RESOURCE INNOVATION INSTITUTE

Best Practices Guide
HVAC

for Controlled Environment Agriculture (CEA) Operations

A Best Practices Guide for CEA Producers

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ACEEE American Council for an Energy-Efficient Economy

USDA United States Department of Agriculture
Natural Resources Conservation Service

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Overview

As a cultivator operating in a constantly evolving industry, **you may feel like it is hard to know who to trust.** The horticultural market has changed a lot, technology has advanced, and so have the technical terms used to describe everything. It can be hard to navigate the purchasing process when planning a facility and challenging to understand minimum performance requirements for equipment.

We are here to help. As a non-profit organization, the Resource Innovation Institute establishes industry standards, facilitates best practices, and advocates for effective policies and incentives that drive resource efficiency. Our peer reviewed Best Practices Guides are a way of helping growers like you understand the most resource-efficient technologies and how to use them to boost your bottom line.

The operational changes necessary for an efficient cultivation facility may be detailed, but **it does not have to be a mystery.** Our membership is composed of subject matter experts with the knowledge to help you build and operate the most high-performance and cost-effective facility for cultivating plant life indoors.

You may be looking for **a source of reliable third-party information,** motivated to reduce overhead for your business, or have goals for a more energy efficient facility. Whatever the reason, when you are considering a decision related to the systems used in your facility, we hope you lay the groundwork with the insights offered in Resource Innovation Institute's Best Practices Guides.

INPUT from industry leaders and partners → RESOURCE INNOVATION INSTITUTE → **EDUCATION** and advocacy about best practices for growers

COVER: FINN & ROOTS; THIS PAGE: SURNA

Purpose

Heating, ventilation and air conditioning (HVAC) and systems for cultivation applications are process-driven and drive plant production. Understanding HVAC equipment and how to stage systems efficiently and effectively can be difficult to navigate for CEA producers.

The purpose of this CEA HVAC Best Practices Guide is to support you, the cultivator, and your design, construction, and operations professionals with:

- Speaking the language relevant to HVAC in horticultural applications
- Reviewing manufacturer's literature to evaluate your purchasing options
- Understanding crucial considerations when selecting HVAC equipment
- Installing and operating successful HVAC solutions in alignment with your business model

Demystify Terms

Throughout this guide, you will learn key terms related to optimizing the design and construction of HVAC systems for food and floriculture for plant growth and development in controlled environments. Greenhouses are planned and built differently than indoor farms, and use HVAC equipment differently to maintain desired conditions.

This guide is intended to serve producers and their partners seeking to optimize controlled environments for cultivating food and floriculture crops. CEA project partners may include architects, engineers, equipment and hardware manufacturers, suppliers, systems integrators, data aggregators, controls contractors, commissioning agents, utility and efficiency program energy engineers, and horticulturists.

IMAGE: ROB EDDY

Throughout this guide, you can learn about key terms related to horticultural HVAC, their units of measurement and how they are used, why the terms are important to you as a cultivator, and how the terms may be commonly misunderstood or misapplied.

The key terms address the topical areas listed below:

- Cultivation
- Energy & Power
- Horticultural HVAC and Environmental Control
- Cultivation Key Performance Indicators (KPIs)

Consult our online glossary of key CEA HVAC terms to expand your horticultural HVAC vocabulary.

To learn about how to effectively design and build CEA facilities, consult our *Facility Design & Construction Best Practices Guide for Controlled Environment Agriculture (CEA) Operations*. To understand the interactive effects between your HVAC and lighting systems, check out our *LED Lighting Best Practices Guide for Controlled Environment Agriculture (CEA) Operations*, a guide that covers the lighting terms and systems used for cultivation environments. To effectively automate your lighting, HVAC, and controls systems, check out our Controls & Automation Best Practices Guide for Controlled Environment Agriculture (CEA) publishing in 2023.

IMAGE: ROB EDDY

SECTION

01

Optimize HVAC for CEA Facilities

IMAGE: CONSUMERS ENERGY

IMAGE: IMEG CORP.

Crop production and quality in CEA facilities is dependent on the capabilities of HVAC systems to maintain target environmental conditions. Growing plants in controlled environments introduces biological activities to protected agricultural environments like greenhouses and indoor farms. CEA cultivation involves using HVAC equipment to minimize pest, disease, mold, and fungus issues and maximize consistent yields.

Sub-optimal performance of HVAC systems negatively impacts your competitive advantage. There are diverse strategies and many types of equipment you can use to accomplish your goals. Understanding the process application for facility systems equipment enables growers to choose efficient HVAC products to reduce energy use and operating costs.

Utilities want to incentivize the adoption of emerging technologies, and HVAC is a key system in CEA facilities supported by efficiency programs. To ensure HVAC systems achieve their energy savings potential, efficiency programs also may offer technical assistance during design, installation, and operation. To offset the first cost of high-performance HVAC equipment, CEA producers can receive financial assistance to subsidize efficient HVAC products.

Standards for safety, efficacy, and quality help ensure the technology you install is built to last on your farm. Today's horticultural HVAC market offers a wide variety of solutions suited to best fit the needs of CEA producers. Selecting the right system for your application is your best bet for long-term performance.

HVAC solutions verified by third parties can optimize crop productivity and facility efficiency. Testing requirements specific to CEA facilities are under development by industry organizations[1]. Certification programs[2] are on their way, likely within the next three years. Qualified product libraries (QPLs) maintained by certification organizations can be developed once standards are adopted. QPLs can give you the information you need to judge the energy performance and durability of hundreds of options that have met technical performance requirements.

Regulations for energy performance have emerged in some regions that affect greenhouses and indoor farms. Cultivators everywhere can benefit from understanding how high-performance HVAC systems can be a tool for facility compliance and operational success. Greenhouses and vertical farms have different climate control needs and create diverse impacts. Facility operators and their project partners can work together to minimize environmental impacts like high energy demands and greenhouse gas emissions from energy use.

Resilient producers plan for competition by managing operational energy and improving resource efficiency. Models for production and associated resource consumption differ by facility type and location. In the following sections, you will learn how HVAC systems in CEA facilities affect your plants and support productivity, profitability, and optimized conditions for plant growth and development. Understanding the terms used to describe your indoor grow environment requires a slight learning curve, but is essential if you want to ask informed questions, make informed business decisions, and achieve a resource-efficient and high-performance operation.

1 ASHRAE and ASABE are collaborating to develop standardized test conditions and evaluation methods for CEA HVAC solutions like moisture removal equipment.
2 AHRI is prepared to adjust their certification programs to serve CEA HVAC solutions once testing methods are standardized.

Benefits of Using Efficient HVAC in CEA Facilities

High-performance HVAC systems offer diverse benefits for plants, producers, and CEA facilities. In the past five years, hundreds of products developed specifically for plant growth and development have become more available and less expensive, while efficiency programs have increased their support with financial incentives.

Save Energy - Efficient HVAC solutions can demand less energy than traditional HVAC design and equipment. HVAC systems can save even more on utility bills if operated to avoid peak hours. Table 1 below describes the diverse technology that can support substantial energy savings in indoor farms and greenhouses. Energy-saving HVAC technology can receive incentives from utility efficiency programs. Using HVAC equipment with advanced and integrated controls can help minimize facility energy costs while maintaining the environment your plants need.

Table 1: Energy Savings Potential of High-Performance HVAC Solutions

Energy-Saving HVAC Solutions	Energy Savings Potential
HVAC Systems[3]: • Heating systems • Root zone heating systems • Cooling systems • Variable frequency drives (pumps and fans) • Humidity management equipment • Environmental controls • Airflow controls	20 - 30%

Optimize Crop Quality - CEA HVAC systems drive crop quality as environmental conditions like temperature and humidity directly impact plant growth and development. Swings in temperature and humidity can adversely affect crop appearance, taste, and pigmentation. Inadequate air circulation or air movement can also cause plant stress. Operating CEA facilities outside of target ranges can increase risk of pathogen outbreaks, impact biomass quality, and reduce wholesale price of many crops. Stressed crops are more vulnerable to attack from pests and pathogens and are susceptible to fungal growth like powdery mildew. Certain crops affected by microbial outbreaks may fail product testing and may not be allowed to be sold in some markets. Avoid reductions in canopy productivity and total crop loss by using the right HVAC systems to maintain optimal environmental conditions.

Steer Crops - Equipment and control systems able to properly maintain desired targets for cultivation spaces can ensure crop quality metrics are met and consistently achieved. High-performance HVAC equipment that is integrated and automated to satisfy crop needs can meet and maintain target environmental conditions better than manually controlled HVAC equipment or standalone climate control systems that do not communicate with each other. Integrated HVAC systems can also provide richer data growers can use to boost yields and validate energy savings of efficient strategies.

IMAGE: ROB EDDY

[3] Opportunities in Controlled Environment Agriculture, Commonwealth Edison, 2021.

Maximize Performance - Maintaining optimal conditions in your facility is crucial for cultivating CEA crops and achieving expected yields. High-performance HVAC equipment and controls designed for cultivation environments can help keep facility operating costs low and crop canopy productivity high. Overall, efficient climate control equipment can improve energy productivity (unit of energy used per unit of yield) of CEA facilities and help growers achieve key performance targets.

Ensure Resilience - HVAC equipment specialized for cultivation applications will have a longer useful life as it is designed to continuously handle the dynamic conditions of CEA facilities. Lower-cost off-the-shelf equipment may have shorter lifetimes, higher emissions impacts, and be designed for human comfort. Horticultural HVAC solutions are more customizable, durable, and suitable for cultivation facilities. Purpose-built solutions can provide diverse forms of energy recovery and can implement more sophisticated controls strategies, both of which can further reduce life-cycle costs.

How CEA Facilities Use Climate Control Solutions

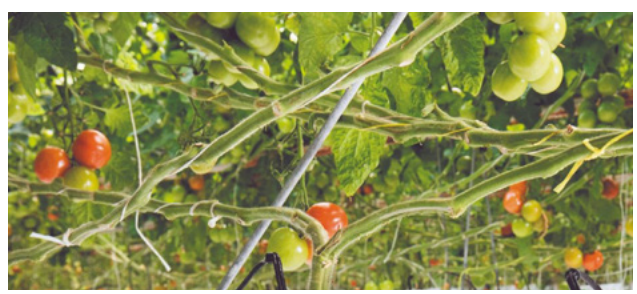
The strategies for conditioning CEA facilities depend on the optimal environmental targets for crops and the types of heating, cooling, ventilation, and airflow equipment the facility can use for crop growth. Three major styles of CEA cultivation drive horticultural HVAC decisions. For every stage and style of cultivation, there is a high-performance HVAC solution and controls strategy.

This document starts with key concepts that apply to all three cultivation methods – and then examines what makes these concepts vary when applied differently in vertical indoor and greenhouse environments.

- Greenhouse: Traditional protected agriculture
- Greenhouse: Advanced
- Indoor vertical farm

Cultivation Approach - Greenhouses and indoor farms may value the benefits of efficient horticultural HVAC systems differently based on production goals. The three most common CEA cultivation approaches have different pros and cons in regard to climate control. Greenhouse HVAC strategies must handle the heat gains and losses due to dynamic solar and local weather conditions. Climate control strategies for indoor farms are less affected by the outdoor environment.

Greenhouses may use *passive ventilation* strategies like vents as a primary method for cooling, dehumidification, ventilation, and air circulation. Depending on the crops being grown and greenhouse location and construction, *active cooling and heating* solutions are used to meet target environmental conditions to optimize quality



IMAGES FROM TOP: FIFTH SEASON; GRODAN; CONSUMERS ENERGY and yield. Greenhouses use *active* HVAC solutions like fans and evaporative cooling walls to maintain desired environmental conditions for crops to optimize quality and yield.

Indoor farms and sealed greenhouses use active HVAC solutions to drive evapotranspiration and typically do not use outside air. Indoor vertical farms employ equipment like chillers, boilers, air handling units, and high-airflow fans (HAFs) to meet all crop needs and depend on HVAC systems to maintain the optimal conditions for plant growth. Vertical cultivation approaches use unique HVAC approaches to avoid microclimates within and on different levels of tiered racking systems.

How CEA Crops Use Air and Moisture

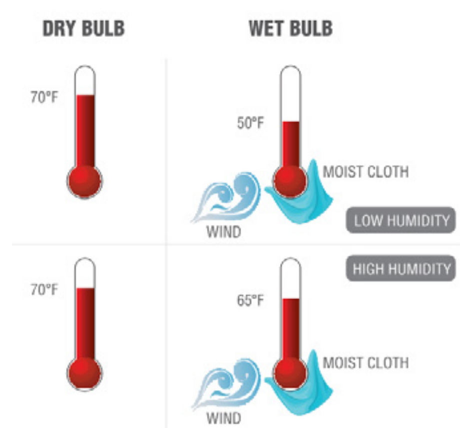
HVAC is a mission-critical system in CEA facilities that must meet the needs of your crops, and the crops you grow are as unique as your cultivation approach. Producers benefit from understanding how crop development and morphology is affected by temperature, humidity, and airflow.

Understand Inputs - Air quality factors like heat and moisture directly influence plant and fungi vitality and yield. CEA crops need specific environmental qualities to effectively grow and produce quality characteristics. The growth and development of your crops are influenced by genetics, fertigation, and grow room environmental factors like light, CO_2, temperature, humidity, and airflow. Different properties of the air interact to control yield and quality attributes of your crops. Learn about the interactive effects on page 23 to understand how cultivation spaces are impacted by the simultaneous operation of HVAC, lighting, and watering systems.

Support Transpiration - Like humans perspire (sweat), plants transpire using cellular structures called stomata, the pores on plants' leaves that exchange moisture with the air. CEA facility space *temperature, relative humidity, vapor pressure deficit*, and *air speed* are some of the components of your facility's *environmental conditions* that directly affect your plants and the ability of their stomata to transpire effectively.

Describe Conditions - *Temperature* must be managed within preferred ranges throughout various growth cycles for optimal crop health and growth. The units of temperature in North America are degrees Fahrenheit (°F) and Celsius (°C). There are two temperatures to be aware of: *dry bulb* and *wet bulb. Dry bulb temperature* is the temperature used by your weather reports and displayed by thermostats. Wet bulb temperature relates to both dry bulb temperature and how much moisture is in the air; it is the temperature where there is an equilibrium between water condensing on a surface and evaporating from that surface (like wet sheets on a clothesline hanging outside). If the difference between the wet bulb and dry bulb temperature is small, the air is very humid.

Figure 1: Wet and Dry Bulb Temperature



Pinpoint Saturation - Air is saturated when it holds the maximum amount of *water vapor* it can at a given temperature. As air gets warmer, it can hold exponentially more water. The *dew point temperature* is the temperature at which the air reaches saturation and cannot hold any more moisture. Dew point is affected by the humidity of the air and not the air's *dry bulb temperature*. This is when *condensation* occurs, which is when moisture in the air condenses as water droplets on surfaces in your cultivation space.

Evaluate Evapotranspiration -In your CEA facility water applied for irrigation either transpires through your crop or evaporates directly into the air in your cultivation space. *Evapotranspiration (ET)* is the process adding together water vapor from transpiration and evaporation in your cultivation spaces that your HVAC equipment must manage to maintain environmental conditions. When determining your HVAC system needs it is important to account for the impacts of ET so that the right type and size of equipment is applied for your processes.

Figure 2: High and Low Moisture Content

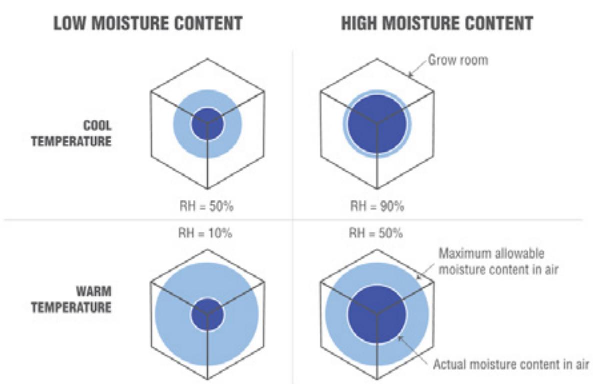


Figure 3: Evaporation, Transpiration & Relative Humidity-

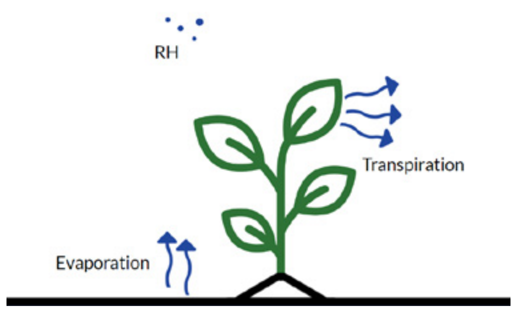
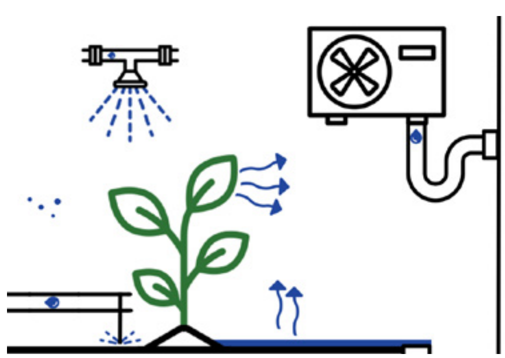


Figure 4: Water Movement Within CEA Cultivation Spaces



Quantify Moisture - *Relative humidity (RH)* is the amount of water vapor in the air, expressed as a ratio of actual vapor pressure to the saturated vapor pressure, described in percent (%). Some plants grow better in different RH ranges during their various growth stages; you can use different RH ranges to influence your crops and manipulating RH values can increase yield. The amount of water in the air at a given RH is dependent on the temperature of the air. When the wet bulb temperature is equal to the dry bulb temperature, the air is at 100% relative humidity.

Keep Fungi Moist - Mushrooms require evaporation of water from the surface of the fruit body for development. Steady moisture flow through the fruiting bodies is necessary for continued growth as the movement of water through osmosis within the mycelium allows the transportation of nutrients. Mushroom houses maintain very moist environments for optimal mushroom production. Researchers recommend high RH (90%) for higher airflow rates, and lower RH (80%) for lower airflow rates. RH lower than 60% will cause drying of substrate and higher than 95% will cause pockets of condensation on the fruiting bodies.

Understand Vapor Pressure Deficit - *Vapor pressure deficit* (VPD), also phrased as as difference or differential, is the pressure difference between the vapor pressure measured at the surface of the leaf and the vapor pressure of the air measured in your cultivation space. Using Teten's equation, vapor pressures for both leaf surface and cultivation space air can be calculated.

VPD of cultivation space[4] (kPa) = VP of leaf - VP of air

$$VP\ (kPa) = 0.61078 * e^{(17.27 * T/(T + 237.3))}$$

T = Temperature (°C)

VP of leaf = Saturation VP of leaf using temperature of leaf

VP of air = Saturation VP of air using temperature of air * Relative Humidity of air

4 Dewpoint and Vapor Pressure Deficit Equations, Oregon State University.

In greenhouses, depending on the crop and the location of the leaf in the canopy, leaf temperature can be 10 - 30 °F higher than the air in your cultivation space when the sun is out. On cloudy days, leaf temperatures may be just a few degrees above the air temperature. Leaves lower in the canopy may be several degrees below air temperature[5].

Leaves of crops in indoor farms can be 2 - 5 °F[6] cooler or hotter than the temperature of the air in cultivation spaces. Because this can be more consistent for indoor facilities, this is sometimes described as the *leaf offset temperature*, which varies depending on the crops being grown.

Manage VPD for effective transpiration; if at the two ends of a straw are stomata and roots, the force pulling on the straw is VPD. VPD is commonly described using kilopascals, which is a metric unit that can be translated from pounds per square inch: 1 psi = 6.895 kPa. When relative humidity is high, VPD can be higher and so water within your crops transfers into the surrounding air quickly; when relative humidity is low, VPD can be lower and so water within your crops transfers to the air more slowly. Figure 5 below illustrates a *psychrometric chart* to describe environmental conditions and calculate VPD. The example scenario illustrates a cultivation space at 78 F and 60% RH and a crop canopy with leaf surface temperature of 78F and 100% RH. The difference between the two points on the chart's Y axis describes the VPD of the cultivation space.

Figure 5: Example Vapor Pressure Deficit for CEA Facility Cultivation Space

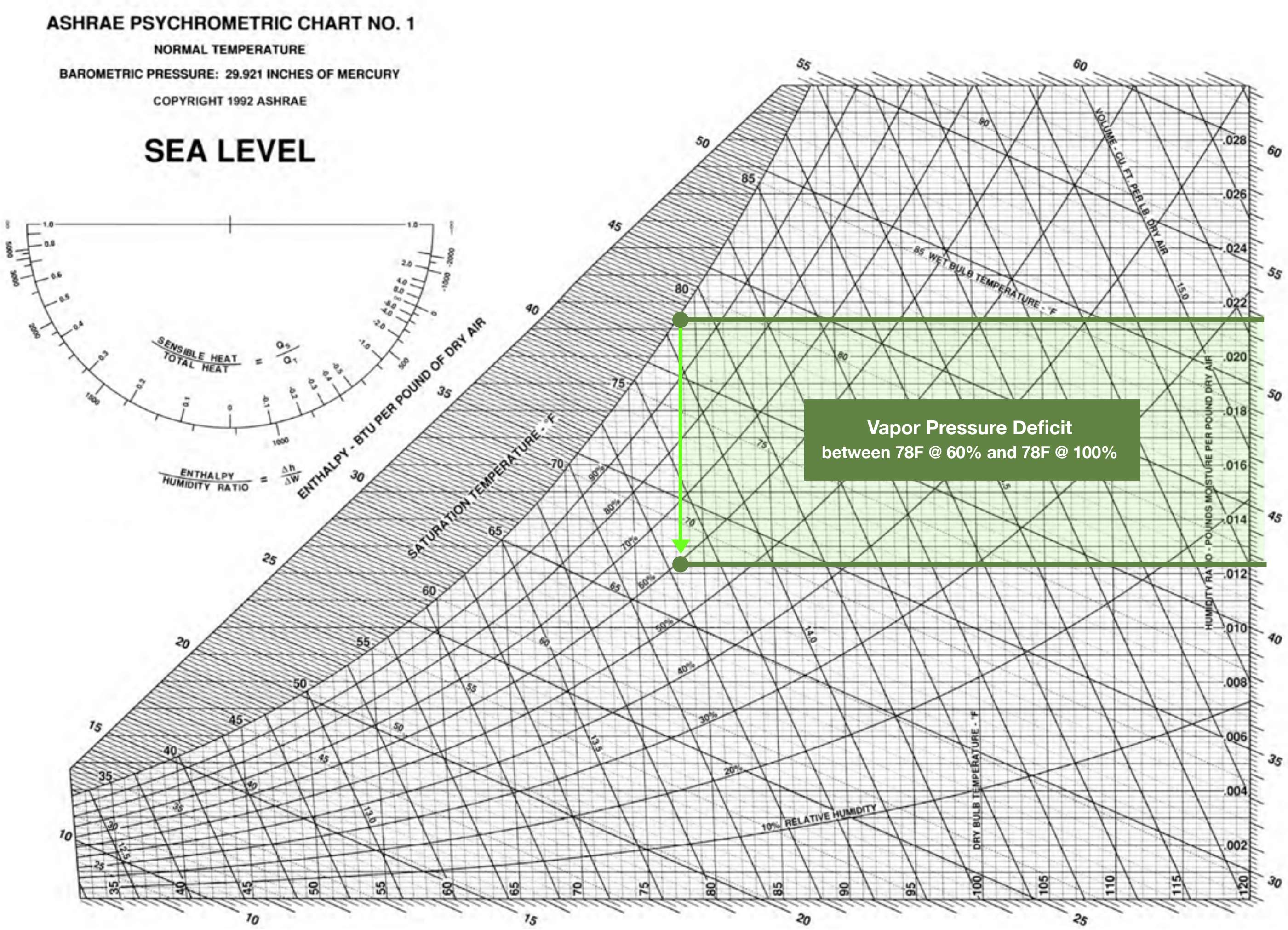


IMAGE: COURTESY OF DESERT AIRE ASHRAE

5 Reducing greenhouse temperatures with shading, Greenhouse Mag, 2011.
6 VPD: The Pressure to Transpire, Dr. Greenhouse

Support Crop Development - Plants and fungi use changes in environmental treatments to trigger transitions between stages of growth and to provide the optimal conditions for biological processes. The impact of different environmental conditions on CEA crops is described in more detail in **Table 2** below. As technology develops and research continues, the CEA industry is still learning how different VPD, temperature, and humidity values influence crop development, yield, and expressions of quality.

Table 2: Summary of the Effects of Environmental Conditions on CEA Crop Growth[7]

Characteristic	Quality	Plants	Fungi[8]
Temperature	Too High	High leaf temperatures, leaf tip burn, wilting, early bolting, root rot, heat stall, lower number of branches	Triggers thermophilic microflora, mycelium and spore death
	Too Low	Reduced metabolic rate, reduced yields, reduced number of flowers, delayed flowering	Reduced mycelium growth, limited development
Humidity	Too High	Pathogen outbreaks like powdery mildew and Botrytis, leaf tip burn	Insect infestation, condensation on mushrooms, slimy caps, mold
	Too Low	Outer leaf edge burn, foliar diseases	Casing hardening, dehydration, aborted primordia
Airflow	Too High	Reduced transpiration (closed stomata), desiccation	Scaly mushrooms
	Too Low	Mold growth, diseases	Thin stalks, open mushrooms, reduced second flush

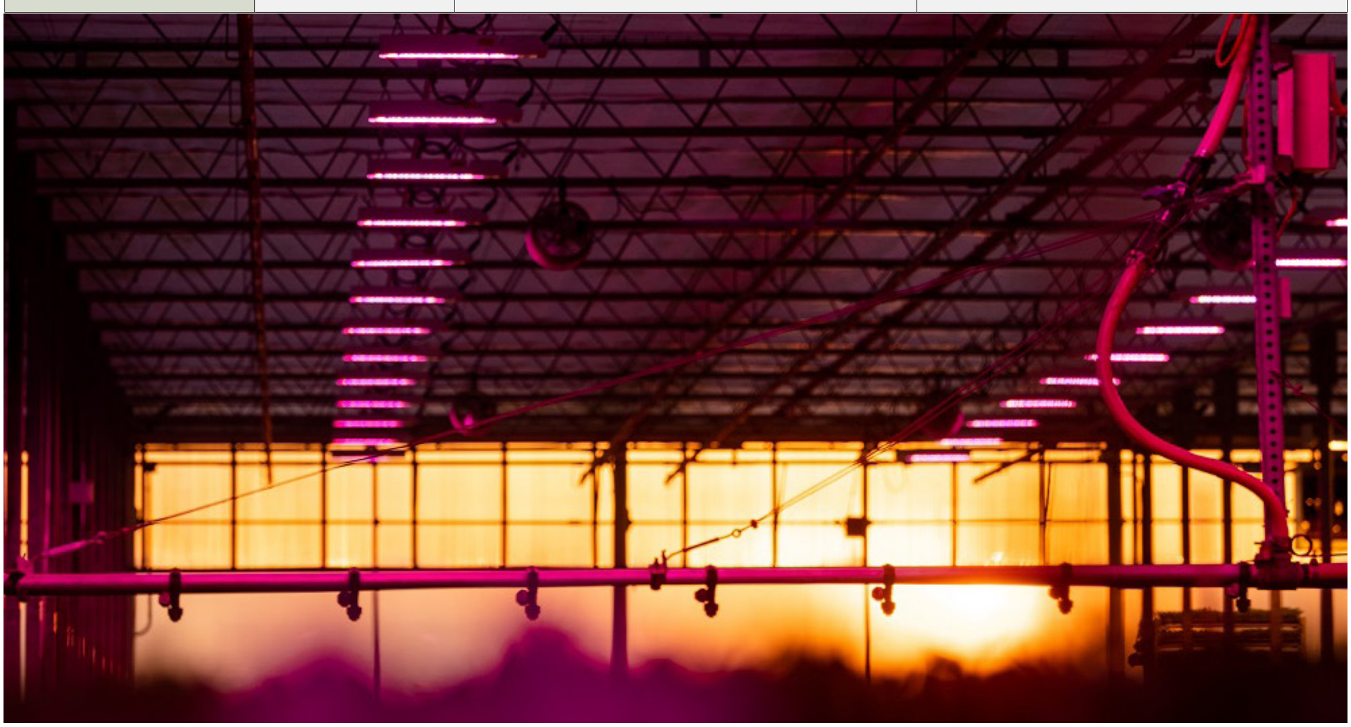


IMAGE: SIGNIFY

7 Greenhouse Vegetable Production, New Mexico State University, 2019. ANSI/ASABE/ASHRAE Engineering Practice Heating, Ventilating, and Air Conditioning (HVAC) for Indoor Plant Environments without Sunlight EP653, 2021. Monitoring is crucial for growing lettuce and leafy greens year round, HortAmericas, 2021. Ball RedBook Volume 1: Greenhouse Structures, Equipment, and Technology, 19th Edition, Ball Horticultural Company, 2021. Mean Daily Temperature Regulates Plant Quality Attributes of Annual Ornamental Plants, Michigan State University, 2014. Low temperature diminishes the photoperiodic flowering response of three petunia cultivars, Michigan State University, 2015.

8 Mushroom Cultivation IV, various chapters, Oei, 2016.

SECTION

02

Understand CEA HVAC Options

IMAGE: ROB EDDY

Crop and facility type impact the HVAC solutions you may need to achieve your goals for production and efficiency. Learn how CEA crops benefit from diverse HVAC systems. Greenhouses and indoor farms can maximize different benefits of high-performance HVAC equipment.

Major drivers of CEA facility profitability are labor and energy costs, crop yields, and product quality. Capital expenditures for many cultivation operations are in the six to seven figures, and with energy representing 30 to 60% of the operational expense of indoor and greenhouse facilities producing a range of crops, this variability in energy efficiency represents profit potential. Increased demand for products and cost compression in CEA markets have led to new beliefs about efficient and optimized HVAC systems, as growers consider energy and resource efficiency to rise above the competition by reducing operations and maintenance costs through using high-performance systems.

When assessing HVAC options, CEA producers growing plants and fungi have different goals that are influenced by facility type. Growing some crops in greenhouses may be possible with passive HVAC strategies; ventilated greenhouses may need different equipment than sealed greenhouses. Screens can reduce pest infiltration for passively ventilated greenhouses that bring in outside air. Crops in indoor farms likely must have environmental conditions maintained with active HVAC solutions. Facilities in colder climates may require more heating, while facilities in warmer climates may require more cooling.

Return on investment for CEA HVAC systems is multifaceted and depends on crop type, facility type, geographic location, support from utility efficiency programs, and facility energy costs. Some CEA crops have higher retail value than others, and producers may have a larger appetite for longer returns on investment. Greenhouse growers may be interested in extending seasonal production windows and boosting yields per harvest on lower-margin crops. Some operators may be able to obtain financial incentives for efficient HVAC equipment, while others may be located in a region without efficiency program support for CEA producers.

Many diverse products are created in controlled environments. At the start of this journey, producers and design teams should understand common CEA crops and the typical facilities used for production. Some crops may have sprouts of seedlings grown indoors before being moved to greenhouses for later growth stages.

Key: Greenhouse Indoor

Vine Crops

Cucumbers and indeterminate tomato varieties are mostly grown vertically on high wires in greenhouses. HVAC needs depend on facility location and construction. In colder climates, heating loads may be higher to maintain fruit production year-round. In warm regions, cooling loads may determine HVAC system choice.

Vegetables and Herbs

Vegetables like peppers and herbs like basil are grown in greenhouses and indoor vertical farms. Leafy greens are grown by both greenhouses and indoor facilities. Facilities growing vegetables and herbs may need different HVAC equipment depending on facility type and environmental targets for crop production. Microgreens require precise management of environmental conditions to achieve optimum quality and facilities often use active HVAC systems.

Floriculture

Nursery crops (young plants) and finished crops (bedding plants) are often cultivated in greenhouses or outdoors and may not need active HVAC solutions, depending on facility location. Some facilities use fans for ventilation and unit heaters to keep temperatures within preferred ranges for crops.

Mushrooms

Mushrooms are primarily commercially cultivated indoors. Environmental conditions like temperature and humidity have a direct impact on fungi spawning and building fruiting bodies. Active ventilation can be used to introduce outside air for temperature and humidity management. Moisture must be managed throughout production to minimize drying and maximize pin formation.

Berries

Strawberries and other berries have historically been grown in greenhouses but are starting to be cultivated indoors. Depending on target environmental conditions and facility type, active HVAC solutions may be necessary for optimal fruit production.

What Sells - Final products grown by facilities dictate the diverse production processes that impact CEA HVAC system energy consumption. Understand the stages of growth and associated activities performed at your facility to determine which lighting systems and strategies will be best suited for the application. Figure 6 below illustrates the stages of plant growth for CEA crops.

Figure 6: Growth Stages for CEA Crops

Determine HVAC Needs - Demands for CEA facility climate control mostly depend on the cultivation approach and target light intensity for crops. Table 3 on the following page describes ranges of horticultural environmental conditions by crop type. Target temperature and humidity for different crops will vary during different growing stages or even times of day. CEA crops are diverse and can be broken into three categories: cold-tolerant, cold-temperature, and cold-sensitive crops.

Define Optimal Conditions - Plants and fungi have different minimum acceptable, optimum, and maximum acceptable temperatures for growth and production. As crops move between different stages of development, ideal environmental conditions for CEA crops may change. Also, target conditions like temperature may shift between day and night. The growth habit and flowering time of many ornamental and greenhouse crops can be shaped quite dramatically by alternating day and night temperatures[9]. *Day-Night Temperature Differential (DIF)* affects internode elongation, plant height, leaf orientation, shoot orientation, chlorophyll content, lateral branching, and petiole and flower stalk elongation. Table 3 on the following page describes the major CEA crop types and the ranges of temperature and humidity for optimal crop steering and production. For example, nighttime temperatures between 50 - 55 °F are vital for strawberry production. Temperatures above 60 °F can result in undesirable acidic flavors and drastic reduction in fruit yield.

IMAGE: GRODAN

9 Greenhouse Management: A Guide to Operations and Technology, Chapter 9: Managing Temperature in Greenhouse Crops: Temperature Requirements for Greenhouses. Ted Goldammer, 2019.

Table 3: Ranges of Horticultural Environmental Conditions by Crop Type

Crop Type	Category	Target Temperature Range10 (°F)	Target Humidity Range (%)
Cucumbers[11]	Cold-sensitive	65 - 80	60 - 70%
Tomatoes[12]	Cold-sensitive	64 - 81	60 - 90%
Peppers[13]	Cold-sensitive	65 - 85	60 - 90%
Strawberries[14]	Cold-temperate	50 - 77	40 - 95%
Greens[15]	Cold-tolerant	50 - 65	50 - 70%
Herbs & Microgreens[16]	Cold-tolerant	60 - 70	40 - 60%
Mushrooms[17]	Cold-tolerant	50 - 68	75 - 95%
Nursery & Floriculture[18]	All of the above	64 - 82	60 - 80%

Evaluate Setpoint Ranges - Temperature and humidity targets can be translated to *Vapor Pressure Deficit (VPD)*. Different temperature/humidity targets can result in the same VPD. For most food and floriculture crops, a VPD = 1.0 kPa is a reasonable target to maintain crop vitality and yields. Target VPDs vary by stage of growth and light treatment. A range for VPD acceptable to most CEA crops is 0.8 - 1.2 kPa. As VPD drops below 0.8 kPa, transpiration is inhibited which slows the rate that water and nutrients flow through plants and fungi, which ultimately slows growth. A VPD higher than 1.2 kPa can lead to water stress.

Figure 7: Example HVAC Systems for CEA Greenhouses

Evaluate Systems - Along with facility type and crop type, the stages of plant growth that occur in your cultivation spaces can also influence the HVAC equipment you choose. Figure 7 to left illustrates the variety of equipment that can be used in CEA facilities to heat, cool, ventilate, control airflow, and manage humidity. The example ventilated greenhouse shows common systems employed in these CEA facilities like a boiler for warm-floor slab heating[19], fogging/misting, an evaporative fan-and-pad system, roof vents, thermal/shade curtains, fertigation system, supplemental lighting, and exhaust and horizontal airflow fans. Figure 7 also shows an external weather monitoring station and internal sensors that inform and control the HVAC systems.

Table 4 on the following page describes the traditional and high-performance HVAC equipment used for the three major phases of CEA crop production. Different equipment types may be more feasible depending on the size and location of the facility. Consider systems purpose-built for your horticultural application and cultivation approach.

10 During early stages of propagation, temperature and humidity targets may be higher. Some crops may need swings in temperature to trigger flowering/fruiting.
11 Cucumbers 101: a production guide, Produce Grower, 2018. Tips on Producing a Better Greenhouse Cucumber, Greenhouse Grower, 2021.
12 Review of optimum temperature, humidity, and vapour pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato: A review, International Agrophysics, 2018.
13 Basics for Growing Peppers, University of North Carolina, 2020.
14 Strawberries Can Be Adapted To Greenhouse Production Systems, 2017. Greenhouse Strawberry Production and Technology, Ohio State University, 2022.
15 Greenhouse Vegetable Production, New Mexico State University, 2019. Monitoring is crucial for growing lettuce and leafy greens year round, HortAmericas, 2021.
16 Commercial Microgreens: Production and Best Practices, Alberta Ministry of Agriculture, Forestry and Rural Economic Development, 2018.
17 Mushroom Cultivation IV, Chapter 4, Technical data of mushroom species: an overview, range for Agaricus bisporus, Oei, 2016.
18 Ball RedBook, Volume 1, Ball Horticulture, 2021.
19 Warm-floor slab heating or bench heating may be sufficient for some crops to not need any ducted or ceiling-hung heating equipment. However, fine control can be difficult and not instantaneous. If facility changes are needed in the future these systems can be challenging to retrofit

IMAGE: PRIVA

Utilities and efficiency programs support the adoption of emerging technologies like high-performance HVAC systems based on the energy savings over traditional options. Throughout this guide, opportunities for efficiency program support of HVAC equipment will be highlighted with **bold green** text so you can work with your local program teams to get technical assistance and financial incentives for installing efficient HVAC solutions.

Table 4: Typical CEA HVAC System Types by Facility Type

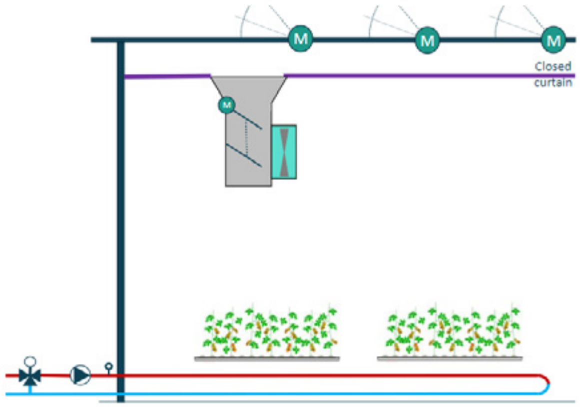
<table>
<tr><th>HVAC System Type</th><th>Facility Type:
Ventilated Greenhouse</th><th>Facility Type:
Sealed Greenhouse</th><th>Facility Type:
Indoor Vertical Farm</th></tr>
<tr><td>Heating</td><td>Unit heaters

Hot water systems: boilers connected to radiant warm-floor slab heating or bench heating, hydronic unit heaters, root zone heating

Biomass heating, furnaces</td><td>Hot water systems, geothermal heat exchange systems, air to air heat exchangers, fan coil units, electric resistance systems, latent heat converters</td><td>Electric resistance systems, heat pump systems, hot water systems, steam systems, heat recovery chillers</td></tr>
<tr><td>Ventilation</td><td>Natural ventilation - ridge vents, gutter vents, side wall vents, open-roof, retractable roof, powered fan systems for ventilation and exhaust</td><td>100% recirculating systems, no air exchange with outside</td><td>100% recirculating systems, no air exchange with outside</td></tr>
<tr><td>Airflow</td><td>Horizontal airflow fans (HAF)</td><td>Vertical air fans, destratification fans, air handling units</td><td>Air handling units, HAF and in-rack fan systems</td></tr>
<tr><td>Cooling</td><td>Evaporative fan-and-pad, fogging or misting for cooling and humidifying, chillers[20]</td><td>High-pressure fogging or misting for cooling and humidifying, integrated cooling & dehumidification</td><td rowspan="2">Integrated cooling & dehumidification</td></tr>
<tr><td>Humidity management</td><td>Exhaust fans, wood-fired heating, sometimes plug-in dehu units</td><td>Central dehumidification system</td></tr>
</table>

20 Required for certain floriculture crops like orchids.

Figure 8: Example of Horizontal Airflow & Curtain System



Optimize HVAC Designs for CEA Facilities

Determine the goals of your climate control systems by using your horticultural HVAC vocabulary to establish design conditions for CEA environmental control systems. The crops you grow, your facility type, and location inform your choice of HVAC equipment and control strategies.

Document Goals - Designing the HVAC equipment in your facility to both successfully serve the needs of your plants and run efficiently requires thoughtful planning before you start construction or a major renovation. Create an *Owner's Project Requirements (OPR)* document to guide design development and define your goals, objectives and performance metrics for your HVAC systems. Consider the basis of your facility design so that you can optimize the efficiency and impact of your HVAC decisions. A *basis of design (BOD)* gives designers and installers a better understanding of the details of your operation, allows them to specify and construct HVAC systems that meet your expectations, and provides a point of reference when evaluating effects of changes being considered.

Describe HVAC Needs - The energy stored in the air in your cultivation spaces as heat and humidity are the *loads* from horticultural processes in CEA facilities. There are two kinds of HVAC loads: sensible and latent. *Sensible loads* come from external influences like heat from the Sun or internal sources like heat emitted by horticultural lighting equipment and other internal loads like motors on fans. Sensible loads are *dry loads*, the heat you can feel. In facilities that grow plants, sensible load is a portion of the total load your HVAC equipment needs to manage. *Latent loads* come from evapotranspiration (ET). This can also be thought of as the *wet load*, the moisture in your grow rooms. Both sensible and latent loads can be measured in Btu per hour (Btuh[21]), or *tons* (12,000 Btuh). Work with your design team to accurately describe and quantify sensible and latent loads in your facility spaces to properly size the equipment to serve them. Temperature, relative humidity, and airflow requirements and target ranges for these parameters might be different in different parts of the facility and can affect HVAC choices.

Consider Peak HVAC Loads - Cultivation facilities have very high loads per cubic foot when compared to the average commercial building. Grow environments are also unique because the latent load is often equal to or greater than the sensible load, which is unusual for buildings in which people work or live. When plants are small, sensible loads may be at their highest. When plants are larger and lights are off, your HVAC equipment may experience peak latent loads. Factor both into your system design to effectively meet all grow room conditions.

IMAGES FROM LEFT TO RIGHT: PRIVA; IMEG CORP.

Figure 9: Geothermal Greenhouse HVAC System Design

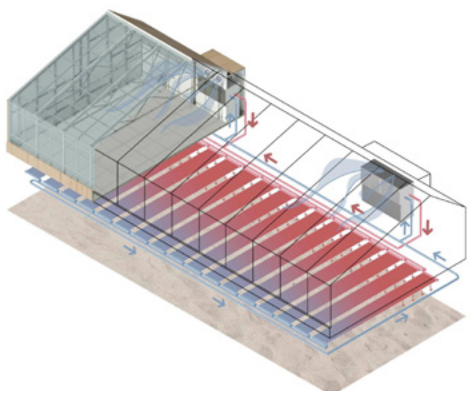


IMAGE: CERES GREENHOUSE SOLUTIONS

Use Thermal Storage - Greenhouses and indoor farms can both apply thermal storage technology to use energy when utility costs are lower and save it to use during more expensive times of day. Greenhouses can use tanks to store cold water in the summer and hot water in the winter to lower and shift peak HVAC demands to different times of day to take advantage of excess thermal energy when it is available. Greenhouses can also use geothermal heat transfer to pre-heat or pre-cool hydronic systems, as shown in Figure 9. CEA facilities can also utilize *phase change materials* in greenhouse coverings to maximize the benefits of thermal storage and use less space than water tanks.

Ratios for Cultivation - Most HVAC equipment for commercial buildings is designed for high sensible loads. *Sensible Heat Ratio (SHR)* is the ratio of sensible heat load to total heat load (sensible and latent). Understand the ratio of sensible to latent heat in your facility for different design conditions (summer, winter, day, and night) to evaluate the range of SHR your HVAC equipment can achieve. For some CEA crops that need more dehumidification, latent load can be half of the total load (SHR = 0.5), but for others like lettuce have latent loads that make up less of the total load (e.g., SHR = 0.8). At night, SHR can be as high as 1. For this reason, it is especially important to use equipment purpose-built for cultivation that can handle these dynamic design conditions and ranges of SHR. Typical commercial HVAC systems are manufactured to satisfy static SHR values of 0.7 to 0.9, which may not work for a cultivation space with environmental targets of 80° F and 60% RH, which would result in an SHR of 0.5. Commercial HVAC equipment is also usually not equipped to handle the dynamic ranges of SHR experienced in CEA facilities.

Prepare Your Facility - Lager operations should supply facilities with 480V 3-phase electrical power if possible. This can reduce the infrastructure costs for powering HVAC systems by lessening the amount of copper needed for wiring and panel (breaker) space. Horticultural HVAC systems operate best when served by AC power at 277V. There are more products available that run at higher voltage. There are also energy savings benefits of running at higher voltage as equipment can operate with higher efficacy.

Meter to Monitor - Work with your design team to evaluate how key performance factors of HVAC systems and energy use of HVAC systems will be monitored. *Submetering* gives you the ability to monitor systems for efficiency and receive rebates from utilities and efficiency programs. Metering systems can also send remote alarms which can be critical for avoiding serious problems before they develop into disastrous issues and cause production delays.

Plan for Automation - Determine the ways horticultural HVAC equipment could be controlled in your facility and whether controls hardware and software may be used to automate operation. Document daytime and nighttime setpoint ranges for operation of climate control equipment based on the minimum, optimal, and maximum temperature and relative humidity values for your CEA crops by stage of growth. For greenhouses, consider how HVAC equipment will be staged to respond depending on transition temperatures. **Integrated climate control strategies** can be beneficial for all CEA facilities as a way to orchestrate equipment in harmony, smooth spikes in HVAC system operation, and save energy.

Gather Information - Determine the area of the cultivation spaces in your facility that will need passive and active climate control solutions. Discuss HVAC system efficiency with your project team members using the proper terms for heating, cooling, dehumidification, and filtration. Review with your project team what ranges of efficiency metrics will minimize your energy bills.

Choose Minimum Efficiencies - The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) develops standards for the efficiency of HVAC equipment. ASHRAE's Energy Standard for Buildings Except Low-Rise Residential Buildings (ASHRAE 90.1) is often used to develop state and local standards[22]. Your design team should know minimum efficiencies from the latest standard and local building codes. Depending on facility location, the 2016 or 2019 version of 90.1 may be applicable to your new construction or renovation project.

Table 5 below describes the different parameters used to rate efficiency performance of various CEA HVAC system types. Note that many of these efficiency ratings are at 'designated operating conditions, which means when you install it in your facility, it may not run the same way.

Table 5: Efficiency Characteristics of CEA HVAC Systems

Efficiency Metric Name	Description	Efficiency Metric Unit	Notes
Energy Efficiency Ratio (EER)	Ratio of net cooling capacity to total rate of electric input under designated operating conditions. Does not account for partial load scenarios and does not represent actual field performance.	Btu per Watt (Btu/W)	EER can allow you to compare two different HVAC systems at rated conditions, but does not help you determine the energy use of your facility's equipment.
Seasonal Energy Efficiency Ratio (SEER)	Used for equipment sized smaller than 5.4 tons. Ratio of cooling output of equipment during typical cooling-season conditions, divided by the total electric energy input during the same period.	Btu per Watt-hour (Btu/Wh)	SEER can allow you to compare two different systems at typical seasonal conditions and partial load scenarios.
Integrated Energy Efficiency Ratio (IEER)	Used for equipment sized larger than 5.4 tons. A weighted average of efficiency values for equipment across a cooling season for a diverse set of climates, and so is more representative of actual efficiency but is still rated at designated operating conditions.	Btu per Watt-hour (Btu/Wh)	IEER is more representative of actual efficiency but is still rated at designated operating conditions. Does not account for partial load scenarios and does not represent actual field performance.
Moisture Removal Efficiency[23] (MRE)	Ratio of net moisture removal capacity to total rate of electric input under designated operating conditions.	Pounds per hour per Watt (lb/hr/W) per Watt or kilograms per hour per Watt (kg/hr/W)	MRE can allow you to compare two different HVAC systems at rated conditions, but do not help you determine the energy use of your facility's equipment.
Annual Fuel Utilization Efficiency (AFUE)	Ratio of heating equipment annual heat output compared to total annual fossil fuel energy consumed.	Percent (%)	AFUE measures how efficient heating equipment is in converting the energy from fuel to heat over the course of a typical year.
Heating Seasonal Performance Factor (HSPF)	Ratio of heat output (measured in BTUs) over the heating season to electricity used (measured in watt-hours). It, therefore, has units of BTU/watt-hr.	Btu per Watt-hour (Btu/Wh)	HSPF describes the efficiency of air-source heat pumps.
Coefficient of Performance (COP)	Ratio of useful heating or cooling provided to work (energy) required under specific operating conditions.	Value from 1 to 4.5	COP describes the efficiency of HVAC equipment like ground-source and air-source heat pumps.
Minimum Efficiency Reporting Value (MERV)	Measures the effectiveness of air filters. The higher the MERV rating, the smaller the particulates the filter can trap.	Value from 1 to 16	Filters with high MERV ratings induce a greater pressure drop across the thicker filter media. This can result in greater fan power consumption.

22 Addenda for standards affecting indoor farms and greenhouses are being developed to address horticultural systems in CEA facilities like lighting. It is possible that an addendum focused on horticultural HVAC systems could be developed and adopted and affect future projects.

23 Note that there are no performance standards for rating the moisture removal capacity of dehumidifiers operating at temperature and humidity levels commonly observed in controlled environment agriculture facilities as of February 2022. The dehumidification capacity reported by HVAC system manufacturers may not represent actual dehumidification capacity because dehumidifiers are tested and rated at 80°F and 60% RH, which may differ from your target temperature and RH. De-rating of efficiency can be performed with manufacturer de-rating tables to get a more accurate number.

Avoid Microclimates - HVAC system distribution infrastructure contributes greatly to uniform canopy conditions. Uniform environmental conditions are necessary for your crops to minimize pathogen outbreaks and maximize yield. Understand the layout of cultivation spaces and location of HVAC equipment which impact distribution of heat and air in CEA facilities. Ensure consistent spacing of circulation and ventilation equipment. Strive for minimal temperature differences between the intake and fan (exhaust) ends of greenhouse bays to maintain little temperature variation across cultivation spaces. In indoor farms, consider how HVAC systems will reach every level of tiered racking systems and how stale areas will be removed at the ceiling to counteract *stack effect*.

Understand Interactive Effects - Consider the interactive effects of HVAC and lighting systems and retrofit to LED light fixtures thoughtfully. New construction projects should use lighting system type as a key input for HVAC system selection and design. If your grow spaces were originally designed for HID lights, retrofitting spaces to LED lighting systems may change the heat loads of the space as LED lighting systems can emit less heat[24] (often expressed as Btu per hour, or Btuh) than other horticultural lighting systems. To keep greenhouses at the same temperature, more HVAC capacity for heating may be required in colder climates.

Determine Your Targets - Use Table 3 on page 18 to review the ranges of temperature and relative humidity that are acceptable for your CEA crops. These ranges can be used by your project team members to evaluate several combinations of temperature and relative humidity *setpoints* that result in your desired VPD. Setpoints for climate controls can greatly influence the efficiency of HVAC systems. Establish potential *design conditions* to accurately estimate your HVAC system's capacity. Experienced engineers use design conditions to accurately size and select HVAC equipment to meet your requirements.

Consider Energy Recovery - *Energy recovery* is an efficiency strategy that exchanges heat between exhaust and supply air or water streams to recover energy and use it again without introducing outside air into your cultivation rooms. Work with designers to evaluate how your CEA facility could incorporate **energy recovery systems**[25]. Energy recovery strategies like hot gas reheat may be required in your jurisdiction; consult local energy codes to determine their adoption and enforcement of ASHRAE Standard 90.1 and how it is applied to greenhouses and indoor farms. Heat exchangers for exhaust air energy recovery include wheels and cores that are made out of materials very effective at conductive heat transfer. Plate heat exchangers can be used to recover energy without bringing outside air into facilities. Indoor facilities with low temperature and humidity targets can use heat recovery chillers to supply chilled water and maximize energy efficiency by capturing rejected heat from the chiller and using the energy to preheat water for dehumidification processes.

Enrich Safely - Some CEA facilities enrich cultivation spaces with CO_2 to maintain levels of 800 - 1,200 ppm. CO_2 can be sourced as a byproduct of natural gas heating or cogeneration processes or from delivered CO_2 containers. Consider and document safety protocols for fire and human health hazards. Ensure HVAC controls monitor CO_2 levels and sequences of operation are programmed to enable emergency ventilation. Design and functionally test for emergency situations such as power loss or gas leaks. While international fire codes[26] or local requirements may address some safety aspects, many regions do not have specific codes addressing CO_2 enrichment in CEA facilities.

Vent for Fungi - Mushroom production decreases when CO_2 levels are elevated above ambient as CO_2 suppresses mushroom growth. Fruiting bodies get stemmy, deformed, and then will fail to produce at levels above 800 ppm. Exhaust mushroom house air to maintain ppm of 450 - 600 ppm to keep morphology normal. Researchers have found environmental and business benefits from connecting mushroom houses to vegetable or floriculture greenhouses to vent excess CO_2 to help plant production while also reducing mushroom water use.

[24] Consult manufacturer specification sheets to understand heat output from lighting systems. When retrofitting to LED, heat loads may decrease, but lighting layout impacts how loads change. For example, if total fixture quantity is increased, heat loads may stay the same or increase compared to high-intensity discharge or fluorescent light fixtures.

[25] Chapter 8, ANSI/ASABE/ASHRAE EP653, 2021.

[26] Section 5307.4 of the 2018 International Fire Code is specific to carbon dioxide enrichment systems. This section requires the use of a gas detection system and exhaust ventilation.

Cool for Free - For more efficient CEA facility operation, consider **economizing equipment** that takes advantage of outdoor conditions. Adding a *water side economizer* for *free cooling* operation to your chiller loop can provide attractive energy savings and lower utility bills by using outside temperatures to pre-cool water before it enters (or perhaps even bypasses) the chiller. Using *air side economizers* can be more challenging for indoor facilities enriching environments with CO_2 or cultivation spaces needing sensitive humidity and pest management. Airside economizer strategies may decrease sensible cooling requirements but increase the energy required to dehumidify. Cold and dry air introduced when economizing may necessitate more humidification. Consult designers about ventilation control strategies for air side economizers.

Dehumidify to Dry - Dehumidification can happen as a side effect of cooling system operation or can be directly performed by dedicated moisture removal equipment. Technologies for dehumidification can be standalone or integrated with cooling systems. Consider the benefits of an **integrated dehumidification system**. Centralized or integrated dehumidification systems can offer energy savings as well as finer control of the indoor environmental conditions of your cultivation space. Units that fully integrate cooling and dehumidification offer integrated control of both air conditioning and dehumidification sequences. While standalone plug-in dehumidification[27] units are inexpensive, they reject heat back into cultivation spaces and require air conditioning systems to work harder and more often. This increases your operational costs and offsets the lower first cost of the standalone units. Another issue with standalone dehumidifiers arises when lights are off and cooling is not required, humidity can spike or be challenging to manage with only the capacity of standalone dehumidifier solutions.

Mist for Moisture - CEA facilities growing grafted plants, pre-rooted plants, and young plants may need to humidify cultivation spaces to account for the low transpiration rates of these kinds of crops. Greenhouses elevate relative humidity levels with evaporative pan-and-fad systems, misting systems spraying small vapor droplets into the air (approximately 10–100 microns), and high-

IMAGE: KATRIEN VAN CROMBRUGGHE

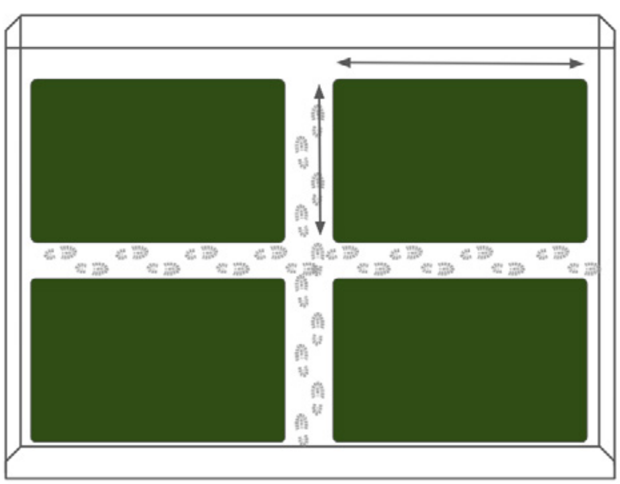
pressure fogging systems spraying very small droplets (approximately 1–10 microns). Indoor farms may use systems integrated into vertical racks to maintain optimal humidity levels. Water from these systems can affect horticultural lighting systems in your cultivation spaces, which is why vapor-tight light fixtures are recommended for CEA facilities.

Plan Airflow and Ventilation - Once cooling, heating, and humidity management needs are considered, review the ways air will be moved around and through your CEA facility. Greenhouses may use roof and side wall vents to exhaust hot and humid air and accomplish ventilation, cooling, and dehumidification simultaneously. If natural ventilation strategies are not sufficient or feasible for your greenhouse or indoor farm, exhaust fans can supply mechanical ventilation. Air circulation is critical for CEA crops to achieve their yield potential. Both greenhouses and indoor farms can use a combination of horizontal and vertical air fans to mix and destratify air and minimize microclimates. Vertical farms can incorporate in-rack fan systems to supply tiers at every level with enough air movement to promote growth. Use of **variable speed drives** to operate fans can maximize energy efficiency while also offering dynamic environmental control.

[27] Standalone dehumidifiers tend to operate on single-phase power, so electrical infrastructure can be more expensive. This equipment can also be more difficult to tie in to emergency power supply systems.

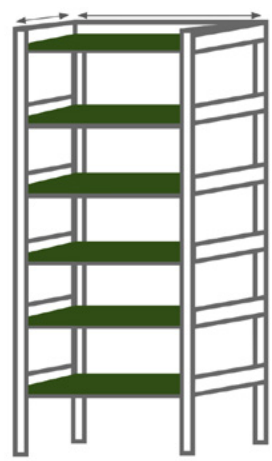
Choose HVAC Energy Sources - Before deciding on equipment, consider the ways your facility will use energy to accomplish heating, cooling, ventilation, airflow, and humidity management goals. All CEA facilities use electricity to drive motors that run pumps and fans for hydronic and ducted systems. HVAC systems for greenhouses can use fuels like propane and natural gas for heating and electricity for running fans. Climate control systems for indoor farms can use more electricity from refrigerant-based cooling systems, electric resistance heating systems, and humidity management equipment. Both greenhouses and indoor farms limited by electrical service can use **combined heat and power (CHP) systems** driven by natural gas. As regions seek to achieve decarbonization & electrification goals, energy efficiency programs may incentivize CEA facilities to consider HVAC systems that do not use fossil fuels, like electric **heat pump equipment** in order to utilize electricity generated from renewable energy resources on-site or supplied through the grid. Gas-fueled heat pump technology can be prudent in colder climates where a fossil fuel backup would be necessary for an electric heat pump; these systems can utilize biofuels like renewable natural gas. Heat pumps have both heating and cooling capabilities, and the same *sensible* and *latent* considerations apply.

Figure 10: Illustration of Greenhouse Canopy Area



Quantify Canopy - Document *canopy area*, the crop area under production in your cultivation spaces. Understand the number of plants occupying cultivation spaces, as the latent load to be managed by your HVAC equipment is dependent on the moisture given off by your plants, their grow media, and irrigation systems. Consider how the density of plant canopy, size of plants, and cultivars may fluctuate and change based on time of year, growth cycle, market forces, and issues with regulations or crop damage. In Figure 10, canopy area would be calculated by adding the green areas which represent bench space used for crop production and do not include aisles or walkways between benches. In Figure 11, canopy area would be calculated by adding the green areas which represent levels of each vertical rack used for crop production and also do not include aisles or walkways between racks.

Figure 11: Illustration of Canopy Area for Vertical Racking Systems



Watch Your Water - Determine your *net watering rate* per plant, which is the gross watering rate provided to your rooms less your waste and return water. This affects the moisture load your HVAC equipment has to manage in your grow space. Watering rate can contribute less to HVAC loads when crops are grown in small containers or covered media as less water evaporates into cultivation spaces. However, growers of larger crops or cultivating in raised beds filled with substrate may find water vapor from irrigation to be significant. CEA growers describe watering rate in volume of irrigation water less drained and recirculated water applied per day or per plant. Some cultivators calculate watering rate by observing the usage of stored water and how frequently water is gathered and stored.

Size Capacity - To effectively size HVAC systems, you must understand whether equipment can satisfy design conditions. *Capacity* is your HVAC equipment's maximum ability to satisfy loads, and describes the rated heating, cooling, or moisture removal your equipment can handle. For heating and cooling equipment, capacity can be described in terms of kW, Btuh or tons (1 ton = 12,000 Btuh). For dehumidification equipment, capacity can be described using pints (or pounds) of water removed per hour or per day. The sum of sensible and latent loads determines the total energy load your HVAC systems need to manage.

Satisfy Loads - Match the sensible and latent load of your space to the sensible and latent capacity of your HVAC system closely for the most efficient and effective HVAC system. Pay attention to both the sensible and latent capacities of the system, not just the total capacity. Work with qualified design professionals to perform design calculations. Table 6 below illustrates how HVAC system capacity can influence the types of CEA HVAC systems that are feasible and cost-effective to apply in greenhouses and indoor farms. Note that crop type, facility location, and ranges for target environmental conditions drastically impact these choices. For example, if your facility location is very hot and target temperature range for your crops is low, your required HVAC system capacity may be higher than a facility growing the same crop in a cooler climate, and result in your facility using a different type of HVAC equipment.

Table 6: HVAC System Capacity and Associated CEA HVAC System Types

HVAC System Capacity	Greenhouse CEA HVAC Solution	Indoor CEA HVAC Solution
75 tons or less	Direct expansion (DX) cooling, unit heaters, passive venting systems	Direct expansion (DX) units with standalone dehumidification systems like roof-top units (RTUs) split systems, and ductless heat pumps
75 - 300 tons	Evaporative fan-and-pad systems, hot water heating systems, active ventilation and circulation fans	Air-cooled chillers, hot water coils, heat pump systems, electric resistance heating systems
Greater than 200 tons	Geothermal heating systems, comprehensive ventilation systems	Water-cooled chillers, heat recovery systems, comprehensive ventilation system

Size Appropriately - Correctly sizing your HVAC equipment for your ideal grow room conditions can help you avoid mismanaged environmental conditions in your cultivation spaces, and potentially crop loss. The HVAC capacity needed to maintain a VPD of 1.5 kPa is about 25% greater than the system needed to satisfy loads and maintain a VPD of 1.0 kPa, requiring both larger equipment and more energy to operate it. Sizing your HVAC system around a VPD that is too high (or temperature and humidity rates that are too low) can lead to oversizing HVAC systems.

IMAGE: IMEG CORP.

Right-Size - Oversizing your HVAC equipment can result in higher energy use and *short cycling*, which can result in less latent heat removal and humidity control during cooling. Short cycling is hard on your equipment and can reduce useful life. Undersizing climate control equipment can be detrimental to CEA operations because target environmental conditions cannot be met, affecting plant health. and impacting canopy productivity. Crop degradation can manifest in many ways. Losing days of biomass production due to suboptimal conditions means plants are not hitting their full potential. Reductions in harvested yield from crop loss can be a result of sustained crop degradation from poor climate control.

Understand Sequences of Operation - Your engineers will use the loads, setpoints, and targets for your grow room environmental conditions you developed in OPR and BOD documents to create *sequences of operation* that your HVAC equipment will be programmed with to effectively serve the specific needs of your cultivation facility. Work with them and your controls contractors to understand how different pieces of equipment will be staged on and run to manage heat and moisture in grow rooms so you can identify situations that are outside the normal range of operation.

Maximize Incentives - Efficiency programs in many states support **efficient horticultural HVAC equipment**. Share HVAC design details with utilities and efficiency programs so they can calculate your facility's energy savings and custom financial incentives. Share HVAC energy sources, how equipment will be sequenced, and target environmental setpoints as inputs for modeling energy consumption and validating savings. In some regions, growers can receive rebates for horticultural HVAC equipment through rebate programs that do not require energy modeling.

Purchase HVAC Equipment for CEA Facilities

Once you understand the vocabulary used to describe the indoor environment your plants need and the metrics of performance for HVAC systems, you will need to apply them to make informed decisions when selecting equipment for your facility.

Review Manufacturers' Literature - Manufacturers' specification documents, often known as *specification sheets* or *submittals*, describe the performance characteristics of equipment so you can determine if it will meet your needs. Compare HVAC technology using metrics like rated capacity, input power and efficiency ratings. Review specification sheets for performance parameters under different operating conditions and discuss the balance of efficiency and cost with your design team. Equipment specification sheets can also describe the noise levels from systems when operated at design conditions.

Find the Right Fit - Review minimum performance metrics to sort and eliminate equipment by intended use, efficiency ratings, and warranty terms. Many growers have experienced the pain of rooftop units freezing up in the winter; recognize that most rooftop units are only designed to provide cooling down to ambient temperatures of roughly 50 - 55 °F, though some equipment may operate at lower temperatures. Many units have optional factory-installed low-ambient kits that allow for cooling during much lower ambient conditions. There are also kits that can be retrofitted onto most existing rooftop units in the field.

Verify Quality - Look for independent verification of quality claims made by HVAC equipment manufacturers. For best results, confirm that the equipment is rated by a third party such as AHRI. It is important to compare the performance of the equipment relative to your operating conditions. The conditions that the equipment is rated at (typically rated in accordance with AHRI 340/360) may not match your cultivation conditions. Review the UL1995 safety test reports produced by certified laboratories like CSA, Intertek, and TUV. Code officials may enforce special requirements upon facilities operating equipment not rated by national testing labs. A list of nationally-recognized testing labs (NRTL) is published by the Occupational Safety and Health Administration (OSHA) at https://www.osha.gov/dts/otpca/nrtl/nrtllist.html.

Choose System Type - Consider how you want your spaces to be conditioned. Assess systems' ability to satisfy the requirements laid out in your OPR and BOD. Table 4 on page 15 demonstrates the variety of choices CEA facility owners and growers can make for heating, ventilation, airflow, cooling, and humidity management. Some HVAC and dehumidification system types will be more or less feasible for your climate, and some systems may be more or less expensive to operate depending on your local electric and gas utilities and their rates. Some HVAC system types may not be an option or can be less affordable for your facility if there is no natural gas service available or insufficient service to support HVAC system capacity. Setpoints can make some systems more viable than others. Facility type can also influence how an HVAC system can operate to achieve target environmental conditions. Work with members of your design team to evaluate several options that can feasibly meet and maintain environmental conditions within your target ranges.

Save Space - Anticipate the space needed for your equipment depending on the systems you choose to maintain different environmental processes. HVAC equipment and infrastructure like ductwork take up space in your cultivation areas and on your facility's site. For roof-mounted systems or equipment suspended from ceilings, the weight of HVAC systems also must be evaluated to ensure building structural systems can support equipment and ductwork. Engage design engineers so systems can be laid out thoughtfully for easy maintenance. Consider integrated systems to maximize canopy area.

Validate How Your Equipment Will Run - Work with your engineer, commissioning agent and mechanical and controls contractors to understand how the sequence of operation in your design drawings is going to be executed by the equipment being installed. If you have a *environmental control system* that controls your HVAC equipment, choose what *points* are important for you to monitor, which ones should be trended, and for how long. Environmental control systems automate operation of equipment in your facility to provide accurately and finely tuned indoor environments but are not a substitute for good HVAC system selection and design practices. *Points* measured and recorded by your control system refer to the prescribed and actual measured parameters like temperature, power, and relative humidity in your facility, and are important to *trend* over time so you can visualize your facility's historical operation.

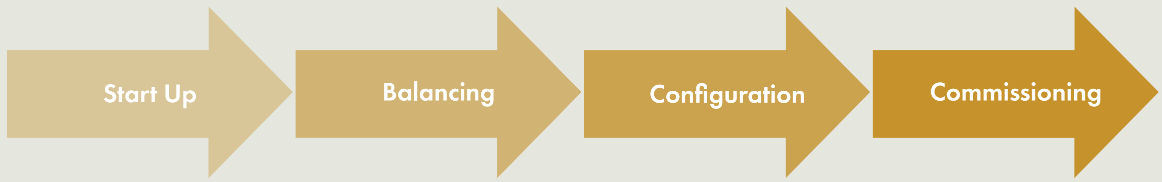
Install HVAC Equipment in CEA Facilities

Once you have ordered your climate control equipment, it is time to put everything together properly to influence the indoor environment your crops will experience.

Get Construction Support - Engage with your engineering team during the construction phase to follow through with design goals and review issues identified in the field; the upfront investment can pay off by avoiding problems that can be costly to address later in construction. It takes time to dial in CEA facility performance and tune controls properly, so reserve time on-site with project team members to fully commission HVAC systems. Engage a third-party commissioning agent to validate that climate control systems can meet your criteria for success and share issues reports with your entire project team and ensure resolution.

IMAGE: VERTICAL HARVEST

Figure 12: Construction Phase Verification Processes



Start-Up - Once equipment arrives on site and is connected to power, the *start-up* phase can begin. When HVAC equipment is turned on for the first time, a *start-up checklist* must be completed by your installing contractor to receive the warranty from the manufacturer. These reports should be provided to commissioning agents to review for any issues.

Balance - Once HVAC equipment is up and running, the *testing and balancing (T&B)* phase can commence. In this phase, air and water flow rates are verified and adjusted to meet design documents. *Balancing reports* are critical to verify the system is set-up correctly to achieve the required flow rates and function as designed. Without proper balance, the HVAC units cannot meet their required performance and your facility could risk crop degradation or reductions in yield.

Configure - Your mechanical and electrical contractors start up equipment (sometimes with the assistance of the equipment manufacturer or supplier), your balancing contractors adjust air and water flow rates, and then your controls contractors configure the sequence of operations to program HVAC systems to function as designed. Many pieces of equipment have integrated controls and controls systems integrators may be helpful to get components to communicate and automate. Some controls contractors create *configuration reports* to describe the steps taken to configure equipment, and these can be used to inform commissioning activities.

Consider Commissioning - Ideally commissioning activities will span both design and construction phases, and pre-functional checks may occur before, during, or after start-up, balancing, and configuration activities[28]. Check local energy codes to understand if commissioning activities are required for new construction or retrofit projects in your region. Once programming is complete, *functional performance testing* of HVAC systems and their associated controls allows your commissioning agents to run equipment through its paces to ensure it responds as designed and check that system alarms are connected and enable as expected. Commissioning allows for facilities to better achieve energy performance goals by addressing modifications to controls sequences earlier, which can be economically beneficial in the long run, especially when commissioning activities are performed by a third party consultant.

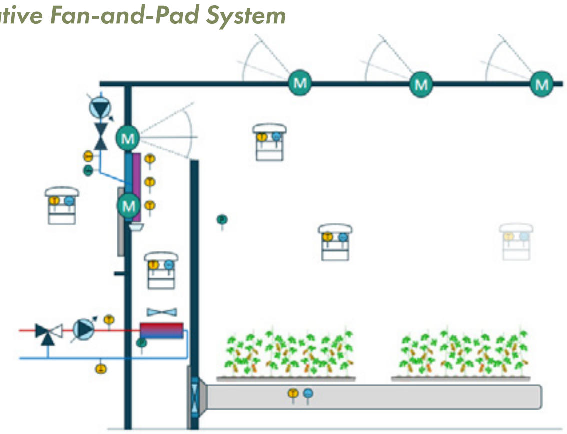
Measure Right - Taking one humidity reading for an entire greenhouse or one temperature reading directly below a light source is not representative of the entire grow room. Temperature and relative humidity should be measured in multiple places on a grid at crop canopy height or at the grow media (for shorter crops). Take readings with a calibrated meter so values can be averaged across the canopy area and compared to the target conditions for plants' growth cycle.

Place Sensors - Install sensing equipment to track and report environmental conditions to observe changes between harvests. Use climate sensors to inform the operation of your environmental control systems and automate HVAC sequences of operation and control cooling, heating, ventilation, airflow, and humidity management equipment. Consider where you will place sensors to calculate canopy temperature and relative humidity; at the canopy level is appropriate but on a

28 Commissioning (Cx) verifies whether a building is performing according to its original design and intent and meets the needs of its owners and occupants. This quality-assurance process helps to identify deficiencies that could lead to equipment failure, increased energy use, and poor indoor air quality so that building operators can better maintain their facilities.

wall is not. Ensure greenhouse weather stations gathering information about outdoor conditions are installed in places outside of direct sunlight and in a location representative of the facility (on the roof of the facility, not far away). Figure 13 below shows placement for three types of environmental sensors. The diagram uses yellow icons for temperature (T), blue icons for relative humidity (RH), and green icons for flow (F). The large M icons indicate motors for roof vents and valves for the cooling system.

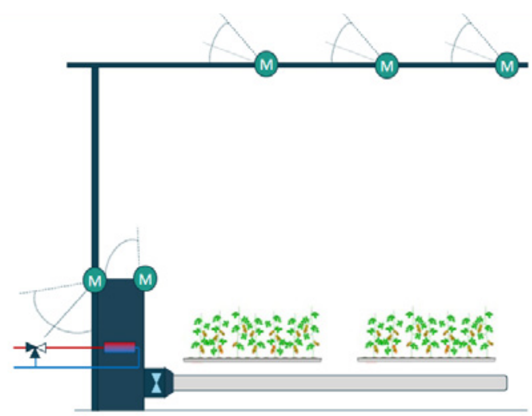
Figure 13: Sensor Placement for Greenhouse with Evaporative Fan-and-Pad System



Integrate - Connecting environmental controls for HVAC equipment with controls for horticultural lighting and irrigation systems like can be beneficial for optimizing target conditions for plants and energy efficiency. As light delivery influences photosynthetic and transpiration rates in plants, which in turn influence ambient temperature and humidity, communication between systems allows for better coordination. Work with design and construction partners to understand which systems will inform each other and how equipment can be staged for precise control and low operating costs.

Validate Performance - Work with partners like commissioning agents to create *functional performance tests* to verify HVAC systems can achieve goals established in design. Verify the HVAC equipment is capable of meeting targets for VPD by maintaining set points for temperature and humidity. Test equipment before plants are moved into rooms, and again after. In project documents, specify the equipment that should be used for measuring environmental parameters. Some tests that HVAC Working Group members recommend include ensuring HVAC systems manage temperature and humidity when actual environmental conditions in cultivation spaces are outside of target ranges, observing how climate control systems respond to significant changes in HVAC loads (such as when lighting systems are turned on and off), and verifying that day-night temperature differential can be achieved in various scenarios. Figure 14 below shows an example greenhouse system with motors controlling roof vent actuators and valves for a hydronic heating system. During functional testing, commissioning agents can simulate different cultivation space conditions by editing temperature and relative humidity inputs to environmental control systems to observe how motors enable and systems respond to maintain target VPD.

Figure 14: Motor Controls for Greenhouse Heating Block and Roof Vent System



Commission Well - To avoid wasting time, ensure that commissioning agents visit the site to functionally test equipment only when the system to be evaluated is on-site, hooked up to power, started up, and configured by the manufacturer or your construction contractors. Reserve enough time for site visits on several days at different points in construction and instruct construction partners to resolve issues identified in commissioning reports. Have tests performed both before and after plants are in the room. Employ an integrated commissioning plan that stress-tests environmental and lighting controls equipment in concert to stage equipment and observe interactive effects and appropriate responses. Tests may need to be conducted at different times of the year to capture diverse outdoor

IMAGES: PRIVA

conditions for greenhouses. If crops have a wide variation in target set points between different growth cycles or different crops with varying set points are grown seasonally in the same cultivation space, commissioning may be required for the first time the facility is at those set points.

Review Reports - Review start-up checklists provided by manufacturers, balancing reports provided by contractors, and pre-functional checklists and functional performance tests developed for your project by your engineers, contractors, and commissioning agents to ensure they can assure you that equipment is performing as designed and can satisfy your design parameters. If energy is being saved, energy efficiency programs can use commissioning reports to provide rebates. Ensure you request these documents and read them completely to follow up on issues identified within, as it is much more expensive to resolve problems once your building is occupied and operational. Have final reports include target ranges of temperature and RH and actual ranges maintained during testing for each of your cultivation spaces. Verify that climate control equipment can meet the parameters for success laid out in design. Understand that measurements may have a +/-5 - 10% error band. Visual maps of spaces as tested can help operations and maintenance staff troubleshoot when average temperature or RH or quality change, or if energy costs from HVAC shift in unexpected ways.

Operate HVAC Equipment in CEA Facilities

Once you are ready to grow in your new or renovated space, keep an open mind as you operate new equipment and document changes you make as you adjust your growing approach.

Document Everything - As staff implement Standard Operating Procedures (SOPs), it is crucial that your team write down daytime and nighttime target environmental conditions for posterity and as inputs for controls systems. Prepare for turnover or plan for continuous improvement as your growers research and develop new ways to increase yields or maintain consistent crop quality. Create tables of target temperature and humidity setpoints for different crops and cultivation spaces so equipment can be adjusted or replaced accordingly. Include notes about watering activities to link those to HVAC system operation.

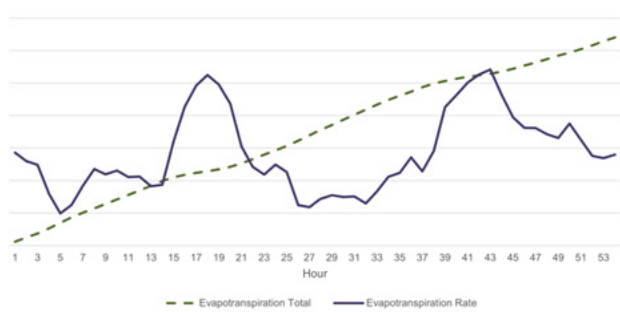
Smooth Transitions - Relative humidity of cultivation spaces often spikes after the sun goes down or after lighting systems turn off. This is because the air begins to cool soon after the lights go out, but the quantity of water in that air doesn't reduce at the same rate the temperature drops. In this scenario, you have a cooler space with the same amount of moisture in it, which raises RH in the cultivation space. Use sensing devices once you are operating your facility to measure and monitor grow room characteristics like temperature and humidity so HVAC systems can respond gradually to bring conditions back to desired targets.

Revisit Environmental Controls - Actual facility loads are inevitably going to be different than those predicted in design, so it is important to document how HVAC loads change and evaluate how to adjust environmental targets. Also, if down the road, equipment is changed out, HVAC loads may also require adjustment of your facility SOPs. For example, if your facility retrofits from high-intensity discharge lighting systems to LED lighting products, LED light fixtures can give off less heat than HID equipment and affect sensible loads in cultivation spaces. To learn more about cultivating with horticultural lighting, benefits of LED lighting, and many more tips for operating lighting equipment efficiently in your facility, check out RII's CEA Lighting Best Practices Guide. Indoor facilities retrofitted to LED lighting may need to be air conditioned less than rooms using HID lights, and greenhouses switched to LED may have to provide additional heat, depending on targets for environmental conditions. When HVAC loads change under LED lighting, plants transpire differently and it can be helpful to change watering controls as well to address overall interactive effects.

Recommission Your Equipment - Continue to verify that installed equipment is operating according to your design documents. You can use mounted or handheld sensors to field verify the performance of your systems and calibration of thermostats after the project team is gone. Some growers use thermal cameras or infrared thermometers to measure canopy temperature, as well as handheld hygrometers for spot measurements of grow room temperature and relative humidity. For mounted sensors, it is typically the same sensors used to control the equipment, but with a nice user interface for growers to monitor.

Ask for Guidance - Growers unfamiliar with some root causes of HVAC issues may experience challenges when trying to rectify them in cultivation spaces. Talk with growers that have similar HVAC systems to yours and benefit from their experience to move quickly up the learning curve. This is where the Resource Innovation Institute can help. Attend Efficient Yields, our grower education events, and workshops led by RII subject matter experts to learn from our industry network of manufacturers, designers, and installers. Join our grower network to connect with other cultivators and get your questions answered.

Figure 15: Trend of Environmental Data from CEA HVAC System



Tweak and Peek - Adopt a 'tweak and peek' approach to observe how your plants respond to changes including new HVAC equipment or setpoints, controls, and growing approaches. Work with your engineer and contractor to understand what setpoints you can adjust as you 'get to know' your new HVAC systems. Tuning your facility requires adjustments to many elements of your cultivation approach, including grow room temperature and relative humidity setpoints. Observe how your plants respond to new targets after making changes and before you make any more. An open and curious attitude is necessary for you to adjust your cultivation activities to match the needs of your plants. Figure 15 shows a trend of evapotranspiration in an indoor growing environment for every hour of a three-day period, and demonstrates the cumulative total moisture removed by dehumidification equipment. Track historical trends of climate information to see how plants behave during day and nighttime periods and after watering events.

Make One Change At A Time - Alter parameters like temperature and relative humidity individually and incrementally and document what changes you made and when, and for how long with both notes and pictures. By understanding the changes you make and their interactive effects, you can make more informed observations on what impact your adjustments are having on your plants before making multiple changes at once. Regularly record adjusted factors to benchmark your operation as you make changes. Record data over time to establish trends.

Monitor Airflow - Monitor and manage airflow effectively to break through the boundary layer of the plant without causing undue plant stress. Assess if field-measured airflows align with readings from your final balancing report and design drawings. Install more sensors to monitor more of your cultivation spaces. Every grower should own a hot wire anemometer. They are crucial to airflow management inside a controlled environment. All CEA crops should have a minimum of 50 FPM of flow at their crop level in order to maximize photosynthetic rates. Some CEA crops need even higher flows of 150+ FPM to reach their maximum productivity.

Control for Indoor Environmental Conditions - If you are looking into changing out filters, assess the MERV rating and pressure drop associated with the various filter choices to understand if they are appropriate for your operation. Higher MERV filters will require more fan power (energy) and may require more frequent changeouts (or maintenance) to meet energy consumption goals. Also, a loaded filter can greatly affect the effectiveness of an HVAC system, so change filters at the proper intervals as recommended by the manufacturer in your O&M manuals.

IMAGE: COLLINSCEA

Continue Optimizing and Maintaining Your Equipment - Manage your HVAC controls strategy with your controls contractor to fine-tune your new systems to operate more efficiently or address issues that were not resolved in construction. Re-read your final commissioning report to prioritize remaining issues and follow up with your engineers and controls contractors if you are unsure about the best path to resolution. HVAC equipment in indoor cultivation facilities experiences high loading and long run times. To ensure reliable and efficient performance, regular preventative maintenance should be performed by a qualified contractor.

Measure Facility Efficiency and Productivity

You can use a variety of metrics to track the success of your business. Tracking efficiency can complement measuring productivity and quality of the crops grown in CEA facilities.

Ask for Guidance - Talk with growers that use high-performance HVAC solutions and automated environmental controls and benefit from their experience to move quickly up the learning curve. Read case studies to understand how facilities like yours adjust Standard Operating Procedures to optimize facility performance. Join our network of CEA producers to connect and collaborate with other cultivators.

Continue Learning - Best practices continue to emerge for greenhouses and indoor farms growing food, floriculture, and medicinal crops. Access the RII catalog to attend live workshops, and watch recorded webinars and Tip Clips featuring subject matter expert speakers. Learn from our industry network of growers, equipment manufacturers, architects, designers, and construction professionals.

PowerScore

Benchmark and Compare - Calculate key performance indicators that matter most to your operation. While canopy productivity may be the greatest driver of revenue, resource efficiency and productivity affect your bottom line by impacting operational expenses. Benchmark your CEA facilities with RII's PowerScore resource benchmarking platform to measure and track the year-over-year trends in environmental KPIs for energy, water, and emissions. Figure 16 right shows a Performance Snapshot for a vertical indoor facility, comparing two years of facility data. Examples of KPIs PowerScore calculates include HVAC Efficiency (measured in units of energy consumed per day) and Canopy Productivity (measured in units of biomass per unit of canopy area).

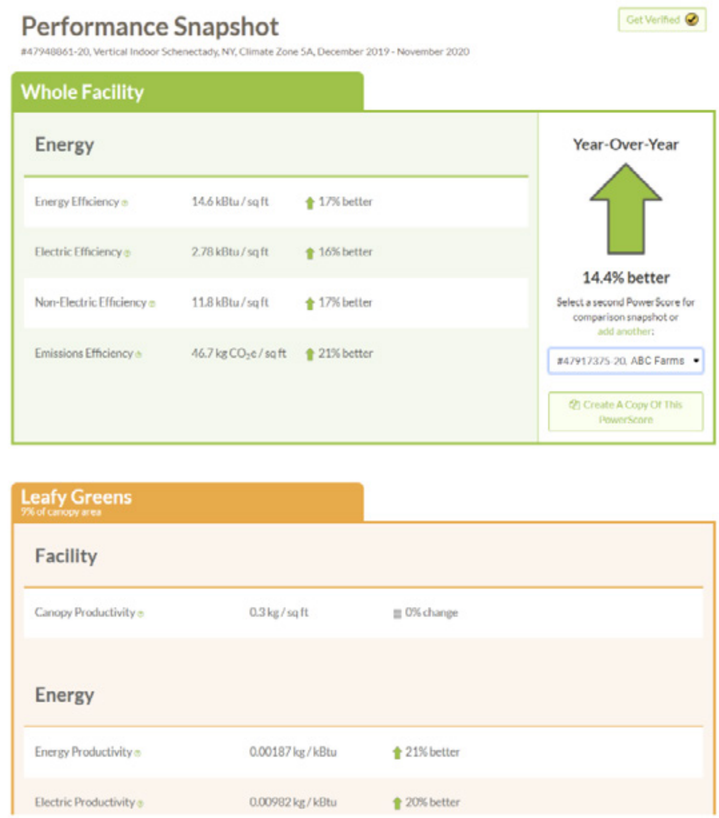


Figure 16: PowerScore Performance Snapshot and Lighting Key Performance Indicators

Acknowledgements

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Resource Innovation Institute is an objective, data-driven non-profit organization whose mission is to measure, verify and celebrate the world's most efficient agricultural ideas. RII's PowerScore benchmarking platform enables producers to gain insights about how to reduce energy and water expenses and improve their competitive position. RII's performance benchmarking service, the PowerScore, enables cultivators to gain insights about how to reduce energy expenses and improve their competitive position. Resource Innovation Institute is funded by foundations, governments, utilities and industry leaders. For more information, go to ResourceInnovation.org.