems. Passive systems optimize naturally occurring conditions with means that do not require continuous energy inputs. They are economical but provide less precise temperature regulation. Active systems use various energy sources to inject cool air into the greenhouse environment.

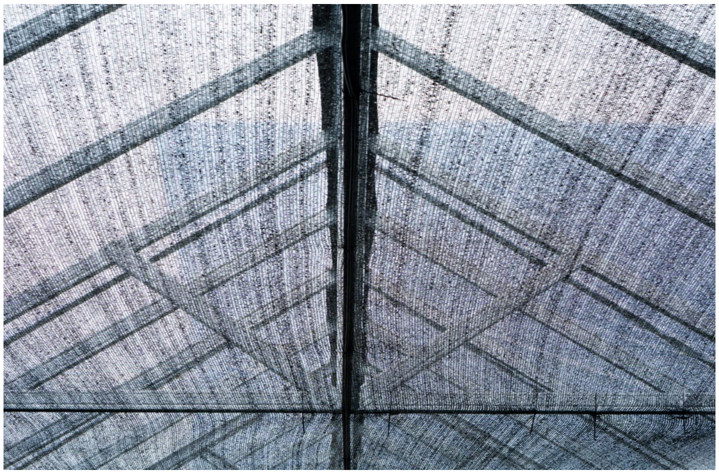
Shade Curtains: Shade curtains, also known as thermal curtains, are a layer of material in the roof space of the greenhouse that can be used for either heat retention or shading to provide passive temperature regulation. For cooling, shade curtains work by reducing the amount of solar radiation that enters the greenhouse and by reflecting radiant heat out. They also create an insulating layer between the hot outside roof the and the inner greenhouse space and reduces the volume of air in the greenhouse that needs to be cooled. The degree of shading depends on the type and porosity of material and is selected as appropriate for the climate and crops. Some materials (ex. aluminum) are more reflective as well. Closing them during the day cools the greenhouse.

Ventilation Systems: Existing ventilation systems can often provide greenhouse cooling as well. The two most effective systems for cooling are mentioned here and discussed in detail in the Ventilation section.

- Passive Ventilation: Side vents that allow cool outside air into the greenhouse in combination with ridge vents that allow hot air to escape can be an effective method of cooling.
- Ventilation Exhaust Fans: Ventilation systems that use fans to draw in cool outside air through air inlets and exhaust hot greenhouse air outside are also effective at cooling the greenhouse. There are several exhaust fan configurations, discussed in the Ventilation section.

Evaporative Cooling: For hotter greenhouses or those with heat-sensitive crops that need active cooling, evaporative cooling is the most energy efficient mechanism for cooling. Although evaporative cooling works better when relative humidity is low and are especially effective in arid regions, they are still the most efficient method for active cooling in any region.

- Evaporative Pad Systems: The most common evaporative system is the fan and pad system. This system consists of cellulose pads, a water pump, a water storage container, and can utilize existing ventilation fans and inlets. The cellulose pads are installed in front of fan inlet vents. They are periodically soaked with water and the fans opposite the pads pull air through them, evaporating water into the air and cooling the greenhouse. This system is most efficient in greenhouses with exhaust fans not utilizing natural venting as primary ventilation.
- High-Pressure Fogging: High-pressure fogging systems provide an energy efficient alternative to the evaporative pad and fan systems. High-pressure fogging systems use a high-pressure pump to inject air into a water distribution network. The aerated water comes out of fine nozzles and sprays billions of tiny water droplets around the greenhouse. The droplets evaporate almost instantly, absorbing heat in the process. This process is more energy efficient and uses less water than the pad and fan systems. Fogging systems also operate independently of the ventilation system, which is part of the energy savings, and allows them to be used in greenhouses that utilize natural venting or that do not have fans at all.



Greenhouse Passive Cooling with Shade Curtains
Photo Credit: (Castellano, S et al., 2008)

Greenhouse Fogging System for Cooling

Low/No-Cost Options

Natural Ventilation: Opening windows or doors on opposing ends of the greenhouse can be effective for cooling and ventilation. Roof vents or open-roof style greenhouses allow even greater passive ventilation capacity. Refer to the Ventilation section of this guide for more information.

Table 6. Typical Energy Savings for Greenhouse Cooling Improvements

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Install Thermal Curtains	20%–60%	$2–$5 / SF	1–3
Install a High-Pressure Fogging System	10%–20%	$5–10 / SF	3–8
Install Natural Ventilation System (sidewall and ridge)	50%–100%	$25–$50 / LF	4–10

Ventilation

Ventilation in greenhouses serve two critical functions – air circulation and air exchange. Both are essential for temperature and humidity regulation, as well as maintaining the airflow required for crop growth and productivity. Proper air circulation around the crop helps drive photosynthesis, reduce disease, and reduce gradients in temperature and humidity creating a more uniform greenhouse climate. Each crop will have different environmental requirements and will also influence the greenhouse ecosystem differently. The crop and type and size of the greenhouse will determine which ventilation system designs are appropriate to achieve these goals. Local climate must be considered as well because ventilation system effects greenhouse heating and cooling.

Greenhouse ventilation should be thought of as a system with an ideal air exchange rate (number of complete air exchanges per minute). The volume of air in the greenhouse (greenhouse length x width x height, in cubic feet) determines what airflow rate (in cubic feet per minute) is required to achieve this air exchange. The ideal air exchange rate and corresponding airflow changes seasonally with ambient temperature and specific crop requirements over its lifecycle, but there are general minimums that can be used as a guideline, shown in Table 7 – Typical Ventilation for a Greenhouse in Northern Climates. A well-designed ventilation system operates at (and not above) these values to achieve appropriate ventilation with as little energy use as possible.

Table 7. Typical Ventilation for a Greenhouse in Northern Climates

General Guidelines for Greenhouse Ventilation				
Ambient Temperature	Cold	Mild	Warm	Hot
Number of Air Exchanges Per Minute	¼ volume	½ volume	¾ volume	1–2x volume

Because of daily and seasonal changes, and varying crop types and lifecycle requirements, systems that are adjustable offer the most for energy efficiency and crop productivity. Natural ventilation systems use no energy but offer less precise control over air exchange and airflow and may be insufficient on the hottest days. Active ventilation systems, such as fans, use some energy but can also utilize adjustable speed controls, thermostats, and airflow sensors, which can significantly reduce the total energy use while also optimizing crop productivity. Table 8 – Example Crop Temperature Requirement shows the specific temperature requirements for crops in a high-tunnel growing system. Because these systems typically utilize natural ventilation, the temperature threshold to activate ventilation is lower than would be required in a more controlled environment. Ultimately, the crop and climate will determine what is sufficient, and it may be a combination of natural venting with active venting, as needed.

Table 8. Example Crop Temperature Requirement (High-Tunnel System)

Crop	Life Stage	Optimal Temperature	Maximum Temperature	Threshold for Ventilation
Pepper	Transplant to flowering	70°F–80°F	85°F	75°F
	Flowering to harvest	70°F–80°F	90°F	75°F
Leafy Greens	Seedling to harvest	60°F–65°F	75°F	55°F
Strawberry	Fall planting	55°F–70°F	75°F	60°F
	Spring harvest	65°F–75°F	75°F	60°F

Source: https://www.sare.org/wp-content/uploads/High-Tunnel-Temp-Management_Jett.pdf

Ventilation Equipment Upgrades – Key Considerations

Crops: Each crop has different temperature, humidity, and carbon dioxide requirements that may vary at different phases of the growth cycle. Ventilation effects all these variables, and the range of crop requirements should be determined before designing a ventilation system.

Climate: Seasonal temperatures strongly contribute to ventilation strategies. If greenhouse heating is required for much of the year, more precise ventilation systems may help reduce heat loss and energy costs.

Ventilation System Design: There are several standard ventilation system layouts used in greenhouses to achieve desired airflow and air exchange rates. The design depends on the type and size of the greenhouse, and determines what type of fans will be used, how many are needed, and where they will be positioned. Often these technologies are used in combination to achieve optimal conditions through seasons and crop cycles.

- Natural Ventilation: Natural ventilation is the use of windows, inlets, and ridge vents to allow air to naturally circulate air through the greenhouse. Although airflow and air exchange are more difficult to control, this is the simplest and most energy efficient ventilation system and can be made easier by using motors for opening and closing.
- Fan Ventilation Systems: There are several design strategies for fan-based greenhouse ventilation, depending on the ventilation requirements. Circulation fans, such as horizontal airflow fans, are used to mix the air in the greenhouse and are often used with natural ventilation to move air through the greenhouse. Exhaust fans are used in a closed greenhouse to precisely pull air through the building, using the pressure difference between the inside and outside.

Table 9. Strategies for Greenhouse Ventilation

Ventilation System Design	Uses
Natural Ventilation Only	• Small to medium sized greenhouses • Heat tolerant and hot climate crops • Seasonal use for other crops • Cooler climates
Natural Ventilation with Circulation Fans	• Small to large sized greenhouses • Heat tolerant and hot climate crops • Seasonal use for other crops • Cool to warmer climates
Natural Ventilation with Bottom Recirculation Fans	• Small to large sized greenhouses • Many crops (year-round depending on vent types) • Cool to warm climates • Good greenhouse environment control
Exhaust Fans with Louvers or Inlets	• Closed greenhouse (no or closed vents so air is drawn only through fan air inlets and inside/outside pressure is maintained) • All crops, but typically high-value (energy intensive) • All climates, but typically warm or hot • Precise greenhouse environment control

Greenhouse Natural Ventilation

Natural Ventilation Systems – Key Considerations

Vent Size: The larger the vent surface area the more air exchange and heat loss. Vent size should be determined for all season requirements, and multiple vents with adjustable opening sizes offer more flexibility.

Vent Location: Roof vents allow air and heat to escape significantly more quickly and are best for hot conditions. Some roof vent designs also allow rainfall, which can reduce irrigation requirements. Locating vents in the roof and on sidewalls will offer options for varying outside conditions and crop needs.

Fan systems provide more adjustability for use over seasons, crop types, and crop lifecycles. When using ventilation fans, there are many variables that effect airflow, exchange rate, and energy efficiency. This includes greenhouse size and shape, fan configuration, fan size, fan performance ratings, and other factors. The ventilation system design will determine the number of fans required, as well as the size and performance parameters of the fans. These performance requirements will drive fan energy efficiency. Selecting fans designed for the fan system configuration and performance range required will result in the most efficient operation. Fans of different manufacturers vary widely in efficiency so specifications and independent test data should be reviewed. Refer to the link at the end of this section for the University of Illinois BESS Lab fan performance and efficiency tests on specific fan models.

A good system design can be achieved with a few key considerations, but for new greenhouses, and bigger multi-structure operations, hiring a ventilation professional to do an airflow analysis and ventilation system design will likely payoff in long-term energy savings.

Fan Ventilation Systems – Key Considerations

Fan System Design: There are several standard fan system layouts used in greenhouses to achieve desired airflow and air exchange rates.

- Overhead Circulation: For air circulation in open areas with higher ceilings, overhead fans such as horizontal airflow fans are used to keep air moving. With this type of system, natural ventilation is used in conjunction with the fans for air exchange and temperature regulation.
- Bottom and Recirculating: Bottom systems use circulation fans that are installed at or below plant level to provide air exchange where it is needed most. With this system, natural ventilation and sometimes overhead fans are still used for temperature regulation, as bottom fans do not move the heated air that collects at the top of the greenhouse. The most efficient approach is to use an air intake tube with a fan at the top of the greenhouse that funnels the heated air to bottom fans at the other end providing even, continuous circulation. This is especially effective in cooler climates when minimizing heat loss from venting is desired.
- Tunnel or Cross Ventilation: For air exhaust and circulation in enclosed greenhouses, fans installed on one end wall to pull air from air inlets on the opposing end wall are known as a tunnel ventilation design. This design requires a static pressure differential between the inside and outside of the structure, so it must be an enclosed area (no vents or vents are closed), and only intentionally located air inlets or louvers are used for air intake. For wider greenhouses, the same concept can be applied for a cross ventilation design in which the fans installed on one side wall pull air across the structure from air inlets on the opposing side walls.
- Air Inlets and Louvers: Properly sized and located louvers or air inlets are critical to achieving the desired airflow with tunnel and cross ventilation designs. They can be used in conjunction with pressure sensors to achieve precise airflow regulation. Size and location are determined by the cross sectional area of the structure and fan specifications. Refer to fan manufacturer recommendations.

Fan Type: Fans are designed to optimize airflow when installed in a specified configuration. The following are the most effective and efficient options for greenhouses in cooler climates such as New York State.

- Horizontal Airflow Fans (HAF): Horizontally mounted overhead fans are the standard circulation fan used in greenhouses. When installed properly they are very effective and efficient at providing uniform temperature and air flow throughout. These fans are typically 12 to 20 inches in diameter and installed at 30-to-40 foot intervals in rows that create a circular pattern through the greenhouse. The key performance specification for these fans is airflow, energy efficiency, and speed control. Total fan system capacity, in cubic feet per minute (cfm), should be about two times the greenhouse area. For example, a 300 x 20-foot greenhouse would have a total capacity of 300 x 20 x 2 = 12,000 cfm. Multiple HAF fans with high-efficiency, low-horsepower motors offer the best energy performance.
- Vertical Circulation Fans: Vertically mounted fans are used in greenhouses to disturb air from the top to the bottom of the greenhouse. While properly positioned HAF fan systems or bottom circulation fan systems can perform this job well, for some greenhouse designs and crop types, vertical fans may be appropriate. For very large greenhouses, high-volume low-speed fans (HVLS) offer excellent energy efficiency and one can replace many standard circulation fans. However, special consideration must be given to potential interference with greenhouse thermal curtains and structures as these fans are 4 to 24 feet in diameter. In cooler climates thermal curtains are likely more important for energy conservation than fan energy use.
- Exhaust Fans: Exhaust fans are large fans with a unique funnel shape that aids in the ability to suck air into an enclosed space through opposing wall inlets. The key performance specifications for these fans are airflow, static pressure performance, energy efficiency, and thermostat-based control. These fans work best in closed greenhouse designs because they are designed to utilize a pressure differential between the inside and outside of the greenhouse structures that are created in this way.

Fan Performance: Fan performance is typically specified as an airflow rate measured in cubic feet per minute (cfm). The fan diameter, motor horsepower, and design affect how much air it moves.

Fan Diameter: Appropriate fan diameter depends on desired air flow for each fan in the ventilation system. Airflow requirements depend on the size of the greenhouse and seasonal air exchange requirements and can be calculated from greenhouse air volume (greenhouse length x width x height). Choosing the appropriate size, and no bigger will minimize overall energy use because the fan will be operating in its best performance range.

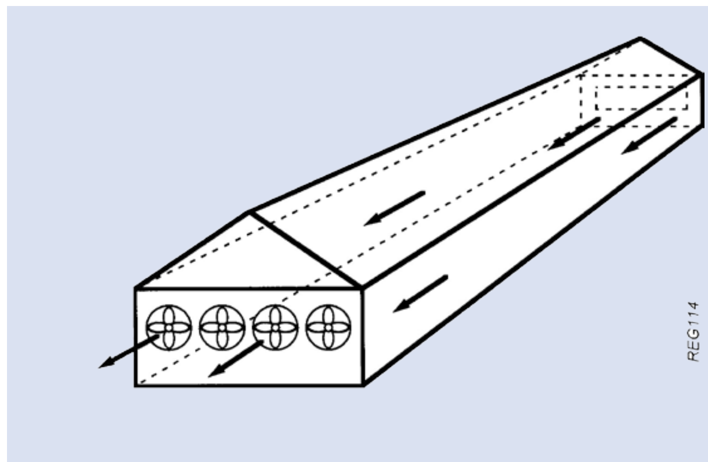
Energy Efficiency: Fan efficiency is rated by the fan manufacturer. Exhaust fans are typically specified in cubic feet per minute per watt at a stated static pressure (cfm/watt @ SP). Circulation fans are typically rated in thrust per watt (lb/watt or lb/kilowatt). Fans of different manufacturers vary widely, therefore specifications and independent test data should be compared. Overall efficiency is affected by fan diameter, blade design, motor design, and fan controls. Refer to the website link at the end of this section for the University of Illinois BESS Lab independent fan performance and efficiency tests on specific fan models.

Fan Motor Controllers: ***Variable Frequency Drives (VFD), Speed Controls, and Temperature-Based Control***
Fan motor controllers offer significant energy savings opportunities by reducing the speed of the fans based on outside air temperature and naturally occurring ventilation. Fan controls can be used manually, on a time schedule, based on target temperatures, target airflows, or in some combination throughout the day and seasons. The best fans are capable of speed control by a built-in or third-party automatic controller such as variable frequency drives (VFD) or speed controllers. Manual controls are an option as well and can be upgraded to automatic in the future. The type of controller to use depends on the type of fan motor and how the fan is being used. Refer to the *Various Use Motors, Fans, and Pumps* section of this guide for more information about motor compatibility and uses.

Horizontal Airflow (HAF) Circulation Fan System

Greenhouse Ventilation Systems Inlets and Covers

Tunnel and Cross Ventilation System For Fully Enclosed Greenhouses



Ideal Fan and Inlet Placement for Fully Enclosed Greenhouses

Low/No-Cost Options

Natural Ventilation: Use natural ventilation whenever practical to aid in maintaining ideal temperatures and airflow.

Fan and Air Inlet Locations: Placement of fans and inlets can affect how well the ventilation system performs. Adjusting them to a more optimal location can help make them move air more efficiently. Refer to fan manufacturer specifications.

Fan Settings and Controllers: Adding a compatible third-party fan controller to fans that do not have them can be a low-cost way to reduce energy use. Programming settings on fans with existing automatic controllers can also help save energy, as well as employing any manual controls.

Fan Maintenance: Fans need regular maintenance to continue to perform at peak standards. Keep fans clean and properly lubricated to ensure maximum performance and minimal energy use. Fan blades coated with dust and debris move less air using more electricity. Lubricating shutters, tightening loose belts, cleaning air inlets, and removing debris caught in screens will all improve fan efficiency.

Variable Frequency Drive for Fan Motor Control

Table 10. Typical Energy Savings for Ventilation System Improvements

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Install Natural Ventilation System (sidewall and ridge)	50%–100%	$25–$50 / LF	4–10
Install High-Efficiency Circulation Fans	20%–35%	$200–$500 each	8–12
Install High-Efficiency Exhaust Fans	15%–25%	$400–$1,500 each	8–12
Install Exhaust Fan VFD Controller	5%–12%	$500–$1,500 each	1–3

Online Resources:

- University of Illinois Agricultural Fan Performance Tests: http://bess.illinois.edu/type.asp
- USDA Farm Energy Website – Horizontal Airflow Fan System Design https://farm-energy.extension.org/horizontal-air-flow-is-best-for-greenhouse-air-circulation/

Irrigation

Drip irrigation and subirrigation systems save energy and water by delivering the water directly to where it is needed at the plant roots, instead of broadcasting it over an entire area with an overhead system. Drip and subirrigation systems utilize a simple, low pressure water delivery and can be used to supply crop nutrients as well. Installed costs for these systems are comparable or slightly higher than overhead irrigation systems. Using automated irrigation control systems is the most effective approach to reduce water, nutrient, and labor inputs. A greenhouse irrigation controller can be pre-programmed with a water management schedule to deliver precise amounts of water and nutrients based on crop maturity. This method of water application also reduces humidity, which reduces the energy needed for heating and venting cycles to dehumidify.

For drip irrigation in greenhouses, application amount for a specific crop is typically measured in volume of water required per day, per plant at the drip emitter. From this calculation as well as crop spacing (plants per foot), the total gallons needed per linear foot of drip tube can be calculated. The information is used to determine the water pump flow rate capacity in gallons per hour (gph), and to determine how long the pump needs to run to distribute the required amount. As part of an irrigation water management plan the pumping time can then be scheduled and executed each day for each crop. The addition of a water pump motor timer can be used to automate this process. For more precise applications, a pump control system with soil moisture sensors can be used to monitor actual crop soil conditions and adjust water application as needed. More sophisticated systems include weather stations and forecasting to further optimize water applications based on light intensity, temperature, and humidity.

Greenhouse Drip Irrigation System

Equipment Upgrades – Key Considerations

Technology Options: Drip irrigation systems (also known as micro irrigation) used in an irrigation water management plan is the most effective, low-energy, and low-water method for keeping crops precisely hydrated for best productivity. Drip irrigation systems deliver water to each plant through a thin polyethylene tape (or tube) with regularly spaced small holes, called emitters. A low-pressure pump (10 to 25 psi) supplies the water from any source, including small ponds, rain catchment and storage tanks, or facility plumbing. This water can also come from waste of another process if it is appropriate to apply on the crops. Depending on the crop being grown and greenhouse setup, subirrigation using an ebb and flow or capillary mat irrigation system may be more appropriate than drip irrigation.

Irrigation and Pump Controllers: Irrigation management equipment can range from simple to sophisticated. The simplest system utilizes a timer or water meter to shut off the water pump when the desired number of gallons has been applied to the crop roots. More advanced pump control systems include soil moisture sensors and adjust water application automatically as needed. For irrigation systems that have changing rates of water or long drip tape that result in water pressure loss, pressure compensated emitters can be used to ensure consistent water delivery rates across the system. A variable frequency drive (VFD) or speed controller can also be used to increase pumping efficiency by automatically adjusting the pump rate. Refer to the Various Use Motors, Fans, and Pumps section of this guide for more information on VFD's. In larger systems controllable valves may be used to turn on/off or adjust water input between different drip lines.

Crop: Each crop has different water and nutrient requirements that may vary at differ phases of its lifecycle. Understanding specific crop requirements must be determined to set up its irrigation water management plan.

Pump and Motor Size: Pumps are rated in gallons per minute (GPM), so once gallons of application are determined, a pump size can be determined based on how long it can take. A faster pump will typically require more energy, so if a slower one can be used it may be more efficient. For larger systems, multiple small pumps may be more efficient and effective than one large one due to the length of the drip tubes and low-pressure requirement. The size of the pump motor is rated in horsepower and, along with motor and pump technology type, will determine what types of controllers can be used. Refer to the Various Use Motors, Fans, and Pumps section of this guide for more information.

Pump Motor Efficiency: Depending on the size and type of pump motor, upgrading to an energy efficient model, such as a NEMA Premium® motor or ECM motor, could result in long term energy savings. Refer to the Various Use Motors, Fans, and Pumps section of this guide for more information.

Low/No-Cost Options

Water Retention: Use of water containers of various types can be an effective and low-cost way to retain water at the crop roots and reduce frequency of watering required throughout the day.

Water Collection: There are many simple and effective rainwater catchment systems that can be used for irrigation in greenhouses of all sizes. Use of natural watering and gravity fed systems can reduce energy and water use in the greenhouse. Commercial installations can be much larger.

System Maintenance: Clean water emitter holes regularly and repair leaks in the water delivery pipes. Replace and repair drip tape as needed.

Pump Maintenance: Perform regular maintenance of the pump motor. Inspect and clean serviceable parts.

Water Catchment for Commercial Greenhouse Irrigation

Table 11. Typical Energy Savings for Greenhouse Irrigation Improvements

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Install Drip Irrigation or Subirrigation System	25%–75%	$2–8 / SF	2–4

Environmental Control Systems

Figure 9. Greenhouse Environmental Control Technologies

Greenhouse environment control systems enable automated control of temperature, humidity, lighting, and irrigation. Control systems come in many configurations, from basic to advanced, but operate using the same principles. They are designed to interface with existing equipment and coordinate their operation to achieve optimal crop performance with as little energy use as possible.

Environmental control systems can be simple, affordable, and easy to install. All systems, from basic to advanced, include sensors to measure the current conditions of a greenhouse such as air, light, water, and soil. The measurements are used by the controller to automatically adjust equipment such as heaters, fans, vents, lighting, and water supply. Most controllers are programmed based on schedules and setpoints appropriate for the climate and crops. More advanced systems also include features such as remote control; historical data viewing; performance analysis; use of weather and day length forecasting; and use of calculations and algorithms to attain crop biological targets such as daily light integral (DLI) and vapor pressure deficient (VPD). Figure 9 – Greenhouse Environmental Control Technologies provides an overview of a full-featured greenhouse control system.

While there are many options to choose from, controller selection should be based on the complexity needed to accommodate the crop sensitivity, within the limitations of greenhouse configuration and equipment. Simpler controllers, such as greenhouse step controllers, are designed specifically for greenhouse use and offer adequate control for many types of greenhouse equipment, and are less of an investment than more advanced systems. Step controllers allow operators to assign equipment based on multiple levels (steps), depending on the environmental conditions and plant requirements. For example, if the first temperature level is reached, motorized vents are opened. Then, if the next temperature level is reached, fans are turned on as well.

Table 12 – Crop Humidity Requirements for Disease Prevention

Greenhouse Temperature	Maximum Humidity
50°F	83%
61°F	89%
68°F	91%
86°F	95%

Source: https://ag.umass.edu/greenhouse-floriculture/fact-sheets/reducing-humidity-in-greenhouse

The controller does not need to be connected to all existing equipment, and equipment can be added to the controller as it makes sense. For example, if lighting is already controlled by a timer and appropriate enough for the crop, it may not be worth wiring the lighting circuits into the controller. However, the same greenhouse may benefit greatly from integrated control of heating and ventilation equipment (and optionally irrigation) because adjustments can be made in combination to achieve target humidity levels, not just based on the temperature setpoint of the heater and designed-in air flow rates of the fans. This helps energy efficiency, crop productivity, and disease prevention. Table 12 – Crop Humidity Requirements for Disease Prevention provides corresponding temperature and humidity conditions for disease prevention. As temperatures go up, crops generally tolerate higher humidity.

To take this concept a step further, controllers that use programmed vapor pressure deficient (VPD) levels to control heating and humidification, equipment can further optimize crop productivity. VPD is the difference in air pressure at the current relative humidity (RH) and temperature from the pressure at which the air would be saturated (100% RH). As VPD goes up, plants release more water into the air (transpiration), which increases plant metabolism. At low VPD, transpiration is greatly reduced, which is appropriate during vegetative propagation (rooting of cuttings). Depending on the crop production phase in process, equipment could be adjusted to influence the conditions for either outcome.

All control systems utilize some combination of sensors such as temperature, humidity, carbon dioxide, photosynthetic radiation, and soil moisture. When installing these systems, placement of the sensors is important for effective regulation by the controller. For example, temperature sensors should be installed toward the interior of the greenhouse, not along sidewalls or next to the heating ducts which are more representative of temperature extremes. Generally, sensors should be placed in locations that enable them to sense what most of the crops are experiencing, and as close to the crops as feasible.

Table 13. Typical Energy Savings for Greenhouse Environmental Controls

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Install Greenhouse Environmental Control System	5%–10%	$500–$15,000+	1–5

Various Use Motors, Fans, and Pumps

Electric motors that are inefficient or improperly sized can have a significant impact on total energy operating costs. Motor efficiency is a measure of how much total energy a motor uses to deliver the rated horsepower or torque to the motor shaft. Motors come in a variety of configurations and each design is optimized for different types of work, can utilize different types of controls, and have a different potential for energy savings. Selecting compatible equipment is an important part of the selection or upgrade process. Table 14 - Typical Motors Used on Greenhouses describes common motor technologies, corresponding controller compatibility, and energy saving options. Using motors with built-in controls or adding external motor controllers can offer significant energy savings but are only applicable to some uses. In a greenhouse, ventilation fans are often an excellent opportunity for gaining energy efficiency through motor control, but for all opportunities, it depends on how often they are used. For efficiency upgrades, motors used over 2000 hours per year may be worth the investment.

All fans and pumps utilize a motor. Fans have integrated motors, while in pumps they may be built-in or a separate component. For applications in which fan speed or pump pressure can change as it is used, a variable frequency drive (VFD) or speed controller on the motor can make them operate more efficiently by adjusting the motor speed to match the changing requirements. The fan and pump must be compatible with the motor controller to use them. For fans this means that the fan motor is compatible, as show in Table 14 - Typical Motors Used on Greenhouses. For pumps, the pump itself also must be compatible. Refer to manufacturer specifications.

Choosing the right motor for any particular use in a greenhouse will depend on performance characteristics that will have to be evaluated for each use. There are two rating agencies, the National Electrical Manufacturers Association (NEMA) and the International Electrotechnical Commission (IEC), that work with motor manufacturers to certify and promote motors with energy efficiency. Selecting motors with these ratings ensure they have high-efficiency characteristics.

Table 14. Typical Motors Used on Greenhouses

Motor Technology	Size Range	Compatible Controller	Potential Energy Savings Upgrade
AC Induction Motor (single phase)	Typically < 10HP	None	• Upgrade to NEMA Premium® rated
AC Induction Motor (three phase)	All sizes	Variable frequency drive (VFD)	• Upgrade to NEMA Premium® rated • Add external VFD (variable load only)
Permanent Split Capacitor (PSC) and Other Small Motors	< 1HP	None	• Upgrade to ECM with optional speed controller
Electronically Commutated Motor (ECM)	< 1HP	Speed controller	• Add external speed controller (variable load only) • Manual speed controller

Equipment Upgrades – Key Considerations

Motor Run Hours: If the motor is only running sporadically, a retrofit to high-efficiency motor may not make economic sense. However, the longer the motor runs, the greater the potential for savings. Typically, over 2000 hours a year is worth the investment. For any new installations, high-efficiency motors should be used.

Motor Size: Using a motor that is rated for the work it will perform is essential to achieving the best performance and energy efficiency. The amount of work a motor can do is referred to as the motor load and is measured in horsepower (HP). Electric motors are typically designed to run best at 50 to 100% of their rated load, with maximum efficiency around 75%. Below 50% the efficiency dramatically decreases, so using a motor that is oversized will increase operating cost. Determining the load requirement for a particular use on the greenhouse is a complex calculation, and it is recommended to work with a motor dealer or manufacturer.

Motor Operating Environment: If the motor is used in an area that is wet or exposed to dust and debris, a motor with the dust tight or sealed housing may be needed. This may limit motor technology options.

Motor Efficiency and Ratings: Motor efficiency is a measure of how much total energy a motor uses to deliver the rated power to the shaft and is typically specified as a percentage of energy conversion. The higher the percentage the more efficient the motor.

- NEMA: National Electrical Manufacturers Association (NEMA) certified motors are evaluated to a United States Department of Energy (US DOE) standard and are guaranteed to have high-efficiency ratings. NEMA Premium® is the highest NEMA rating. NEMA rated motors also have high-manufacturing quality standards so they will last longer with less maintenance cost and downtime. The International Electrotechnical Commission (IEC) has comparable ratings to NEMA for motors manufactured in countries outside the United States.

Technology Options: There are many technology options, and working with a motor manufacturer or dealer is the best way to select the right make and model for a particular use. The options listed below are broad categories with many configurations within each one but serve as a starting point for selection.

- AC Induction: Alternating current (AC) induction motors are versatile and available in many sizes and configurations. Depending on size, some can be connected directly to a utility wall outlet, while others (such as three-phase motors) must be connected to a utility junction box and installed by an electrician. While available in sizes appropriate for most greenhouse uses, AC motors are typically not as energy efficient as DC motors. Three-phase AC induction motors can utilize an external variable frequency motor controller.
- Permanent Split Capacitor (PSC)/Other Small Motors: PSC motors are more efficient and simpler to maintain than AC induction motors but are limited in the amount of horsepower they can produce, typically less than 1 HP. PSC motors cannot accept external controllers.
- Electronically Commutated Motors (ECM): ECM motors come in a similar size as the PSC motor (< 1HP) but are far more efficient motors and can be used with variable speed controllers. Certain ECM motors have variable speed controls built-in.
- Internal Combustion Engines (ICE): Motors that run on gasoline or diesel use internal combustion technology and are most useful for portable applications such as in tractors, irrigation systems, or as a backup power source. For these applications there may be opportunities for energy savings by converting to an electric system, especially if the motor is oversized for its use. Regional fuel cost, utility rates, and electric motor technology are limiting factors to the economics of savings associated with fuel conversions.

Motor Controllers: For motor applications that have variable loads during usage and are not utilizing a motor that already has built-in controls (some ECM motors), adding an external variable frequency drive (VFD) or speed controller may be a significant opportunity for energy savings. These controllers automatically regulate the speed and rotational force as the motor load changes, which allows the motor to run more efficiently. VFD’s are used with 3-phase AC induction motors, while speed controllers are used with ECM motors.

Low/No-Cost Options

Motor Maintenance: Inspect and clean motors regularly to ensure optimal operation. Verify proper ventilation, check for loose connections, drain condensation, and lubricate bearings as applicable.

Motor Belt Type: Replace V-type belts with notched belts for better belt efficiency.

Engine Block Heater Timer: For internal combustion engines utilizing a block heater for cold weather starting, the addition of a timer to the heater can save significant energy costs. Program the timer to turn on the block heater a few hours before the equipment is needed instead of leaving it on overnight.

Manual Speed Controllers: Simple manual speed controls, such as those used for ventilation fans, offer a low cost way to reduce energy use by turning down the motor speed when less power is needed.

Table 15. Typical Greenhouse Motors: Uses and Improvement Opportunities

Motor Application	Area Used	Potential Improvements
Ventilation Fan Motors **General Use Fan Motors**	Greenhouse General use	High-efficiency motor upgrade (NEMA Premium® preferred)
		ECM motor upgrade (< 1HP motors)
		Install VFD motor controller (3-phase AC induction motors)
		Install speed controller (< 1HP ECM motors)
Irrigation Pump Motors **Other Pump Motors**	Greenhouse Crop beds General use	High-efficiency motor upgrade (NEMA Premium® preferred)
		Install speed controller (< 1HP ECM motors)
Water Circulation Pump Motors (Boiler Heat/Hot Water/Other)	Greenhouse General use	High-efficiency motor upgrade (NEMA Premium® preferred)
		ECM motor upgrade (< 1HP motors)
Tractor Engine	General use	Install block heater timer

Table 16. Typical Energy Savings for Motor Improvements

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Replace Small Motors (<1 HP) with ECM	65%–75%	$250–$750 each	3–5
Replace AC Induction Motor with NEMA Premium® Motors	2%–5%	$50–$150/hp	8–15
Install Motor VFD Controller on AC Induction Motors with Variable Loads	50%–80%	$200–$500/hp	3–5
Install Timer on Internal Combustion Engine Block Heaters	65%–90%	$30–$50 each	3–5
Replace Internal Combustion Engine with an Electric Motor	20%–50%	$50–$150/hp	4–6

Online Motor Selection and Energy Guides:

- NEMA Standard Motor Manufacturers
  https://www.nema.org/docs/default-source/advocacy-document-library/nema_premium_partners.pdf
- VFD Saving Calculator
  http://www.vfds.org/vfd-savings-calculator.html

Refrigeration

Many greenhouses utilize walk-in coolers, display cases, and other refrigeration equipment. While there are many refrigeration system configurations, they all consist of a few key components, and each have opportunities for energy-use improvements. They include the refrigeration enclosure, the evaporator, the condenser, and the compressor.

The refrigerator enclosure should be maintained with good seals and insulating materials to contain the cold air. If it is not fully enclosed, switching to an enclosed unit is a good option and can be done with a simple anti-condensation heater that keep viewing windows clear. The evaporator and condenser are similar components except one absorbs heat and is sometimes located on the inside of the cooler (evaporator) and the other releases heat and is always located on the outside of the cooler (condenser). Both may utilize fans to assist energy transfer. Buying systems with high-efficiency ECM type fan motors or replacing these parts in an existing refrigeration system can result in significant energy savings. Refer to the Various Use Motors, Fans, and Pumps section of this guide for more information on these motors. Figure 10 – Greenhouse Produce Walk-In Storage Cooler shows a walk-in cooler system with refrigeration evaporator units, strip curtains, and LED lighting.

Figure 10. Greenhouse Produce Walk-In Storage Cooler

Another opportunity for energy savings in a refrigeration system is with the compressor, which is usually located with the condenser and has internal mechanisms that compresses refrigerant gas to a liquid, which aids in transferring the heat from the evaporator to the condenser. For systems with stand-alone compressors, upgrading to the most efficient technology, such as a scroll or discus-type compressor can lead to significant energy savings in the long term.

Refrigeration Equipment Upgrades – Key Considerations

Refrigeration Unit Energy Efficiency: For smaller self-contained refrigeration systems that do not have separate refrigeration components (evaporator, condenser, fans, and compressor), upgrading to a high-efficiency model can be a simple and cost-effective way to reduce energy costs. Refrigeration efficiency is rated with a coefficient of performance (CP or CoP) specification which is the ratio of cooling to energy used. Higher CP is a more efficient system. Many self-contained systems are EnergyStar® rated as well.

Enclosure Type and Size: Refrigeration systems should be selected in an appropriate size and configuration for the usage. A refrigerator or cooler that is not big enough may be running continuously to try and keep the products cool, while one that is too large may use more energy to keep the larger space cooler than is needed for the items being stored. All modern refrigeration systems should be fully enclosed. For cases with windows, utilize small anti-condensation heaters to keep the contents viewable and the doors closed as much as possible.

Enclosure Insulation: The ability of the refrigeration wall insulation to retain cold air is specified with a rating known as R-value. The higher the R-value, the better the cold retention. Walk-in coolers should have a minimum of R-25 insulation value in the walls and ceilings. Walk-in freezers should have a minimum insulation value of R-32 in the walls and ceilings and R-28 in the floor.

Fan Motor Efficiency: Updating to high-efficiency condenser and evaporator fans, motors such as ECM motors, or purchasing refrigeration systems with this type, can reduce energy use by about 70%.

Compressor Type: Updating to a high-efficiency scroll type or discus type compressor or purchasing refrigeration systems with this compressor type can reduce energy use by about 30%. These units utilize a built-in variable controller that matches the cooling requirements, and typically run much quieter.

Low/No-Cost Options

Sealing: Replace gaskets and seals around doors and openings is an easy and low-cost way to save energy.

Settings: Observing the temperature inside the refrigerator enclosure during normal use will reveal if the thermostat setting is appropriate for what is being stored. Generally, refrigeration temperatures should be maintained below 40°F during normal use to prevent common bacteria from forming, and below 0°F to keep items frozen. Crops often have post-harvest temperature specifications as well to keep them fresh. For example, lettuce is best stored at 32°F. But, if the temperature inside the refrigerator enclosure is well below that during normal use, the thermostat setting can be turned up to conserve energy.

Strip Curtains: Strip curtains are soft plastic curtains used in doorways and openings between heated and non-heated areas or cooled and non-cooled areas to minimize air exchange. They can be used in addition to doors if the door is opened frequently, or to cover non-enclosed display cases after hours.

System Maintenance: To maintain most efficient operation and extend the life for the equipment, following manufacturer recommendations for service. Verify proper ventilation, clean evaporator, and condenser coils, check for loose connections, drain condensation, and lubricate bearings as applicable. Inspect equipment regularly and fix any leaks or damaged components. This includes the condenser coils, evaporator coils, drain pan, fans, screens, grills, filters, and drier cores. Add or remove refrigerant as needed. Check and change the oil, filter, and inlet screen as directed by the manufacturer.

Automatic Door Closers: Install automatic door closers on coolers that will be open and closed frequently.

LED Lighting: Install LED lighting in walk-in coolers and display cases.

Table 17. Heat Pump Water Heater with Electronic Controls

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Replace Degraded Cooler and Freezer Gaskets	5%–15%	$50–$100 each	1–3
Upgrade Refrigeration Compressor to High Efficiency Technology	20%–30%	$15–$25 / Btu h	5–10
Install Strip Curtains Between Cooled and Non-Cooled Spaces	15%–30%	$3–$6 / SF	1–2

Online Refrigeration Selection and Energy Guides:

- https://www.energystar.gov/products

Water Heaters

Some greenhouses have general purpose water heaters. Having a properly sized and energy-efficient water heater is the most effective way to minimize water heating costs, and it may be worth replacing even if it is not at the end of its life. There are also several low and no-cost opportunities for energy savings that can be implemented on any water heating system, old or new.

Water Heater Equipment Upgrades – Key Considerations

Fuel Type: Investing in a new water heater can be an opportunity to switch to a lower cost energy source. Electric water heaters are more efficient and can use energy saving electronic controls. However, electric heaters may cost more to operate depending on local electric rates. In that case, the best option is a high efficiency gas unit that utilizes electronic control.

Energy Efficiency: Water heater efficiency is rated by energy factor (EF). The higher the energy factor the more efficient the heating. If gas or oil is used, select a heater with an EF rating of 0.77 or more. If electric is used, look for an EF rating of 0.91 or more. An EnergyStar® rated water heater ensures it has high EF.

Technology Configuration: There are many water heater options but they generally fall into these categories.

- Storage or Tankless: Storage systems utilize a water tank that continuously heats the volume of water in the tank throughout the day. Tankless systems use a high intensity heating element and coil system to heat only as needed. Tankless systems are more efficient because they are not affected by standby losses. Both storage and tankless system come in several configurations.
- Stand-Alone or Indirect: Stand-alone water heaters run independently of other heating equipment, while indirect systems (including tankless coil systems) are integrated with a heating system boiler. The indirect systems can provide heating efficiency in the winter but are very inefficient in the warmer months. Overall, a stand-alone system will typically offer more energy saving over time even if they cost more up front.

Technology Options: The following describes the best technology choices for efficiency and general use.

- Heat Pump: Heat pump technology draws heat (and moisture) out of the surrounding environment (air or soil) to heat water. Geothermal or ground-source heat pumps systems are most efficient, but costly to install and require underground space. Electric heat pump tanks are a good alternative. Although electric heat pump water heaters use a storage tank, the heating technology allows them to be more efficient overall if sized correctly. They are only suitable for indoor use and basements are preferred because the pump can be noisy.
- On-Demand: On-demand water heaters are stand-alone tankless systems that are very efficient and effective if sized correctly. They are available in electric or gas, but because of the high-intensity energy required to heat water instantaneously, the electric units require a high-rated electrical circuit which may or may not be available on site. They are still very efficient because they only use the electricity for a short time.
- High-Efficiency Tank: The standard tank style water heater comes in high-efficiency models in both gas and electric. While not as efficient as heat pump or on-demand water heater, they can still offer significant savings when replacing an older model and are very affordable.

Tank Size: For tank systems, tank size should be determined based on how much hot water is typically needed at one time (typical usage). Heat pump tanks will typically need to be bigger than conventional tanks for the same usage. Refer to manufacturer recommendations.

Low/No-Cost Options

System Maintenance: Install a valve on the tank drain. When the tank is at a low-water level, drain the remaining water for daily general-purpose uses. Completely empty the tank at least twice a year to reduce sediment buildup. Inspect and repair leaks on fittings and faucets.

Insulation: Insulating the water heater with a water heater jacket and installing pipe insulation on hot water lines reduces heat loss and water heater energy use for a very low cost. At a minimum, pipe insulation should be installed on the first 20 feet of pipe from the water heater. Electric water heaters can be fully insulated, while gas and oil heaters should not be covered near the hot flue.

Temperature Setting: For sanitizing and washing, water should be heated to between 180°F and 200°F. For general purpose uses, 120°F is recommended. Any higher temperature is a waste of energy.

Water Conservation: Using less water is an easy way to save energy through energy conservation. Look for ways to reduce hot water usage without reducing cleaning effectiveness or adding process time.

Heat Pump Water Heater with Electronic Controls

Table 18. Typical Energy Savings for Water Heater Improvements

Improvement Recommendation	Annual Savings Range (% of energy cost reduction)	Total Installed Cost Range ($)	Typical Payback (years)
Install High-Efficiency Water Heater	10%–20%	$1,200–$6,500	8–12
Insulate Water Heater and Pipes	3%–4%	$0.5–$1.50/ft	1–2

Online Water Heater Make and Model Energy Guide:

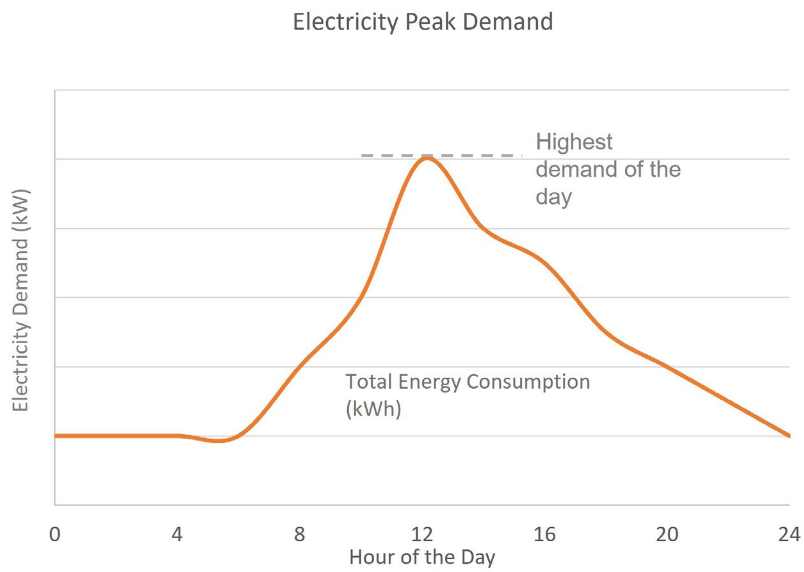
- https://www.ahridirectory.org (search by model number)
- https://www.energystar.gov/products/water_heaters/
- https://www.energy.gov/articles/new-infographic-and-projects-keep-your-energy-bills-out-hot-water

Time-of-Use Management

Electric peak demand is the instantaneous amount of electricity that is being used at any given time, measured in kilowatts (kW). Electric utilities are concerned about peak demand because they must maintain power quality with appropriate equipment and power supply capacity to meet their peak load. Peak demand is typically monitored on a moving 15-minute average each month. To pay for the generation and transmission capacity to meet peak demand, utilities charge energy users a fixed demand charge based on the single highest 15-minute demand period measured per month (or some other a specified period).

Demand is different than actual electricity consumption. Consumption is the actual usage of electricity, measured in kilowatts per hour (kWh). Some utilities have consumption rates that vary throughout the day based on the time of day when the peak occurs. This is known as time-of-use rates. Higher rates are associated with periods of the day when the utility sees higher demand across all users on the grid.

Since this demand is based on when energy is used, there may be opportunities to reduce individual demand charges by better managing the time at which equipment is used. This is what is referred to as time-of-use management. Review of electric utility rate structures will determine if rates vary throughout the day and what peak demand value the greenhouse is being charged for. Comparing that to what time of day greenhouse equipment is running will determine if there are opportunities for savings.



Example Electric Utility Peak Demand Curve for One Day

By running equipment during off-peak hours and reducing your peak energy requirement, energy costs can often be considerably reduced. Examples include shifting supplemental lighting to early morning instead of evening hours or staggering the use of high-energy equipment (such as heaters and fans) to reduce peak power draw.

Renewable Energy

Renewable energy refers to an energy source that is continuously replenished or replenished in a short amount of time. Energy from the sun, wind, water, or biological processes are considered renewable resources. Specific renewable energy technologies include biodigesters, solar photovoltaics, solar thermal, geothermal, hydro, wind turbines, and more.

There are often several opportunities for renewable energy systems to meet at least some greenhouse energy needs; however, the energy production potential is very location specific. Renewable energy systems often require significant investment as well. Before undertaking these projects, energy use should be minimized through conservation and efficiency projects, such as those described in this guide, so that the system installed is only as big as it needs to be. Following that, a feasibility study should be conducted at the greenhouse site to fully understand the potential energy production of the location, the resulting overall greenhouse energy costs and payback periods, and local utility grid opportunities and regulations.

Typical renewable energy projects at greenhouses include solar photovoltaic systems for electricity and solar thermal or geothermal systems for heating. Most renewable energy systems are scalable and can be used at any size operation and added to over time. Small systems that are not connected to the electric grid can sometimes be utilized in remote areas.

Greenhouse Solar Photovoltaic Renewable Energy Production

Producer Resources

Programs and Project Funding Opportunities

There are several resources for producers interested in accessing assistance and/or funding for energy audits, feasibility studies, energy efficiency, and renewable energy projects. Below is a summary of each of the resources currently available to New York State greenhouses for such assistance. It is best to check with these agencies and programs directly as funding availability and program offerings are subject to change.

NYSERDA Agriculture Energy Audit Program

NYSERDA offers technical assistance to identify energy efficiency measures for eligible greenhouses. NYSERDA will assign Flexible Technical Assistance (FlexTech) Program Consultants to perform energy audits for eligible greenhouses. Greenhouses must be customers of a New York State investor-owned electric utility and pay the System Benefits Charge (SBC). Please check your greenhouse's current utility bills for eligibility.

Audit Level	Audit Activities	Type of Report that the Greenhouse Receives
Comprehensive	Detailed energy audit	Energy audit report with calculated evaluations of appropriate energy efficiency measures including simple payback; meets ANSI/ASABE S612 standards (includes Type 2 Audits required by USDA NRCC programs)
Targeted	Energy audit focused on specific systems, energy efficiency measures, or renewable energy	System-specific energy analysis report

These energy audits provide an overview of your current energy usage and make efficiency project recommendations based on those findings, as well as recommending other energy goals for farms. Utility bills from the previous year are used along with existing equipment specifications and run-time information to complete the analysis on a farm. Site visits are conducted to inventory existing equipment and systems currently in use. A comprehensive audit report provides a list of recommended improvements with associated energy and cost savings and anticipated payback period, while a target audit analyzes specific systems or can evaluate renewable energy system cost-effectiveness.

Producers can request the level of energy audit that best fits your greenhouse's needs. NYSERDA will assign a FlexTech Consultant to visit your greenhouse and perform an energy audit at no cost to you.

To apply visit www.nyserda.ny.gov/agriculture or email aeep@nyserda.ny.gov or call 1-800-732-1399.

NYSERDA Greenhouse Benchmarking

NYSERDA offers greenhouses a benchmark report to help facilities track their energy usage over time and compare energy use to anonymous greenhouses of similar size and technology. Operation receives a report with personalized recommendations on how to improve energy use in your greenhouse and can track improvements over time. Applicants must be a USDA-defined farm ($1000+ a year agricultural products produced and sold) and greenhouse facility, be customers of New York State investor-owned utilities, and contribute to the electric System Benefits Charge (SBC).

To apply visit https://glase.org/benchmark/ or email greenhousebenchmarking@nyserda.ny.gov

NYSERDA Commercial New Construction Program

NYSERDA may provide technical and financial support to applicants and/or their design teams to identify and install energy efficiency, beneficial electrification, and carbon reduction opportunities to achieve Carbon Neutral Ready levels of performance in non-residential and mixed-use new construction, change of use, and substantial renovations to existing buildings. A carbon neutral building is one where the design, construction, and operations do not contribute to emission of greenhouse gases that cause climate change.

The Commercial New Construction Program is available for eligible customers to design and build projects that achieve carbon-neutral-ready levels of performance in new construction, substantial renovations, and change of use for commercial, industrial, and institutional buildings in New York State.

Get in touch at NewConstructionProgram@nyserda.ny.gov

New York State Utility Programs

All commercial customers including greenhouses are eligible to apply for incentives from their New York State investor-owned electric utility.

National Grid Customers

www.nationalgridus.com/Upstate-NY-Business/Energy-Saving-Programs/Agri-business-program

Upgrade your equipment or plan an expansion with the help of our energy efficiency incentives and grant opportunities. Call 855-236-7052 or email energysavings@nationalgrid.com to discuss the opportunities for your agri-business.

NYSEG & RG&E Customers

For a complete list of eligible upgrades, view our rebate catalogs at www.nyseg.com/cirp or www.rge.com/cirp
Call 888.316.8023 or email at cleanergysavings@franklinenergy.com

Orange and Rockland

www.oru.com/custom www.oru.com/prescriptive

Rebates and incentives for energy-efficient upgrades. Contact a representative for more information.

Call 1-877-434-4100 or email at dlenergyefficiencyprograms@coned.com.

Central Hudson

www.cenhud.com/my-energy/save-energy-money/business-incentives/

Contact us with questions at CHGEPrograms@icfi.com or 800-515-5353. Our program staff are available to discuss your project and assist.

ConEdison

https://www.coned.com/en/save-money/rebates-incentives-tax-credits/rebates-incentives-tax-credits-for-commercial-industrial-buildings-customers

The Con Edison Commercial & Industrial (C&I) Energy Efficiency Program offers incentives for installing energy-efficient electric and gas equipment and technologies. Energy efficiency can help improve the bottom line by reducing energy use and maintenance costs while increasing operating efficiencies. These upgrades can also help protect the environment. Email applications to commercial@coned.com

Natural Resource Conservation Service

Environmental Quality Incentives Program (EQIP)

NRCS offers financial assistance and technical assistance to help agricultural producers and other landowners address resource concerns and maintain conservation improvements on their land. The Environmental Quality Incentives Program (EQIP) Energy Initiative at NRCS helps producers, farmers, and ranchers make voluntary improvements that can boost energy efficiency on the farm. This emerging agricultural trend produces benefits, including reduced input costs, increased productivity per unit of energy consumed by equipment and lighting, and reduced air pollutants and greenhouse gas emissions caused when energy is generated for agricultural use.

EQIP provides financial assistance for farm energy audits, as well as for certain energy efficiency equipment purchases. Note that a qualified energy audit is required to apply for equipment financial assistance. NRCS generally will accept ASABE Type 2 energy audits, which are available to Controlled Environmental Agriculture (CEA) producers through NYSERDA's Agriculture Energy Audit Program.

More information about NRCS EQIP is available at the program website: https://www.nrcs.usda.gov/wps/portal/nrcs/main/ny/programs/financial/eqip/

To apply for technical or financial assistance though EQIP, you can contact your local New York USDA Service Center. You can find your local service center using this tool: https://offices.sc.egov.usda.gov/locator/app?state=NY

Rural Development

These programs offer funding to complete energy audits, provide renewable energy development assistance, make energy efficiency improvements, and install renewable energy systems. Programs can help convert older heating sources to cleaner technologies, produce advanced biofuels, install solar panels, build biorefineries, and much more. USDA Rural Development is at the forefront of renewable energy financing, with options including grants, guaranteed loans, and payments.

Value Added Producer Grant

The Rural Development Value Added Producer Grant (VAPG) provides grant funds for planning and working capital expenses to help agricultural producers enter value-added activities. The maximum grant amounts are $75,000 for planning grants and $250,000 for working capital grants.

More information about VAPG grants is available at the program website: https://www.rd.usda.gov/programs-services/value-added-producer-grants

Rural Energy for America Program (REAP)

Rural Development provides grants and loan guarantees for renewable energy installations, and energy efficiency improvements to existing facilities or processes through REAP. REAP grants are competitive and can cover up to 25% of project costs for renewable energy projects and energy efficiency projects. The maximum grant amounts are $250,000 for energy efficiency improvement projects and $500,000 for renewable energy projects.

More information about USDA Rural Development REAP grants is available at the program website: https://www.rd.usda.gov/programs-services/energy-programs/rural-energy-america-program-renewable-energy-systems-energy/ny

New York USDA Rural Development REAP contact:

Gary Pereira, Business Program Specialist, USDA Rural Development

Email: Gary.Pereira@usda.gov

Office (315) 570-2233 Cell (315) 530–3433

Technical Resources

USDA Farm Energy website - Greenhouse Energy Efficiency
https://farm-energy.extension.org/introduction-to-greenhouse-efficiency-and-energy-conservation/

Fuel Switching Cost Calculations
https://www.canr.msu.edu/floriculture/resources/energy/assets/ComparingFuelCostsbyBartok.pdf?web=1&wdLOR=c137B7DD5-0EDF-4240-8D10-6CBB725D80D9

NEW YORK STATE | NYSERDA

New York State Energy Research and Development Authority

17 Columbia Circle
Albany, NY 12203-6399

toll free: 866-NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov

AG-bpgreenhouse-bk-1-v1 1/23