RESOURCE INNOVATION INSTITUTE

Best Practices Guide
Facility Design & Construction

for Controlled Environment Agriculture (CEA) Operations

A Best Practices Guide for CEA Producers

JUNE 2022

In Partnership with

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 producer operating in a constantly evolving industry, **you may feel like it is hard to know who to trust.** The indoor farming market is dynamic, technology is advancing, and there are complex terms to know for every strategy. It can be hard to navigate the design and construction process and challenging to understand how to plan a highly productive and resource-efficient facility.

We are here to help. As an objective, data-driven non-profit organization, Resource Innovation Institute measures, verifies, and celebrates the world's most efficient agricultural ideas. 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 food or floriculture 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 in controlled environments.

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 resource-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.

COVER: CERES GREENHOUSE SOLUTIONS THIS PAGE: ROB EDDY

Purpose

IMAGE: LUDVIG SVENSSON

Growing food and floriculture crops can be intuitive, but designing and building high-performance greenhouses and indoor farms efficiently and effectively requires specialized expertise.

The purpose of this Facility Design & Construction Best Practices Guide is to support you, the producer, and your design and construction partners with:

- Speaking the language relevant to greenhouses and indoor farming facilities
- Understanding types of CEA facilities that optimize environments for crop health and vitality
- Planning your greenhouse or indoor operation for efficiency and productivity
- Designing facilities for low-maintenance and autonomous operation
- Building solutions in alignment with your business model
- Demonstrating energy savings for utility energy efficiency incentive programs

Demystify Terms

Throughout this guide, you will learn key terms related to optimizing the design and construction of facilities for food and floriculture for plant growth and development. Greenhouses are planned and built differently than indoor farms, and use different systems to maintain desired conditions. It is important to consider how key terms are used and how the terms may be commonly misunderstood or misapplied.

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, hardware manufacturers, suppliers, systems integrators, data aggregators, controls contractors, commissioning agents, and utility and efficiency program administrators.

The glossary companion to this guide defines these design and construction terms and more:

- Retrofits
- Programming
- Modeling
- Commissioning
- System Integration
- Operations & Maintenance
- Benchmarking

Consult our online glossary of key CEA Facility Design & Construction terms to expand your horticultural project vocabulary.

To understand the interactive effects between your lighting and HVAC systems, check out our HVAC Best Practices Guide for Controlled Environment Agriculture (CEA), which covers the heating, ventilation, air conditioning, and dehumidification terms and systems used for cultivation environments. 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 July 2022.

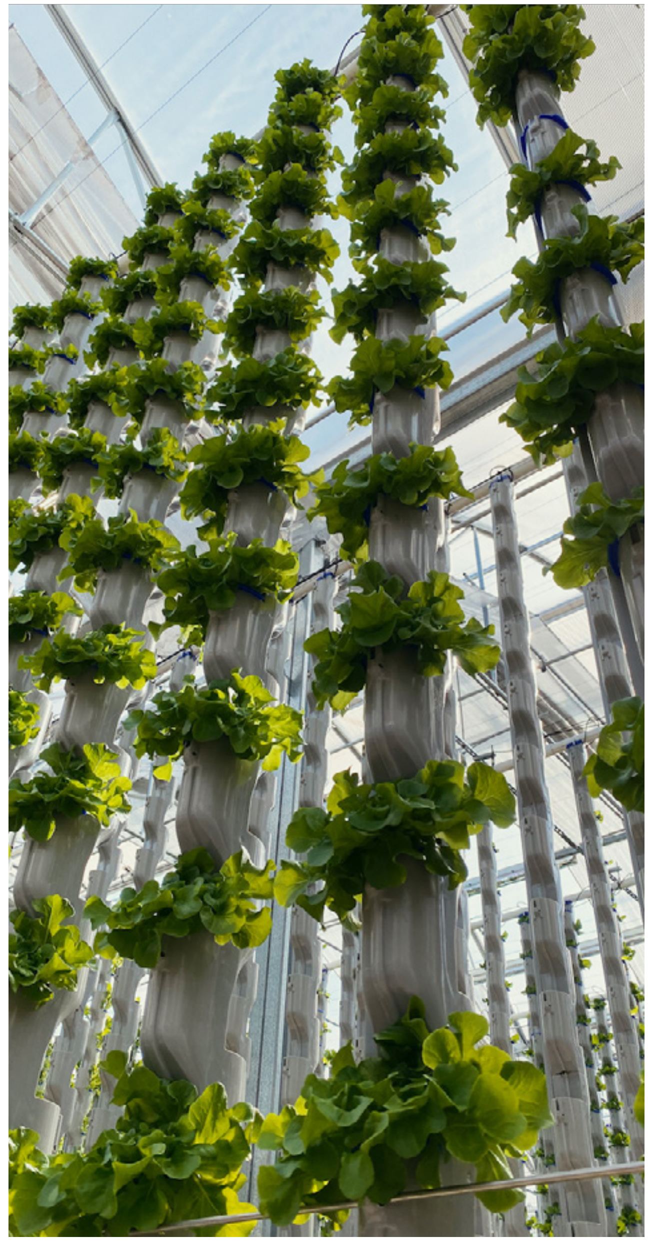


IMAGE: EDEN GREEN TECHNOLOGY

SECTION

01

Optimize CEA Facilities for Productivity and Efficiency

IMAGE: ROB EDDY

High performance CEA facilities can maximize production and minimize operating costs. In the U.S., capital expenditures for building high performance CEA cultivation operations vary widely based on cultivation approach and project type. Limited capital means understanding the return on investment of efficient strategies is even more crucial.

Resilient producers plan for competition by reducing operating expenses in design. Designers and manufacturers have solutions purpose-built for cultivation that have integrated the lessons learned from diverse commercial and industrial applications.

Project partners can steer CEA facility planning in the right direction. High performance CEA facilities reduce operating costs with efficient and automated HVAC, lighting, and water management systems that can generate energy savings of up to 50%[1] over traditional approaches. Strategic energy management practices offer a systematic structure that can generate annual energy savings of up to 30%[2].

Poor facility design and construction limit productivity and efficiency. The CEA industry is competitive, information is not readily shared between producers, and rules of thumb for design are not widely available. There are diverse strategies and many types of equipment you can use to accomplish your goals.

Varying requirements of crops can be addressed by thoughtful design. Choices during planning can be affected by crop-specific standards, and design teams are the experts in determining what codes apply and what elements of facilities must comply. Avoid schedule delays from permitting and code issues with good planning.

In the following sections, you will learn how design and construction of 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.

Determine CEA Facility Approach

Cultivators are motivated to grow in greenhouses and indoor farms to maximize profitability while minimizing operational expenses. Understand the key performance indicators and targets for producers to select the appropriate facility approach.

Many diverse products are created in controlled environments. At the start of this journey, producers and their 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.

Vegetables and Herbs

Vegetables like peppers and herbs like basil are grown in greenhouses and indoor vertical farms. Leafy greens are grown in both greenhouses and indoor facilities, while microgreens are generally grown only in indoor farms. Dwarf determinate tomato varieties are grown in greenhouses and are starting to be cultivated indoors.

Floriculture

Nursery crops (young plants), cut flowers, and finished crops (bedding plants) are often cultivated in greenhouses or outdoors.

1 Controlled Environment Agriculture Market Characterization Report: Supply Chains, Energy Sources and Uses, and Barriers to Efficiency, Resource Innovation Institute, 2021

2 Making Permanent Savings through Active Energy Efficiency, Schneider Electric, 2011

Mushrooms

Mushrooms are primarily commercially cultivated indoors. Some greenhouses cultivate mushrooms under benches and grow vegetables or other crops above them.

Berries

Strawberries and other berries have historically been grown in greenhouses and high tunnels but are starting to be cultivated indoors. Dwarf blueberry and caneberry cultivars have been developed to be suitable for CEA cultivation.

Just like any manufacturing process, cultivation in controlled environments comes in multiple different forms. Cultivators use distinctly different buildings to cultivate a variety of crops, and sometimes facility choice correlates with facility location, resource availability, real estate prices, climate zone, crop, and final product. Each method has different pros and cons for businesses.

The three most common CEA cultivation approaches are:

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

The images right and **Table 1** describe the three major methods of growing and the ways operations may find value in diverse facility and system approaches.

IMAGES FROM TOP TO BOTTOM: CONSUMERS ENERGY, SIGNIFY, PETR MAGERA

Table 1: Benefits of Controlled Environments

	Traditional greenhouse	Advanced greenhouse	Indoor vertical farm
CEA Value Proposition	Extend growing seasons and improve productivity over field farming	Maximize benefits from sunlight while optimizing and automating environmental control	Comprehensively control all inputs for plant growth and development to outperform greenhouse productivity
Common Facility Priorities	Building envelope, heating, ventilation	Building envelope, controls	High-tech, data-rich MEP, lighting and other systems
Common Structural Approaches	Low-insulation coverings, long spans	High-performance enclosures with perimeter insulation, long spans	Structure to support MEP systems
Common Enclosure Approaches	Vented coverings & high light transmittance glazing	High-insulation coverings and sealed envelopes with high light transmittance glazing	Highly insulated and tightly sealed building envelopes
Common Interior Approaches	Shade and thermal curtains	Moving benches, racking, multiple shade and thermal curtains	Finishes, racking

CEA operations can range in size depending on facility type.

Table 2 right describes the range of canopy area for greenhouses and indoor farms in the U.S

Table 2: Canopy Area of U.S. CEA Facilities

Facility Type[3]	Minimum Canopy Area (square feet)	Median Canopy Area (square feet)	Maximum Canopy Area (square feet)
Greenhouse	13,500	348,000	5,000,000
Indoor	5,000	60,000	280,000

Assemble CEA Project Teams

Teams of professionals help producers make planning decisions and get facilities operational on schedule and within budget. Design and construction experts can also influence purchasing decisions depending on the type of project. Effectively gather project teams together frequently to achieve goals for CEA facility productivity and efficiency.

Experts on CEA project teams help producers determine facility approach, like what type of greenhouse, or how many tiers to grow vertically. Your project team may be big or small, depending on the size and scope of the project you are planning for your operation. Figure 1, right shows an example project team for designing and building a new CEA facility. For new construction or a major renovation project, you should consider having the following members on your team, or at least consider having someone to fill the following roles:

- You, or your Owner's Representative
- Your Head Grower
- Your Architect
- Your Engineer(s)
    - Agricultural and Biological
    - Civil
    - Structural
    - Mechanical (includes Plumbing)
    - Electrical
    - Horticultural Process
- Your Energy Modeler
- Your Utility or Efficiency Program Advisor
- Your Construction Manager and/or General Contractor
- Your Equipment Suppliers / Manufacturers
- Your Subcontractor(s)
    - Mechanical
    - Electrical
    - Plumbing
    - Air & Water Balancing
    - HVAC Controls
- Your Commissioning Agent(s)
    - Building Envelope
    - Mechanical, Electrical, Plumbing & HVAC Controls

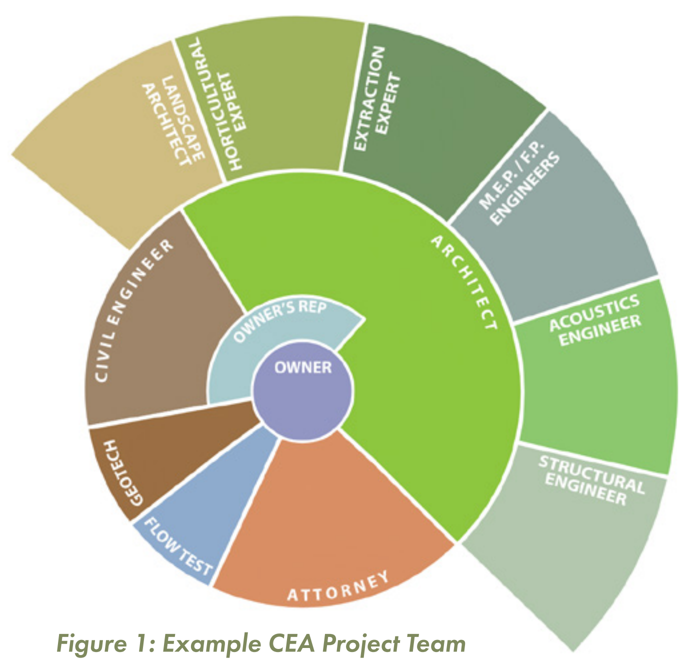


Figure 1: Example CEA Project Team

IMAGE: ANDERSON PORTER DESIGN

[3] Controlled Environment Agriculture Market Characterization Report: Supply Chains, Energy Sources and Uses, and Barriers to Efficiency, Resource Innovation Institute, 2021.

Determine Who You Need - State and local requirements and zoning must be considered when building a new greenhouse or indoor facility. Indoor facilities more often require an architect as part of the process, and sites in light industrial zones may require design professionals to stamp drawings. Smaller facilities may be able to move forward with a leaner team, while larger operations often require comprehensive and integrated teams with more specialized roles.

Select Your Professionals - Ideal professionals selected for your CEA project team convey an understanding of the dynamics of CEA facilities. They empathize with the unique needs and solutions of growers and are able to translate their needs into construction terminology. The landscape of CEA professionals has expanded as producers engage more specialized partners. Experienced CEA professionals can plan projects in a way to allow phased growth during operation without creating conflicts with operational activities or blocking future development. The CEA industry values working with subject matter experts as greater availability of education specific to CEA (like this guide) help growers employ more purpose-built equipment.

Establish Roles and Scopes - Teams can successfully complete projects by using a lean project delivery[4] approach, as shown in Figure 2 below. Describe roles and document dependencies between roles for effective communication down the road. For the smoothest process, consider assigning a lead designer (generally an Architect, but sometimes an Engineer or a General Contractor) as the main point of contact for all design team members, including equipment suppliers and manufacturers. Greenhouse projects may use the greenhouse manufacturer as the lead design-builder allowing for a level of standardization. Select the members of your project team based on their expertise relative to cultivation applications. Consider using qualified and experienced designers, consultants, and contractors in your region to receive local customer support. Request case studies and references to qualify the experience of your designers, consultants, and contractors.

Figure 2: Lean Project Delivery System Phases

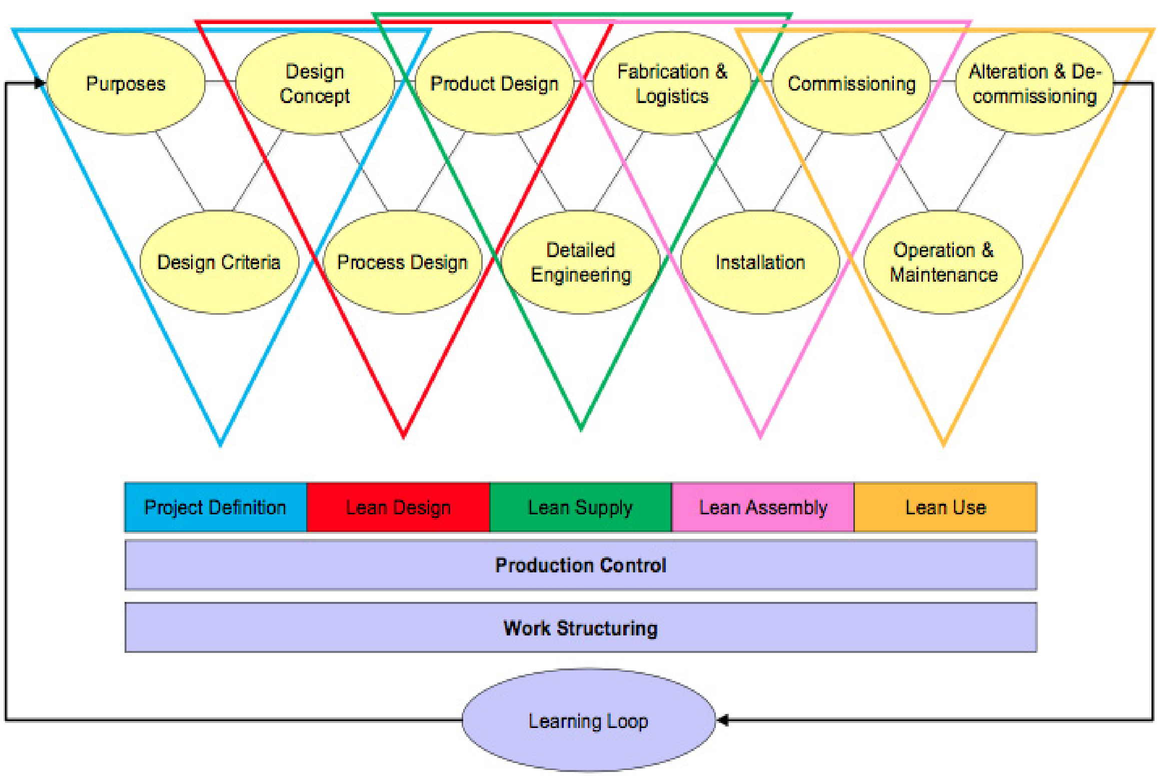


IMAGE: BALLARD, G., 2008, 'THE LEAN PROJECT DELIVERY SYSTEM: AN UPDATE', LEAN CONSTRUCTION JOURNAL.

4 Ballard, G., 2008, 'The Lean Project Delivery System: An Update', Lean Construction Journal.

Be Recognized for Excellence - Credentialing for CEA professionals is an emerging opportunity as the industry becomes more established with increasing engagement from key industry actors, like energy efficiency programs, who may use credentialing for funding and approval processes. Design and construction professionals with experience on CEA projects and continuing education to build their expertise can soon be recognized as a specialist in CEA through RII's CEA Excellence Network. Credentialing offers an opportunity both for professionals to be recognized for their knowledge and producers to recognize who to add to their team based on project experience and training. Other programs recognizing CEA professionals include the Certified Crop Adviser program by the American Society of Agronomy.

Assemble Early - Engage with team members early in the planning process to establish scopes and responsibilities. Working collectively from the start allows your team to have a better understanding of the project and interactive elements of their scopes of work. By engaging early and frequently, issues can be identified and resolved in the design phase rather than later in the construction or occupancy phases, when resolution is much more expensive and/or disruptive.

Integrate and Collaborate - To improve team coordination and communication, get critical design questions answered as early as possible, ensure code requirements are satisfied and employ a collaborative integrated design approach to affect the greatest changes to your facility's operational efficiency and associated environmental impacts. These strategies can maximize operational efficiency and lower the costs of your project. An integrated design team works together early and often throughout a project's planning, design, construction, and occupancy phases to execute a project to its maximum potential.

Describe CEA Projects

New construction and retrofitting existing buildings present unique challenges for producers seeking to maximize production and efficiency in controlled environments. To meet project deadlines, understand applicable codes and standards and prepare for critical activities like permitting, procurement, and commissioning, all of which can have different requirements for new and existing buildings.

Throughout this guide, best practices will be recommended for designing and constructing three major project types. There are several main design and construction project types focused on optimizing plant growth and productivity:

- New Construction: new buildings and structures; includes new buildings and structures which are constructed as additions to existing buildings and structures. Can include Major Renovations.
- Retrofitting Facilities: renovation and refurbishment of existing buildings to change building use type as well as improve production and energy performance. This may be referred to as repurposing or "adaptive reuse".
- Retrofitting Systems: installation of new or modified equipment in an existing system or building to upgrade to new technology.

New construction, change of use, additions, alterations, and repairs can each trigger different code requirements for energy or safety depending on facility location, project scope, and affected systems. Projects in CEA facilities may include multiple project types as defined by the building code. For example, a warehouse building can be retrofitted for cultivation and processing activities (change of use), and existing HVAC and lighting systems can be retrofitted to serve plants, meet new loads, and reduce operating expenses (alterations). Depending on the scope of the project, the same requirements as new construction may be triggered, or existing building-specific provisions may apply.

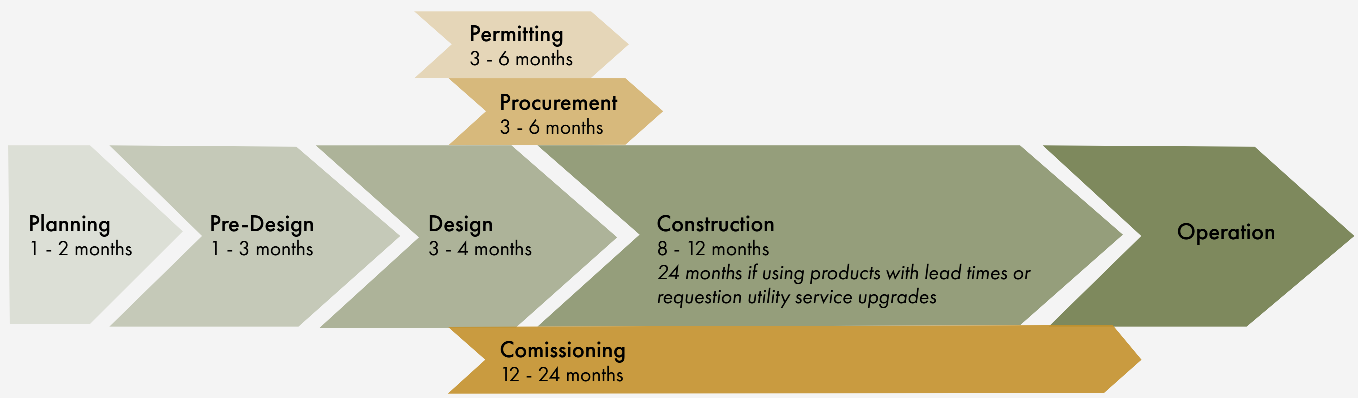
To understand what project types are most prevalent for CEA producers, Figure 3 shows an example of the various phases and activities you may undertake as part of a design and construction project. Actual scopes and timelines will vary by project type and material or resource availability. CEA producers and their project teams will need to make several critical decisions throughout these phases, each of which can significantly impact the ultimate performance of the building:

- Planning
- Pre-Design and Programming
- Design
- Permitting
- Procurement
- Construction
- Operation

For both retrofits and new construction projects, there are several considerations and dependencies to keep in mind.

Define Goals - The Owner's Project Requirements (OPR) is the single most important document to guide design development for an existing or new cultivation facility. An OPR defines the Owners' goals, objectives, and performance metrics and is developed by the owner (not your design team). Creating an OPR should be one of the first items on your to-do list when planning a project. Define what success looks like for your facility and your parameters for success before ending the pre-design phase. Describe the environmental conditions you would like to achieve and elaborate on energy efficiency goals and how you would like the project to accomplish them.

Figure 3: Example CEA Project Scopes and Timelines



Classify - Classification impacts both new construction and retrofit projects. During the design phase, determine building classification to understand how building and energy codes apply to your facility. Building classification can be influenced by the hazards presented by materials and products used inside the facility. Greenhouses are often classified as U (Utility), but advanced greenhouses are considered F-1 (Factory), similar to indoor farms. Some crops, grow media or other material used in controlled environments may be determined to be a fire risk due to their flammability. Note that industry organizations have created definitions[5] for CEA spaces in energy standards for buildings.

Design Right - Before you build or renovate, consider the basis of your facility design so that you can optimize the efficiency and impact of your decisions. A *basis of design* is the foundational design document and is developed by your designers to inform you how they intend to achieve the criteria laid out in your OPR by specifying and describing the systems that can meet your expectations. The OPR document can also be used by the general contractor or others on the project team to help estimate or validate the project cost and schedule early in the process. Ideally, this document is a living document that is updated as the design progresses.

5 BSR/ASHRAE/IES Addendum ar to ANSI/ASHRAE/IES Standard 90.1-2019 defines greenhouse as "a space with a skylight roof ratio of 50% or more above the growing area used exclusively for, and essential to horticultural production, cultivation or maintenance by using a sunlit environment. Greenhouses are those that are erected for a period of 180 days or more." Indoor grow is defined as "a space, other than a greenhouse, used exclusively for, and essential to horticultural production, cultivation or maintenance."

Define Scope of Work - Quantify and qualify the scope of new work involved in your renovation, retrofit, or new construction project. When working with existing buildings or upgrading an existing piece of equipment, describe the current conditions. Your design team can help you write *project specifications* which detail the requirements of every system in the facility that is relevant to your new facility or renovation, at a more granular level than your design drawings can often communicate. Design drawings cannot include all necessary information: the design documents are incomplete without clear, comprehensive specifications that ensure the project achieves the OPR.

Document KPIs - In your facility, some criteria you may care about include key performance indicators (KPIs) relevant to profitability, sustainability, and operational efficiency. In the BOD process, help your design team translate the cultivation KPIs to design criteria related to their scope of work. As you may not be able to do that alone, working with a Horticultural Process Engineer could help you connect the dots.

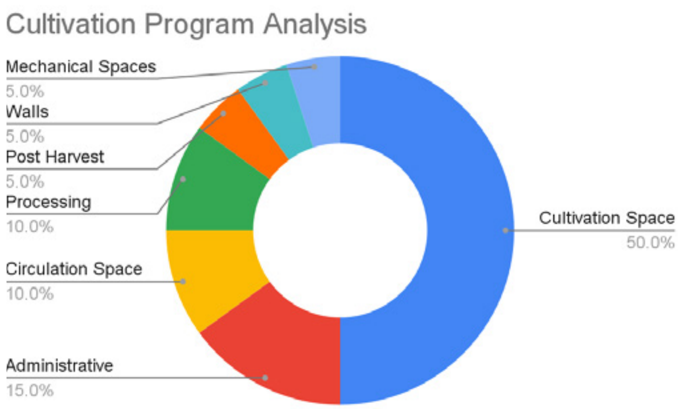
Engage Utilities - Consider the mission-critical services required for facility operation, like power, water, and fire protection to anticipate potential budget and schedule impacts. Requests for expansions and interconnections of utility services can take months to schedule and years to complete in some areas of the country. Regions with constrained water resources may impact maximum supply of source water for cultivation, so your water storage and circularity strategies may be important depending on where you grow. Building safety codes are enforced by *authorities having jurisdiction (AHJs)* who inspect whether sprinkler systems or other fire protection strategies are in compliance. Work with power, water, and fire utility representatives early to get on their schedules, understand their requirements, and minimize capital expenditures for service requests.

Get Efficiency Help - Efficiency programs offer technical assistance and incentives for high-performance technology and to help customers save resources like energy. Energy infrastructure equipment often requires coordination with utilities and efficiency programs. CEA cultivators face unique barriers to efficiency such as high upfront costs, need for capital and financing, general lack of understanding of efficient technologies, lack of trust in product performance, and limited connections to qualified professionals for efficiency projects. Early in the design phase, work with your project team to identify which efficiency programs serve your project location and connect with programs to receive support throughout design, construction, and operation. Throughout this guide, opportunities for efficiency program support of efficient facility design & construction practices will be highlighted with **bold green** text so your project team can work with your local programs to get technical assistance, financial incentives or financing for installing high-performance CEA facility solutions.

Program Spaces - Understand the ways facility spaces will be used for cultivation and non-cultivation activities. *Programming* maps out the core activities happening in a facility and describes the corresponding floor area dedicated to those activities. Members of your design team like architects can share program analysis like the example in Figure 4 on the next page explains how space is utilized to support maximum production within the facility footprint.

Calculate Grow Area - *Cultivation space* describes the facility area dedicated to cultivation activities like propagation, nursery, or finishing; each can have their own design considerations. Within those cultivation areas, there is a portion taken up by plants, which is described as *canopy area*. The space taken up by aisles and walkways within cultivation spaces does not contribute to production but is included in *cultivation space* program analysis. Figure 4 on the following page describes a program for an example CEA facility that has 50% of floor area used for cultivation processes. Some CEA operations like greenhouses may have more space devoted to cultivation and achieve 70% bench area with at least 15% reserved for a headhouse. To maximize canopy area, the non-cultivation areas of a greenhouse or indoor farm should be described in detail to establish how they support production and the human side of CEA businesses. When maximizing canopy area, consider dimensions of benches and racks; you still need to be able to access every part of the bench from all sides.

Figure 4: Example CEA Facility Program Analysis



Iterate Designs - Your design team helps you communicate the Scope of Work to your contractors through Construction Documents (CDs) which include schedules of equipment, design drawings, details, and specifications. Get your general contractor (GC) on board by the end of schematic design (at around 30% design drawings). At 60% design, your GC can issue a new pricing set and it is crucial to bring on your commissioning agent. Throughout design, your project team will stick to your budget by value engineering different decisions against each other. Cost revisions can last up to 12 months. Communication and a commitment to teamwork between the design and construction teams are essential to a successful project.

Commissioning: Quality Assurance for New Construction and Retrofits

Commissioning activities confirm that the final construction and installation and programming of equipment meet the original design intent and owner's project requirements for the facility. Commissioning agents are crucial members of CEA project teams and can act as owner's representatives throughout all phases of projects. Involving the commissioning agent before design completion is ideal for the best results. Ideally, the documentation of commissioning objectives is shared by members of your project team, such as your designers, contractors, and commissioning agents. While commissioning can be the last step of the construction process and thus under pressure to make up for delays, It's important to give the commissioning process the time it needs to be done properly. Your project's commissioning team conducts the following procedures throughout the design, construction, controls programming, and project completion to confirm that the facility meets the original design intent for the facility goals using the following basic process:

1. Review **Owner's Project Requirements** (OPR) created by owner/operators to ensure parameters are defined.
2. Assist design team with creating the **Basis of Design** (BOD) to ensure information from the OPR is included and properly addressed to meet the needs of your facility.
3. Develop a ***commissioning plan*** that establishes the framework and communication protocol for commissioning activities and issues management.
4. Perform ***design review*** of drawings produced by the project team to ensure construction documents align with the OPR and BOD. Identify issues with building system designs and offer suggested adjustments to accomplish the goals of your facility's design or renovation scope of work.
5. Review equipment ***submittals*** to verify that equipment to be purchased meets the intent of the design team's drawings and the project specifications.
6. Create ***prefunctional checklists*** (also referred to as system readiness checklists) and visit new equipment installed in your facility to run through checklists and validate that each system is prepared for functional testing.

7. Create ***functional performance tests*** to run new equipment through its paces. Work with controls contractors to witness and record all functional tests to verify that equipment is operating as the design team intended and therefore meets the OPR established in the beginning of the project.
8. Create staff training agendas to reflect the Owner's priorities and ensure proper operation of equipment so your facility can achieve intended operation and energy performance.
9. Produce a ***final commissioning report*** summarizing issues identified in the design and construction phases, as well as any outstanding issues to be resolved by the owner and other members of the project team.
10. Ensure that Contractors have provided ***operations and maintenance (O&M) manuals*** for engineered systems in the building to provide reference materials for owners and operators to ensure a full understanding of the equipment, building performance metrics, and final sequences of operation.

Plan for Permitting - Avoid delays on project or permit approval which present a costly risk to CEA projects. Understand what is required of indoor cultivation facilities in your jurisdiction and make connections with planning and permitting teams early, an existing relationship helps the process run smoothly. Working with a project team that has experience with this process will ease the learning curve. Design activities should be coordinated with permitting activities so drawings are *Issued for Construction (IFC)* at the same time as the building permit is approved. When design reaches 70%, it is important to initiate permitting activities, which overlap the design and construction phases of projects. Permit submissions for your facility's structure and systems continue throughout 90% design.

Align with Code - Before you receive your building permit, your facility's design may be required to satisfy certain performance requirements aligned with local codes. Incorporate local requirements into your basis of design so time is only spent evaluating equipment or approaches that will be approved. Consider these requirements well ahead of the permitting stage so construction can stay on schedule. If you install a new facility system before receiving permits, you may have to call in an engineer to retroactively design the system to align with code and take responsible charge, which allows you to receive your building permit. If your chosen and installed system doesn't meet the energy code or other jurisdictional requirements, you may be required to make significant changes to your newly installed system in order to get your facility completely permitted.

Order Early - Smart project teams make design decisions to support delivery of materials so construction starts and finishes on time. Supply chain issues can affect operation and production schedules, and their impact fluctuates and varies by building component. Start ordering mission-critical materials after submitting your building permits. Long lead materials such as steel, aluminum, PVC, and electrical infrastructure equipment like switchgears must be ordered before design is complete in order to avoid schedule impacts from delayed shipments or low supply. Specialized equipment may take longer to be custom-built. If the equipment you are ordering is part of a rebate or incentive program be sure to time orders appropriately with the application and approval process. Read more about preparing your project team for schedule impacts of materials procurement starting on page 31.

Schedule Construction - CEA facility buildout timelines are a function of your site, project type, and business goals. RII Technical Advisory Council members caution that projects can have construction phases 24 months in duration if using products with long lead times or requesting utility service upgrades. In certain locations it can be important to consider climate and weather, as greenhouses can be challenging to construct in colder climates in winter and in warmer climates in summer.

STEP 1:
Design Phase Commissioning
Timeframe: months - can seamlessly connect to construction phase commissioning

STEP 2:
Begin Construction

STEP 3:
Startup
Timeframe: days

STEP 4:
Configuration
Timeframe: weeks

STEP 5:
Construction Phase Commissioning
Timeframe: months - can seamlessly connect to design phase commissioning

STARTUP, CONFIGURATION & COMMISSIONING: KNOW THE DIFFERENCE

Understanding the differences between ***startup***, ***configuration***, and ***commissioning*** to assess the value of these activities for your business is important.

- ***Startup*** activities result in a warranty from equipment manufacturers based on a complete startup checklist. Startup is usually performed by manufacturer representatives or your construction contractors once equipment arrives on site, is connected to power, and is turned on for the first time.
- After your mechanical and electrical contractors start up equipment, they or your dedicated controls contractors configure the sequence of operations and program your systems to function as designed. ***Configuration*** reports describe completed programming and inform commissioning activities.
- Ideally, ***commissioning*** occurs throughout design, construction, and operation phases. Pre-functional checks validate installation before, during, or after start-up and configuration. Once programming is complete, your commissioning agents and controls contractors test your systems' functionality, performance and their associated controls to run equipment through its paces to ensure it responds as designed.

For example, if you install new HVACD equipment in your cultivation operation without commissioning, you might get startup and configuration support from your mechanical and controls contractors. But with commissioning, your Cx agent will validate controls sequences for all scenarios and simulate emergencies to confirm your system responds to feedback from grow rooms, can meet target setpoints, and will maintain conditions for your plants during equipment failures.

Commissioning logs are provided along the way to track progress and identify issues and their proposed resolutions. Final commissioning (Cx) reports document all resolved and outstanding issues so you know what was fixed and what still needs attention.

IMAGE: GIE MEDIA

SECTION

02

Design High-Performance CEA Facilities

IMAGE: VERTICAL HARVEST FARMS

Design teams help producers estimate the productivity and efficiency potential of new construction and retrofit projects. Designers and engineers can use industry benchmarks and facility information to calculate design benchmarks and generate key performance targets for CEA facilities.

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 air handling units and ductwork take up space in your growing 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.

Consider System Synergies - Planning your processes, equipment, and organization to take advantage of natural synergies can be an advantage. Waste heat or CO_2 from one system or process may be of benefit to another system of process. If not considered, you may find yourself with systems underperforming due to conflict with other processes of operations.

Leaks are Loss - An airtight facility keeps energy, in the form of heat and moisture, where it is desired. It can also keep out contaminants from outside air. Even for traditional greenhouses that take advantage of venting, airtightness can be an advantage, controlling where and when that outside air comes in and the path it takes through the facility. The level of challenge of achieving airtightness varies depending on the nuances of the facility design or retrofit project. Air leakage can result in heat, cold, moisture, or contaminants at the point of infiltration, creating microclimates and even a potential access point for pests and disease.

Air Barrier - In sealed facilities, the air barrier is often discussed related to airtightness and is vital to maintaining consistent conditions throughout the space. Best practices for efficient building design is to have a continuous and intentionally designed air barrier. This can be especially important outside of mild climates where movement within the structure due to hot-cold cycles and humidity changes outside may result in damage to the air barrier if not designed with this potential in mind.

Control Moisture - Sister to the air barrier is the vapor barrier, these may be the same as the air barrier or not, depending on if moisture can travel through the air barrier. Consider the materials used in your facility and how they may react with changes in moisture for example, insulating masonry walls on the interior of a high humidity space in cold climates can cause the walls to go through freeze-thaw cycles that can damage them over time.

No Bridges - Thermal bridging is caused by a conductive material allowing heat to pass through a building's exterior wall, ceiling, or floor. They are especially common at joints, intersections, supports, and corners. A thermal bridge can mean a cold or hot surface inside your building, which can make controlling consistent conditions difficult and a cold interior surface can cause condensation to form, leading to rust, mold, and other issues.

Plan for Resource Availability - Not all regions are the same in regards to access to water, electricity, and natural gas. Some regions may have limited connections available or long wait times for certain services. Getting in touch with your utility provider early in the design process can help you plan your project around the availability and timing of resource service.

IMAGE: ROB EDDY

CEA Modeling Approaches

There are several kinds of standard practice for modeling CEA facilities for design benchmarks like annual energy consumption, energy savings from efficient technologies, peak electricity demands, and targets for crop yield:

- Poor: not using actual facility information to create design benchmarks
- Good: use industry benchmarks where available and adjust using actual facility information
- Better: use design benchmarks from past project experience and actual facility information to inform an estimate of performance metrics
- Best: use custom energy model to calculate performance metrics using 8,760 hours of typical operation

Model Best Practice - Members of RII's Facility Design and Construction Working Group find that 58% of CEA producers and their project partners currently follow 'good' modeling practices, while 25% of the market employ 'better' practices. 17% of the CEA industry is still following poor practices for modeling CEA facility performance. Understand the available modeling tools for CEA facilities to create accurate design benchmarks specific to facility and crop types.

Try USDA Tools - RSET is a USDA-funded tool that benchmarks resource stewardship and evaluates health of soil, water, air, and wildlife habitat. Resource Stewardship Evaluation (RSE) can be completed with your local NRCS office. Reports include operational benchmarks, goals, and planned measures to meet or surpass those goals. COMET - Farm is a USDA-funded set of tools developed in partnership with Colorado State University focusing on whole farm and ranch carbon and greenhouse gas accounting systems. Producers document current and planned future farm and ranch management practices used to generate a report comparing carbon and greenhouse gas emissions changes between them.

Use Virtual Grower - USDA Agricultural Research Service (ARS) released Virtual Grower in 2006. The most recent version of Virtual Grower (3.1) was released in 2014 and can calculate greenhouse energy consumption and cost using various design inputs. In 2022, Virtual Grower 4 will be released with new features[6] including modeling for plant factories (indoor farms), comprehensive weather analysis, more cultivar options (expanding beyond floriculture to vegetables and others), and more HVAC, lighting, and controls system types. Upgraded modeling outputs include heating fuel, electricity, demand, CO_2 enrichment costs, and side by side energy and financial cost-benefit analysis of efficiency upgrades. The tool will become available entirely online and files can be downloaded or saved in the cloud.

Try Light and Shade System Implementation - LASSI was developed by Cornell University in the 1990s for lettuce production in greenhouses using daylighting controls systems to maintain target daily light integral (DLI). The lighting model can help improve DLI uniformity and shift lighting to cheaper off-peak periods. The original algorithm was developed for HPS and has been adapted for LED lighting. LASSI provides cost-benefit analysis of lighting (e.g., LEDs) and controls (e.g., daylighting) upgrades.

Figure 5: Greenhouse HVAC System Energy Analysis

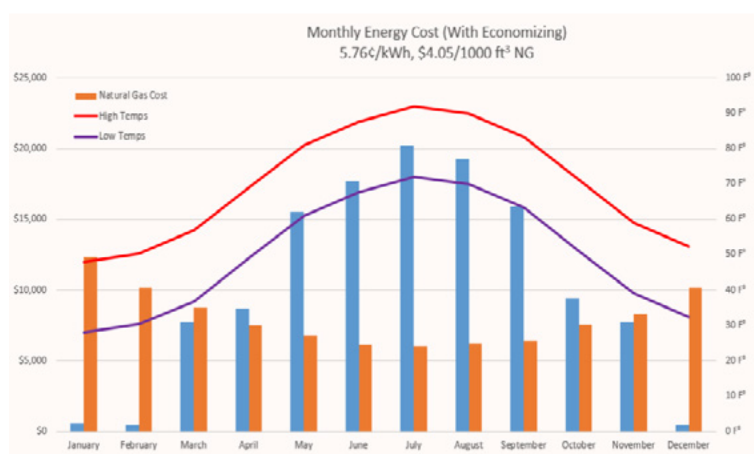


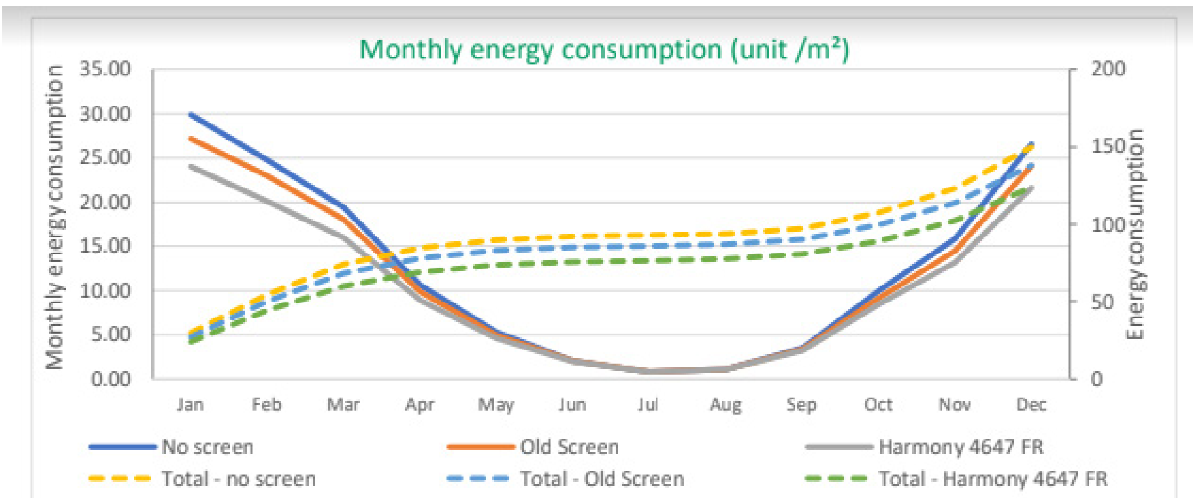
IMAGE: PROSPIANT AND ROB EDDY

[6] Light and Energy Modeling in Controlled Environment Agriculture webinar presented on November 19, 2021 by Dr. Kale Harbick (USDA-ARS).

Ask for Vendor-Specific Modeling Tools - Manufacturers and vendors are best able to calculate the performance outcomes of field implementation of their technology. Ask project partners to provide estimates of energy usage, as shown in Figure 5 on the previous page, which can demonstrate the potential energy use and cost impacts of various facility designs. Equipment providers can offer system-level analysis, as shown in Figure 6, to describe the energy savings potential of a blackout or thermal curtains, LED lighting, high-performance HVAC systems, and optimized sequences of operation

Consider In-House Versus 3rd Party Modeling - For some producers, it may make sense to DIY the modeling for their facility, while for others, it may be preferable to hire an outside firm to model the facility. While it can be less expensive to use in house labor, it can be time consuming to learn if you don't have the skillset in house. Hiring an outside firm for modeling may be more time efficient and result in a more thorough model that takes into account interactive effects of systems and design, which may be challenging for someone with less experience modeling for CEA.

Figure 6: Greenhouse Curtain Energy Analysis



MONTHLY SUMMARY

Table 1: Energy consumption (m3 gas/m²)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
No screen	29.9	24.8	19.4	10.6	5.3	2.1	0.8	1.1	3.5	10.0	15.9	26.6	149.8
Old Screen	27.2	23.0	18.1	9.9	4.9	2.0	0.8	1.1	3.3	9.1	14.5	24.1	138.0
Harmony 4647 FR	24.0	20.1	16.0	8.9	4.6	2.0	0.8	1.1	3.2	8.4	13.2	21.6	123.9

Table 2: Energy expenditure (US Dollars/m²)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
No screen	17.9	14.9	11.6	6.4	3.2	1.2	0.5	0.7	2.1	6.0	9.5	15.9	89.9
Old Screen	16.3	13.8	10.8	5.9	3.0	1.2	0.5	0.7	2.0	5.5	8.7	14.5	82.8
Harmony 4647 FR	14.4	12.1	9.6	5.4	2.8	1.2	0.5	0.6	1.9	5.1	7.9	13.0	74.4

Table 3:Energy saving (% / reference)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Old Screen	9	7	7	7	7	1	0	0	4	9	9	9	8
Harmony 4647 FR	20	19	17	16	13	5	0	1	8	16	17	19	17

IMAGE: SVENSSON AND UNIVERSITY OF VERMONT

Design Benchmarks

Prioritize KPIs - Project teams can work with producers to model facility design options to calculate the key performance indicators that matter most. As your team moves through the design phase, create and review your list of key performance indicators and document desired key performance targets.

Create Targets - Producers inform project teams of their goals for efficiency and productivity using key performance targets. Throughout the project lifecycle, there should be a back and forth of design teams estimating KPTs using information like maximum facility canopy area as an input for productivity calculations and producers assessing whether those KPTs meet their metrics for success. CEA project teams work together to balance inputs like length of season and time to harvest and resource consumption.

Benchmark with PowerScore - Resource Innovation Institute's PowerScore is a specialized resource benchmarking platform for controlled environment agriculture production facilities. PowerScore generates KPIs for resource efficiency and productivity of energy, water, emissions, and waste. The PowerScore platform accepts facility information in a variety of ways. To learn more about different cultivation approaches and how your facility performs compared to growers like you, visit resourceinnovation.org/powerscore. PowerScore's free service enables producers to enter self-reported data through the online PowerScore platform to get a Performance Snapshot sharing key performance indicators and measuring year-over-year changes in your facility performance.

Gather Necessary Data - To generate KPIs for CEA facilities, collect the following information: facility type, crops being grown, facility area, cultivation space area, canopy area, number of harvests per year, time to harvest by crop, annual production by crop, and annual facility energy and water consumption. Table 3 describes the typical time to first harvest for the major CEA crop types. Using this information, project teams can generate KPTs for facility efficiency and productivity.

Table 3: CEA Crop Growth Cycles

Crop Category	Crop Type	First Days to Harvest[7]
Vine Crops	Tomatoes	80 - 95
	Cucumbers	60
Vegetables	Peppers	75
	Leafy Greens	40 - 65
	Microgreens	7
Floriculture	Nursery and bedding crops	Varies
Mushrooms	Edible mushrooms	30 - 60
Berries	Strawberries	110

Compare Productivity - The USDA reports production of crops under protection, reporting canopy productivity of greenhouses, but the high limit of production from high-performance greenhouse and indoor vertical farming facilities is not yet widely documented. Design estimates for indoor vertical farms are not as widely available and baselines are not yet established for many emerging crops. Table 4 describes some canopy productivity KPIs for various CEA crops that can inform Owner's Project Requirements and be inputs for estimates of facility production.

Table 4: Example CEA Canopy Productivity Benchmarks

Crop	Annual Canopy Productivity8 (pounds / square foot / year)
Tomatoes	8.9
Greens	11
Cucumbers	9.0
Fresh Herbs	3.4
Peppers	5.0
Strawberries	2.0
Mushrooms	34

7 Schimelpfenig, G., Smith, D. 2021. Controlled Environment Agriculture Market Transformation Strategy and Implementation Plan. Portland, OR: Resource Innovation Institute.

8 USDA 2019 Census of Horticultural Specialties, Table 15, Food Crops Grown Under Protection and Sold: 2019, American Mushroom Institute

Estimate Efficiency - Facility design is very important to influence energy intensity and manage demand for years to come. Energy demands also vary among cultivation methods. CEA facilities have varying electric energy intensity based on the size, crop, and configuration of the building. Academic researchers are investigating environmental impacts of indoor vertical farms and are estimating energy loads using modeling tools and research chamber performance. Table 5 describes some ranges of energy efficiency KPIs for both electricity and total facility energy use that can inform *Owner's Project Requirements* and be inputs for estimates of facility utility bills and environmental impact.

Table 5: Example CEA Energy Benchmarks

	Greenhouse[9]	Indoor Vertical Farm[10]
Facility Electric Energy Efficiency (kWh / sq ft / year)	25 - 90	40 - 150
Facility Energy Efficiency (kBtu / sq ft / year)	90 - 100	200 - 400

Request Service - Once you have modeled your potential facility energy usage and have assessed efficiency opportunities, review the design loads of your operation to determine if additional utility services are required. If your site has insufficient electricity or natural gas capacity for your processes and demand, coordinate with your power suppliers to get additional service. Since CEA facilities can range so widely in size (see Table 3 on page 22), the size of the electric and natural gas service requests can range very widely, according to members of RII's Facility Working Group. Some smaller facilities may be able to operate without demanding increased electrical service from their electric utility while larger operations may require special projects by the power provider to meet demands. When using natural gas, facilities need to plan for the rate of supply available as well. If sites need to use delivered fuels, consider the size of your fuel storage tanks and frequency of deliveries. Engage the design team to help estimate utility capacities required for the project to help with communicate requirements to the utility providers.

IMAGE: IMEG

9 Online LASSI, Greenhouse as a Source of Energy
10 Inhabitat, Fortune, Pittsburgh Post-Gazette, Mushroom Council, California Emerging Technologies Coordinating Council Market Characterization of Indoor Agriculture (Non-Cannabis), Light and Energy Modeling in Controlled Environment Agriculture webinar presented on November 19, 2021 by Michael Eaton (Cornell University).

Optimize CEA Greenhouse Design

Greenhouse facility design involves balancing daylight with environmental control strategies for preferred plant conditions for growth. Coverings influence energy loads, venting and glazing influence HVAC choices, and shading and thermal curtains manage energy impacts.

Design Greenhouse Enclosure Projects

Controlling the environment of greenhouse facilities starts with the building envelope. Selecting coverings that are highly insulative can benefit plants and reduce operating expenses.

Purpose-Built - There are diverse kinds of greenhouse structures available for cultivation of CEA crops[11]. Greenhouse covering choice is often driven by goals for pest management, disease pressures, and quality concerns. UV treatments can influence enclosure quality characteristics. Understand the benefits of each material for your applications, and know the downsides of each: polycarbonate yellows, glass breaks in hail, poly film breaks down from pesticide applications that can corrode materials, and acrylic is flammable.

Specify for Longevity - Coverings with longer lifespans allow for continuous growing and perpetual harvests. Some greenhouse materials, like films, need to be replaced every two to five years, while others can last up to 20 years (such as polycarbonates and acrylics). Glass can last even longer, which minimizes operational downtime. Consider the life-cycle cost of your building envelope and how maintenance (like cleaning, repairs, and replacements) will be performed. **Table 6**, on the following page describes the first cost and useful life for common greenhouse covering materials.

Tune Transmission - Glazing materials with higher *light transmission* can decrease greenhouse supplemental lighting needs. Glass has high light transmission and a low insulation value but is also the most expensive glazing material. Some greenhouses with specialized coatings allow sunlight to achieve target light levels for crops during parts of the year without using any supplemental lighting. **Table 6** on the following page describes percent light transmission of greenhouse coverings; note that transmission is reduced when coverings are not completely clean. Also, note that manufacturer specification sheets for covering materials describe *direct* light transmission, whereas many greenhouse growers care more about *diffuse* light transmission[12].

Understand Insulation - Building envelopes made of plastic, glass, and other advanced building materials are rated using U-factor, the lower the value, the more insulating. U-factor is like the winter coat and summer sunscreen of an envelope material and is the inverse of R-value. **Table 6** on the following page describes common greenhouse covering types and the U-factors[13] associated with each material and thickness[14]; note that some **high-performance greenhouse coverings** qualify for financial incentives from energy efficiency programs. Materials in italics have performance characteristics that do not meet California's Title 24, Part 6 minimum requirements for U-Factor for greenhouse coverings. Note that ribs in multi-skin glazing alter U-value and may not be fully accounted for in manufacturer specification sheets. Plastic films can have a greater U-factor if an air gap is actively maintained with fans. If converting a Metric U-factor ($W/m^2{\cdot}K$) from a European manufacturer to Imperial U-factor ($Btu/h{\cdot}ft^2{\cdot}F$) for a U.S. facility, divide the Metric U-factor by a conversion factor of 5.678. The use of one or two screens changes the overall U-factor of the greenhouse envelope during some parts of day or night. It is important that the envelope design consider not only the U-factor of individual materials but the overall assembly performance, which accounts for thermal bridging through high-conductivity materials (e.g., metal framing).

11 See Ball RedBook, Volume 2, Chapter 1: Greenhouse Glazing.
12 See ASTM Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics, 2021.
13 Note that manufacturers report normal light beam transmission, not hemispherical light transmission.
14 Coverings can be listed as the same thickness with different numbers of walls inside to provide more air gaps for additional insulation.

Table 6: Common CEA Greenhouse Covering Types

Covering Type[15]	Imperial R-Value (h·ft2·F/Btu)	Imperial U-Factor (Btu/h·ft2·F)	Light Transmission (%)	Cost / Square Foot ($USD/ sq ft)	Useful Life (Years)
Polycarbonate, Five Wall, 25 mm	3.26	0.31	60%	$8.00	10 - 15
Polycarbonate, Triple Wall, 8 mm	2.0	0.50	74 - 78%	$4.00	10 - 15
Double-Pane Storm Windows	2.0	0.50	78%	$6.00	25 - 30
Polyethylene film, Double, with IR	2.0	0.50	78%	$0.25	2 - 4
Polycarbonate, Double Wall, 10 mm	1.89	0.53	80%	$2.50	10 - 15
Acrylic, Double	1.79	0.56	84%	$2.66	15 - 30
Polycarbonate, Double Wall, 8 mm	1.6	0.63	80%	$1.66	10 - 15
Polycarbonate, Double Wall, 6 mm	1.54	0.65	82%	$1.54	10 - 15
Polycarbonate, Double Wall, 4 mm	1.43	0.70	83%	$1.50	10 - 15
Glass, Double Pane	1.43	0.70	75 - 80%	$6.00	25 - 30
Polyethylene film, Double	1.43	0.70	85%	$0.18	2 - 4
Acrylic, Single Wall	0.88	1.13	90%	$2.66	15 - 30
Glass, Single Pane, 3mm	0.95	1.05	88 - 93%	$3.00	25 - 30
Polyethylene film, Single Wall	0.83	1.2	77 - 87%	$0.09	2 - 4
Polycarbonate, Corrugated Single Wall	0.83	1.2	90 - 91%	$1.33	10 - 15

Protect Your Base - Consider adding perimeter insulation to a depth of at least 2 feet, insulating opaque surfaces of north end walls, and insulating knee walls. Insulate knee walls if crops are not grown on the ground and light is not needed at that level. Many older greenhouses have dirt or gravel floors, which insects love. A concrete floor with appropriate drainage is your best insect and disease management tool, suboptimal drainage can provide an environment for growth of undesirable organisms like algae and pests.

Plan for Openings - If your greenhouse has a vented roof, determine how vents should interact with your ventilation and circulation fan system layout and operation. Ensure that wall openings for exhaust fans are properly detailed so coverings between cultivation spaces and the outdoors (as well as between cultivation spaces) are well sealed, and moisture does not penetrate wall cavities and cause structural damage or pathogen outbreaks.

Consider Energy Storage - *Thermal storage* can be used to smooth out temperature swings between day and night and works well for greenhouses. Historically thermally massive concrete slabs have been used as passive solar energy storage in CEA facilities. Water can be stored in buffer tanks and act as a thermal battery, and enclosure materials can offset heating and cooling needs if they incorporate *phase change materials*.

15 Table data compiled from Reducing greenhouse energy consumption - An overview, Codes and Standards Enhancement (CASE) Initiative 2022 California Energy Code, Table 15 (Common Greenhouse Envelope Materials Used) and Table 120.6-D Default U-Factors for Greenhouse Coverings, and the Ball RedBook, Volume 2, Chapter 2: Greenhouse Glazing. Note that coverings in italics do not meet California's minimum performance requirements proposed for Title 24, Part 6 for CEH for newly constructed greenhouses, greenhouses being converted from unconditioned to conditioned, and additions to conditioned greenhouses.

Think Hot Climate - Facilities in colder climates may require more heating, while facilities in warmer climates may require more cooling. In warmer climates, greenhouses can utilize glazings to block some of the heat from sunlight while allowing light utilized by plants to pass through. Infra Red (IR) coverings and *chalking* can reduce cooling demand.

Design Greenhouse Curtain Projects

Interior coverings to manage the dynamic climate of greenhouses are used to save energy and improve conditions for plants. Growers in every region can find benefits from thermal and shade curtains throughout the year.

Determine Goals - Understand what outcomes you want to achieve for your plants and your energy bills. Retrofits for older curtains may be challenging and it can sometimes be better to replace curtain systems completely. Operations in colder climates can use thermal curtains to trap radiation within the greenhouse and minimize heat loss through your enclosure while also protecting your crops. Facilities located in sunny places can use shade curtains to block out sunlight and protect plants from extreme conditions and undue stress while also reducing cooling loads. Energy efficiency programs in some regions support growers installing **high-performance greenhouse curtains** with financial incentives for energy savings.

Select Curtain Types - Once you understand your goals, determine the curtains you need for which purposes. Growers may use separate thermal curtain and shade curtain systems, and others use combined systems to achieve both goals simultaneously. Some facilities may have three screens if they also use curtains for light spill management to minimize light pollution. Be sure your greenhouse structure is able to support the weight of your curtains and any auxiliary systems, this is especially important for retrofit projects.

Choose Materials - Diffusing materials are helpful for glass greenhouses with non-diffusing glass. Shade curtains are often made of open weave fibers like plastic, or metallic strips for reflectivity. Flame retardant (FR) materials are preferred, though they are slightly less durable. Threading is important and impacts durability; many curtains use nylon. Think about moisture transfer characteristics and how you will manage moisture while retaining energy when thermal curtains are closed. Work with consultants on your team to determine the materials most appropriate for your crops and facility location, and talk through these other considerations.

Consider Pricing - Greenhouse curtain material costs depend on many factors like shade percentage, quality of materials used, usage, reflectability, and warranties. Pricing for curtain cloth can be as low as $0.05 USD and as high as $0.60 USD per square foot for the curtains themselves while installation costs can be greater with manual systems close to $2.50 per square foot and more complex systems close to $6/ square foot . High-performance curtain materials can have payback periods of less than five years. Payback periods can be shorter with incentives from utilities and energy efficiency programs.

Understand Energy Savings - Greenhouse curtain technology can achieve nighttime heating energy savings[16] of 30 - 50%. Published energy savings from curtain manufacturers can be informative, but how they arrive at those numbers and what they mean may not be applicable to your facility. Since typical savings estimates are calculated for growing under glass, facilities using poly or double-wall high performance coverings may need to adjust energy savings inputs.

IMAGE: LUDVIG SVENSSON

[16] Using curtains to reduce greenhouse heating and cooling costs, Cooperative Extension of the University of Wisconsin, 2011. Increasing energy efficiency in the greenhouse, Michigan State University Extension, 2014. Estimation of Thermal Performance and Heat Loss in Plastic Greenhouses with and without Thermal Curtains, South Korean Rural Development Administration, 2018.

Orient Curtains - Horizontal curtains shade plants and can decrease energy use for both heating and cooling, the degree to which depends on facility location. Use insulated drop-down sidewall curtains to save additional energy at night and decrease light pollution from nighttime light use.

Motorize - Modern curtain systems are automatically moved by motor systems on racks which open and close curtains depending on control inputs. How often curtains open and close can introduce wear and tear on both the curtain and the motor. Frequent curtain movement may require more frequent replacement of curtain fabric. Curtains should be installed with the proper amount of slack to prevent premature tears. Using high temperatures to disinfect greenhouses can also shorten useful life. Fans should not point directly at curtains that travel on guide wires, or the vibration along the wire will quickly wear holes in curtain cloth.

Lay Out Sensing Equipment - Gather the data you need. Consider how you will monitor environmental conditions and ensure measurements are taken above and below the curtain. If receiving incentives for curtain projects, utilities and efficiency programs may want to understand actual energy savings. Some programs may offer incentives for **greenhouse controllers** that can also monitor energy usage. Set yourself up for verification by measuring the environmental conditions and monitoring the energy used by HVAC systems serving your greenhouse. This information can inform you of when curtains are getting dirty as energy savings or light transmission change and affect sensor trends.

Specify Control - Be cautious with aggressive curtain controls and consider predictive programming that uses 24-hour average temperatures and proactive analysis of the weather forecast to inform operation[17]. Opening thermal curtains in the morning can shock your plants. When the sun comes up, do not open the curtains right away, consider programming curtains to wait until the temperature above the curtain stabilizes with temperature below before opening or closing. Shade curtains have their own strategies based on regional considerations and your goals, take the time to understand your specific system and how to control to your goals.

Protect from Fire - Understand the materials used in curtains and how they behave in a fire and the systems your facility will use to protect staff, building systems, and plants. Some curtain materials may melt, and others may catch fire and burn. In case of fire, motorized curtains can automatically recoil to avoid curtains setting ablaze, HVAC controls sequences can shut down circulation fans, and fire suppression and smoke control systems can protect staff and minimize damage. In greenhouses with multiple curtains, in case of fire, the curtains must close to act as a ceiling, especially in ventilated facilities. Most AHJs that require sprinkler systems agree that greenhouses need sprinkler heads above and below curtains. Facilities located in northern latitudes should consider freezing hazards for sprinkler systems; dry sprinklers are recommended for heads installed above curtains.

IMAGE: FIFTH SEASON

17 Consult Weel, Peter & Geelen, Peter & Voogt, Jan. Plant Empowerment: The Basic Principles, p.231-243, 2018.

Optimize Indoor CEA Facility Design

Indoor crop production facilities can be designed to support structural loads, protect plants and cultivation equipment from fire hazards, and create sealed and insulated environments for optimal growth and development. Vertical racking strategies can offer production benefits and affect the ways lighting and HVAC systems are designed.

Design Indoor Enclosure Projects

Get the highest yields and best energy performance from indoor cultivation operations by thoughtfully installing and configuring building enclosures.

Reserve Space - Plan space and structural capacity for electrical and mechanical facilities including: HVAC equipment, water storage tanks, and potential loads from renewable energy infrastructure, like solar photovoltaic panels on roofs. Ask your design team to show you where mission-critical equipment is located, how it will be accessed, and clearance for maintenance activities like replacing components. Understand how placement of equipment on roofs is affecting weights supported by and therefore material costs for structural members.

Design Walls - Work with your project design team to consider non-cavity walls for interior grow room enclosures. Wall cavities can create concerns related to moisture, room pressurization, air leakage and pests and achieve better environmental control. If using cavity walls, understand how these enclosures will be properly sealed and verified during construction as well as mitigating other potential issues in operation.

Box in a Box - When retrofitting existing buildings, one approach to take is a 'box in a box' build. Consider all six sides of the box including the ceiling and floor to maximize the benefits of high-performance enclosures. Make space above the box for proper maintenance access between the outer and inner 'boxes'. Stack systems and processes so the outer shell is tall enough for crops and the complete assembly. Consider the height of the plant, the mounting height of lighting systems, and the location of HVAC systems in the ceiling.

Design Panel Assemblies - When designing box in a box builds, panel selection is influenced by the structural capacity of your building and the panels you choose, desired energy performance, and applicable cultivation standards. As panels have limited structural capacity, HVAC and lighting equipment can be suspended from structures above using rods in a grid pattern that penetrate the box in the plenum above the panel. Any penetrations made in panels should be sealed with expandable foam and vapor tape in the plenum, and batten strips and escutcheons in the box. Ensure panels are designed to withstand the pressure of suspended equipment and foot traffic from staff access.

Select Finishes - Careful selection of final finishes including flooring, wall panels, paint and coatings can increase your facility energy efficiency and play a key role in determining maintenance and cleaning requirements. Insulated metal panels have good thermal performance and can be coated in finishes acceptable for USDA clean growing guidelines[18]. Facilities subject to FDA or USDA regulation must select finishes that are smooth, durable and easily cleanable; some can even incorporate antimicrobial properties. White or light grey finishes are popular due to higher reflectance and potential for higher yields. As you grow vertically, proper selection of wall finishes becomes more important , so continue your coatings up the walls. Work with your design team to specify a level of reflectivity to optimize effectiveness of your lighting systems.

[18] See FDA Food Code, Chapter 6, 2017.

Design Indoor Vertical Racking Projects

Get the most out of your vertical indoor facility by thoughtfully designing your racking solutions.

Lay Out Canopy - In CEA environments, plants are arranged in a canopy, horizontally distributed at a planting density. In racking systems, plants can be vertically distributed in tiers. The distribution and density of your crops influence the ways designers optimize your facility and systems to maintain optimal conditions for plants.

Plan Tiers - Consider the number of tiers your cultivation spaces can accommodate, given crop type, plant stages of growth, and lighting system mounting height. Some CEA producers cultivate vegetables and herbs in racking systems of three to fifteen tiers. Mushroom producers generally grow in trays in racks of at least four tiers. Refer to the ranges offered in Table 7 below to inform design of vertically racked indoor facilities.

Irrigate Your Racks - Irrigation systems for facilities using vertical racking can vary greatly from single tier systems. Without planning for differences from the bottom row to the top you can end up with large differences in performance like system pressure and watering rate.

Table 7: Vertical Racking Levels for CEA Crops

CEA Crop	Vertical Racking Levels
Vegetables	2 - 3+
Leafy Greens	4 - 6+
Microgreens & Herbs	4 - 6+
Mushrooms	4 - 8+
Berries	1 - 2+

Design Racking Systems - Racking systems can integrate components of lighting and HVAC systems to provide structural support for light fixtures and ventilation infrastructure while also avoiding penetrations in your ceiling. Consider mounting lighting and environmental control equipment on racking systems to lessen the roof load on your facility. Design roof systems for heavier dead loads from HVAC and lighting systems and live loads from your staff as they perform maintenance tasks like cleaning racks.

Protect from Fire - Prepare for code requirements for fire protection which can be especially challenging with mobile racking systems. Plan for sprinklers under benches more than 4 feet wide. Multi-tiered racks over 8 feet tall and built out of certain materials may require sprinkling between racks.

IMAGE: PRIVA

SECTION
03

IMAGE: CERES GREENHOUSE SOLUTIONS

Construct High-Performance CEA Facilities

In the field, facility designs take shape and project teams help producers achieve energy performance and productivity targets in operation. Construction contractors and commissioning agents can work with CEA producers in buildout and occupancy phases to ensure the best outcomes for plants and operators.

Construction Benchmarks

Test Throughout - Don't wait until the end of construction to test components and sub systems. Inspect each delivery for damage and staging requirements upon arrival. Test each component, LED fixture, sensor, pump etc. with the proper equipment, as early in the construction process as possible to make sure they are operating properly. Once installed, or other systems are installed around them, replacement can become a more disruptive project with potential delays and cost implications.

Build Budget - Table 8 below describes the range of construction costs[19] for CEA facilities by facility and project type. MEP can account for 70% - 85% of total construction costs. On top of construction costs, design expenses typically account for 10% of CEA project costs and can range from 3 - 15% depending on project size and complexity.

Table 8: Cost Estimates of CEA Facility Construction Projects

Project Type		$/gross square feet[20]
Indoor Vertical	New Construction	$330-420
	Retrofit Building	$270-360
Greenhouse	New Construction - Advanced Sealed	$250-400
	New Construction - Advanced Vented	$150-250
	New Construction - Traditional	$50-150
	Greenhouse Retrofit	$30-75

Schedule Material Orders - Lead times of CEA project materials and equipment are affected by the network of global supply chains. Freight and shipping timelines have been delayed considerably since 2020 by the coronavirus pandemic. Input costs for growers increased by 8% in 2021 and are expected[21] to increase another 5% in 2022. Lead times for key infrastructure for your CEA facility may continue to be impacted and your project team should consult the latest transit times and material availability for your region in design so ordering activities can support construction schedules. **Table 9** on the following page offers guidance for project teams navigating materials procurement for various CEA facility systems.

IMAGE: EDEN GREEN TECHNOLOGY

19 Expenditure ranges do not include design fee, land acquisition, primary builders' risk, or owner furniture, fixtures, and equipment (FF&E) including typical owner purchased items (racks, benches, lighting systems).

20 Estimates based on a survey of Technical Advisory Council Working Group members in 2021. Cost ranges are fluid and may not reflect the current economic environment.

21 Greenhouse Grower, Cracking the Horticulture Supply Chain Management Code 2022.

Table 9: CEA Facility Lead Times and Ordering Timelines

System Type	Order When	Lead Time
Steel - Structural (Roof Decks and Joists)	Order early enough in design to meet your construction schedule. Put down payments with steel partners to get in their production queue.	Today: 50 week delivery time In the future: not likely to get shorter
Aluminum (Roof Systems)	At time of publishing a magnesium shortage is affecting global aluminum production. Talk to manufacturers as soon as possible to understand available material channels and get detailed timelines.	Today: 12 months (unless you have an allotment reserved)
Electrical Infrastructure (Switchgears)	Supply chain issues affect this infrastructure so pick a supplier at 30% design to understand electrical loads and bring in vendors. Design to what products are available.	Typical: 18 weeks Today: 32 - 38 weeks Future: 48 - 52 weeks
Energy Infrastructure (Renewable Energy)	If your facility will incorporate technology like solar panels, account for both material delivery and interconnection with your utility.	Today: 1-12 months Interconnections can be local issues, dependent on the distribution system, and can take up to 12 months.
Energy Infrastructure (Combined Heat and Power)	Order cogeneration infrastructure 6 month delivery. If you are short of power, you need to work with the utility to get additional service or plan to operate at reduced capacity and scale up when larger service becomes available..	Today: 6 months 12 months when accounting for coordination with utilities to get up and running with appropriate service.
HVAC Equipment	MEP equipment often has to be picked early on in design so you can design to the available equipment.	16 - 24 weeks, some specialized HVAC providers (customized equipment) might be 30 - 35 weeks (some electronic components).
Lighting Equipment	Very product dependent, quantity dependent.	3 weeks to (18 - 24) weeks for the best and a lot of product
Controls Equipment	Sensors can be a mixed bag (4-6 weeks is moving to 8-12 weeks)	8 - 12 weeks before COVID. 12 - 28 weeks now.
Greenhouse Coverings	A lot of glass comes from China. Plants in Europe and North America make high performance plastic.	Stats for container traffic to NA. Glass is impacted by container issues, but long lead times are not yet happening.
Greenhouse Curtains		No significant additional lead times
Insulated Metal Panels	Decided in early stages of design as part of box-in-a-box facility philosophy	7 - 9 weeks before, 12+ weeks now.
Coatings	Often choose later in design, or construction	<6 weeks, often kept in stock
Vertical Racking Systems	Choosing partner from design start.	8 - 12 weeks, seem to be stable at 12 weeks.

Commissioning & Maintenance Best Practices

Choose Commissioning Lead - Understand how you want commissioning activities to be completed: owner-performed, vendor-performed, or third party-validated. In greenhouse construction, owners may contract directly with vendors for commissioning because greenhouses are often built 'turnkey'. Greenhouse manufacturers can hold contractors accountable (10% holdback to ensure builder wants to get paid) until the site acceptance test. Since vertical farms have many vendors providing a variety of different building systems, vertical farms often have engineering groups for each of their sites and owner-performed commissioning activities performed by on-site staff. Owners can provide functional testing forms with expected outcomes to inform controls commissioning.

Pick the Right People - When engaging third-party commissioning services, work with firms that have experience on other CEA projects. Commissioning agents not specialized in CEA facilities can have challenges getting up to speed and knowing what to look for and verify during functional testing. Work with commissioning partners that are aware of what proper operating parameters are for greenhouses and indoor farms, focusing on both the needs of crops and humans in your facility. While there are standards and professional credentialing programs for commissioning commercial and residential buildings, commissioning CEA facilities requires specialized expertise. There is a need for industry organizations to provide guidance for commissioning agents on the unique testing requirements for cultivation spaces.

Orchestrate Activities - It can be challenging to coordinate the right people on site at the right time to identify and resolve construction issues quickly. Often multiple people serve the facility for commissioning different systems like HVAC systems and environmental controls. Your commissioning agents can hold general contractors and the construction trades accountable for quality and functionality of your mission-critical building systems. Third-party commissioning agents organize the chaos and give owners one central person to follow up on issues reports, organize trainings, and compile operations and maintenance (O&M) manuals. It is important for third-party commissioning agents to have a good working relationship with the rest of your project team, but to represent your interests first and foremost.

Meet On-Site - A portion of the control system can be commissioned remotely, a vendor can review performance and change settings, verify responses. However, someone

IMAGES FROM TOP: TIMA MIROSHNICHENKO; CERES GREENHOUSE SOLUTIONS has to be on-site to see the change and verify it meets your expectations. Coordinate all necessary trades so construction partners can respond to commissioning issues and report resolutions. Hold job site meetings for accountability to discuss resolutions. Create overlap between your design team and facility management to ensure a smooth transition from design to operation. Institutional memory and an existing relationship between operational staff and design phase professionals can mean additional support in operation.

Document, Document, Document - Work with your designers, installers, and equipment suppliers to gather together project specifications, equipment manuals and training documentation for different systems during new construction or retrofits. Use these documents as training materials for staff while system learning is fresh to avoid pain points down the line when a system is not operating as expected or new staff joins the team.

Train Effectively - Throughout the life of the facility staffing will change and planning for onboarding of facility staff is vital for maintaining operational excellence. Training your staff can be a commissioning scope of work, involving other construction partners like your installation contractors or equipment manufacturers covering proper preventative maintenance procedures and troubleshooting steps. An outcome of training is to ensure that system settings meet operational targets and staff know how to operate and maintain the facility. Untrained staff may have difficulty differentiating between a hardware equipment problem and a control system problem. Decide which staff members need to be trained and how they will engage cross-functionally for operations and maintenance activities. In project specifications, training is often defined as a number of days on site, but finding time for CEA facility staff to devote to training is challenging.

Make Training Accessible - Store O&M manuals in a centralized physical and digital location accessible to relevant staff. Integrate recommendations and troubleshooting into maintenance processes to more easily resolve issues quickly, accurately and effectively. Consider using follow-up training online so your team can break training sessions into smaller chunks. This way, training meets your staff when they have time and they can better retain important information. Store training documents in the same place as O&M manuals so as staff changeovers occur, your training resources are implemented by your new staff.

Warranty Walk - Decide how you will handle issues identified after operation and when you want people back on site and how often. Getting close to the end of your first year of operation, review a punch list of major facility systems and any failures to report before project closeout. After that point, you hold the keys and are responsible for your facility operation and any issues that occur. Hand off fine-tuning and resolving issues to a third-party commissioning agent once your construction team is gone and empower them to fix problems after the first year.

Budget for Maintenance - Some systems, like greenhouse curtains or cultivation HVAC systems, may require maintenance from a skilled contractor who can keep systems running safely and successfully. Neglected or incorrectly serviced systems can become damaged and negatively affect operation. Plan for the right person to do the job in a timely manner.

Plan for Maintenance - Schedule downtime and consider each system's maintenance requirements and how they can be serviced without significantly disrupting operations. While preventative maintenance can feel inconvenient, it is worth doing to maintain performance and longevity of the equipment. Not to mention how much more inconvenient, and expensive unplanned downtime can be.

Maintain Safely - Protect your business and your staff by managing risk and meeting industry standard safety requirements. Save room for maneuvering; 18-inch aisles are not feasible for cultivation activities or repair and replacement of systems. Use drawings in plan and elevation or 3D models of your space to perform clash detection for installation and operation. In greenhouses, curtains move and affect where electrical conduit and water piping can be placed. See Figure 7 on the following page and note how the floor plan describes irrigation zones, size of bench area, and plumbing layouts so that your project team can coordinate installation of other equipment like curtains, light fixtures, and HVAC equipment. Equipment placement and ability to maintain it are crucial considerations for all CEA facilities. Avoid placing equipment like motors or controllers high up in the air as it complicates testing and maintenance activities.

Know your Retrofit - When retrofitting or repurposing an existing building or greenhouse each project will be unique and can often require more delicate sequencing than necessary in a new build. Make sure critical timing of project activities, as well as any delays, are well communicated to the team to keep the project moving smoothly and avoid costly complications.

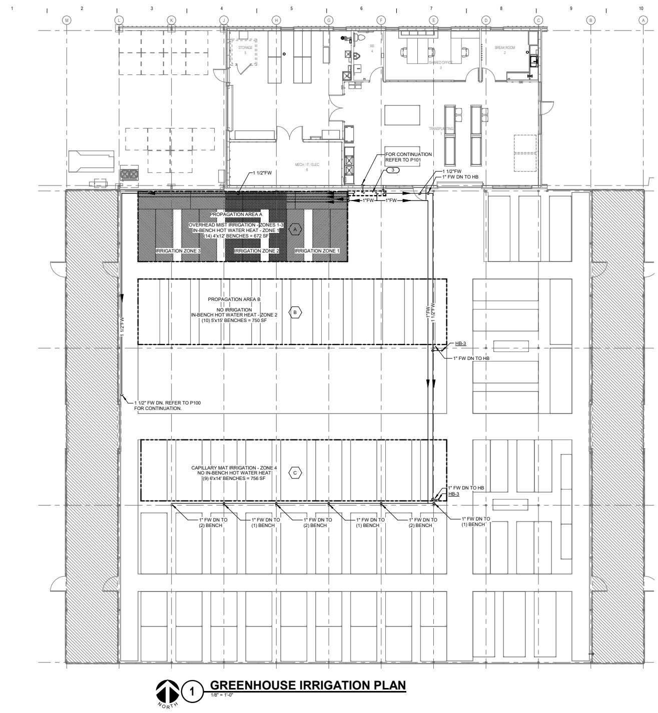


Figure 7: CEA Greenhouse Irrigation Plan

IMAGE: IMEG

Optimize CEA Greenhouse Construction

Greenhouse facilities are assembled to manage the dynamic effects of outdoor environmental conditions with well-constructed enclosures so CEA crops can grow to their full potential.

Configure Greenhouse Enclosure Projects

Installing greenhouse coverings in the field properly requires thoughtful staging and quality control. Consider how you will ensure enclosures perform during construction and how to maintain them in operation.

Work When - Determine your construction schedule to avoid inclement weather conditions. Help builders understand the local geotechnical conditions so the greenhouse manufacturer can pour foundations and avoid unexpected surprises. Saturated soils affect geotechnical conditions and wet conditions can delay buildouts. Many greenhouse builds can mean greater exposure of crews and materials to the elements than indoor facilities may need to consider, take this into account when planning..

Consider Climate - Once you get a greenhouse enclosed, and even while materials are staged it can get very hot. Extreme heat during construction can cause permanent damage to infrastructure. Plan for hot weather mitigation so you don't have to work nights. If you work nights, crews need work lighting. Whitewash the top to keep temperatures down and roll out shade curtains during construction, consider installing vent openings early in construction.

Commission Enclosure - Standard commissioning practices for envelopes include testing for air tightness and validating that the enclosure can withstand local weather conditions, but methodologies that work for CEA are quite different. Work with your greenhouse manufacturer to understand the tests that will be performed to ensure your coverings and vents are ready for operation. Observe how different systems like fans and curtains will operate when vents are open and closed.

Clean Enclosure - If you cannot maintain environmental targets for lighting and climate control, it is time to clean your coverings. If your greenhouse is near other agricultural operations or other dusty environments, you may need to clean more often. Interior sides of glazing also need to be kept clean, sprays used indoors can stick to surfaces. Researchers have found that for most CEA crops, a 1% increase in light received by the canopy results in around a 1% increase in biomass yield. See Table 10 below to determine how a reduction in light received could affect productivity of your crop canopy. Greenhouses can use high-pressure roof washer machines to minimize staff performing maintenance in high locations on stepladders. These roof-mounted cleaning machines allow staff to ride along securely and inspect roof components and replace glazing more ergonomically.

Table 10: CEA Crop Yield Increases Corresponding to Increase in Light Received[22]

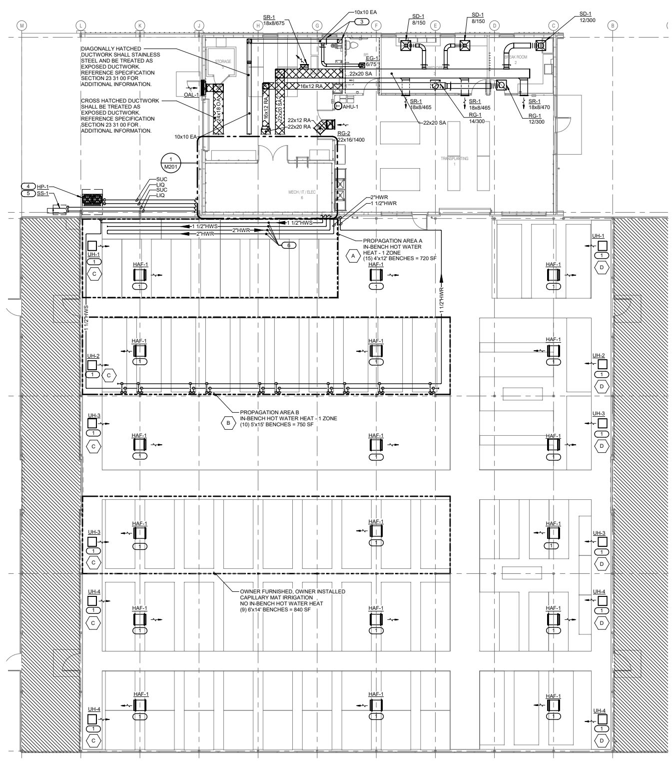
Crop Type	Percent Yield Increase from 1% Increase in Light Received
Soil Grown Vegetables	0.8 - 1%
Fruiting Vegetables	0.7 - 1%
Cut Flowers	0.6 - 1%
Bulb Flowers	0.25 - 1.25%
Flowering Potted Plants	0.5 - 1%
Non-Flowering Potted Plants	0.65%

Configure CEA Greenhouse Curtain Projects

To achieve the benefits of curtain projects, plan for how they will be controlled. Consider how you will test curtain performance and maintain them in operation.

Commission Curtains - Confirm proper sag of curtain fabric. If installed too taut, ripping can occur prematurely. Installers need to follow manufacturer's instructions. Curtains not completely sealed can create a chimney effect in greenhouses, so hold back a portion of payment until verification is complete. Use mechanical floor plans to inform curtain system commissioning like the example in Figure 8 to understand locations and infrastructure for HVAC equipment like the horizontal airflow fans and unit heaters shown.

Figure 8: CEA Greenhouse Mechanical Floor Plan



Access Safely - Greenhouses are typically not built to maintain the equipment hung from the structure like lights and curtains. It can be hard to reach all of the connection points of the curtain as other components like conduits and plumbing can get in the way. A single-person motorized lift is extremely handy for repair and replacement in high and tight spaces.

Commission Curtain Controls - Commissioning agents are often not familiar with climate control systems for greenhouses that integrate with curtain controls, so they often observe your expert contractor who will perform the functional tests. Your greenhouse manufacturer should observe installation of greenhouse curtain systems and record the time it takes to go from full open to full close so that information can be incorporated into control software. During functional testing, commissioning agents and greenhouse manufacturer representatives should check that

IMAGE: IMEG

22 Marcelis, L.F.M. & Broekhuijsen, A.G.M. & Nijs, E.M.F.M. & Raaphorst, M.G.M. Quantification of the growth response of light quantity of greenhouse grown crops, 2006.

there are no gaps in blackout or energy curtains that could allow light or conditioned air to escape. Your commissioning agent can summarize these findings in final reports.

Plan for Curtain Maintenance - Consider programming control systems to reduce the frequency of operation of curtains. Create a schedule for preventative maintenance that incorporates recommendations from your designers, curtain manufacturer, and greenhouse manufacturer for curtain components and systems like cloth and motors. Screens should be cleaned at crop turn or annually to maintain performance and minimize transmission loss from dirt build up. In general water or a weak hydrogen peroxide solution can be used while bleach or chloride containing cleaners should not be applied to screens but follow the recommendations of your manufacturer for best results.

Optimize Indoor CEA Facility Construction

Vertical indoor facilities are built to maximize CEA crop yields in precisely controlled environments which are only possible with well-constructed enclosures and thoughtfully commissioned racking systems.

Configure Indoor Enclosure Projects

Construct indoor CEA facility enclosures successfully by continuing to integrate systems planned in design. Plan for how your team will verify cultivation spaces are properly sealed and coated.

Work When - Determine your construction schedule to avoid inclement weather conditions. Help builders understand the local geotechnical conditions so the construction team can pour foundations and avoid unexpected surprises. Saturated soils affect geotechnical conditions and wet conditions can delay buildouts.

Top and Bottom - Ensure floors are sloped to drain water effectively. Avoid penetrations in the ceiling from hanging equipment like lighting systems by using vertical racking systems as the structural support. When using insulated metal panel systems, mechanical, electrical, and plumbing equipment is surface-mounted so it is crucial to properly configure enclosures to seal wall and ceiling penetrations and ensure biosecurity and effective environmental control.

Apply Finishes - Coat base, transition between wall and floor for continuous seal. Consider applying coatings when the main structure is up and the space can be protected but prior to installation of racking and equipment. This makes it more efficient to install without having to cut-in or around racking and equipment.

Commission Coatings - Special consideration should be paid to transition points between floors, walls and ceilings which may require a curved connection or other specialized finish to seal between them. Consider each of your finishes, how they may interact physically or chemically and when the application of each finish fits into the process of moving into the facility. Ensure a plan for maintenance of finishes is included in O&M manuals.

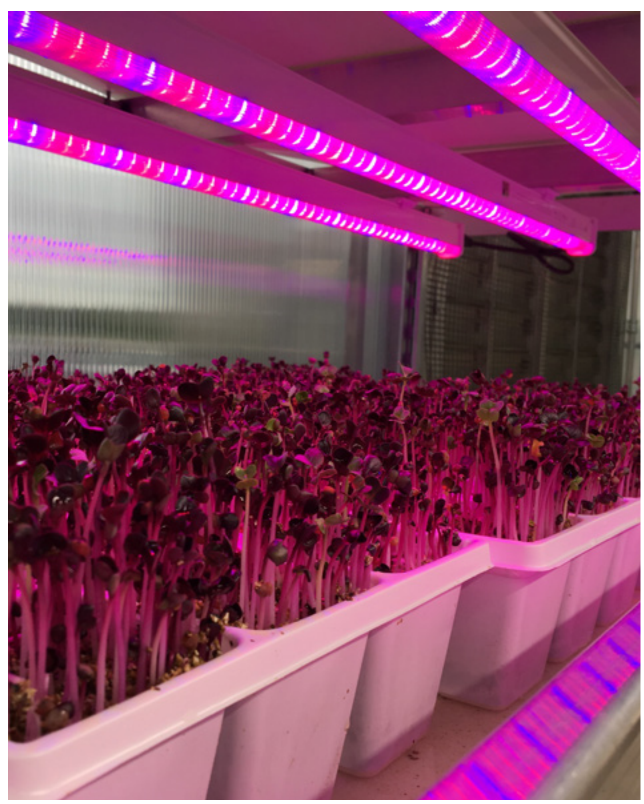
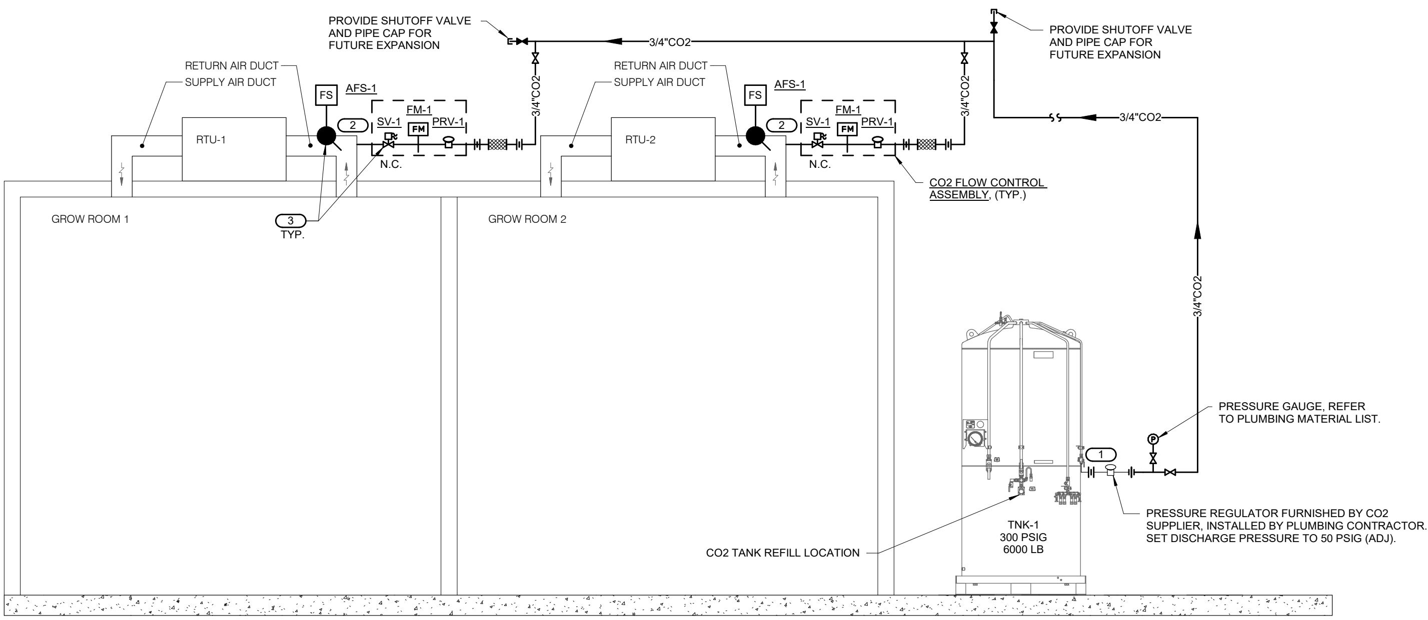


IMAGE: ROB EDDY

Figure 9: Indoor CEA Facility CO_2 Enrichment Flow Diagram



Confirm Box is Sealed - Indoor CEA facilities using box-in-a-box builds must ensure that wall construction like insulated metal panels are built properly to maintain biosecurity and allow for processes like CO_2 enrichment. See Figure 9 above for a diagram showing how HVAC equipment serves grow rooms and how carbon dioxide is piped to the spaces through the ceiling of the cultivation spaces. Before bringing in plants, conduct functional performance tests of the envelope like penetration inspections and blower door tests. After plants are inside, use air sampling to count spores to ensure growing areas are properly pressurized and free of contaminants.

Configure Indoor Vertical Racking Projects

Get the most out of your hardware by thoughtfully installing and configuring your vertical racking solutions.

Commission Racking Systems - Commissioning for racking systems often requires bringing multiple engineers and vendors together to tune to one another. Plan for how racking systems will be tested once they are installed and connected to power. Racking systems need to be installed after floors and walls are properly coated and the other equipment is hung from the ceiling. Stage tests properly to account for identification of issues that may involve engaging several design and construction partners.

Prepare for Maintenance - Indoor facilities are getting taller and taller, and many indoor CEA operations perform a lot of their own maintenance. Safety is key throughout operation. Consider how often racking equipment needs to be cleaned. Often cleaning can be performed during crop rotations. Determine how often staff will clean racks and equipment hung from racks and how they will do so safely.

IMAGES FROM TOP: IMEG; GORDAN

Measure Facility Efficiency and Productivity

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

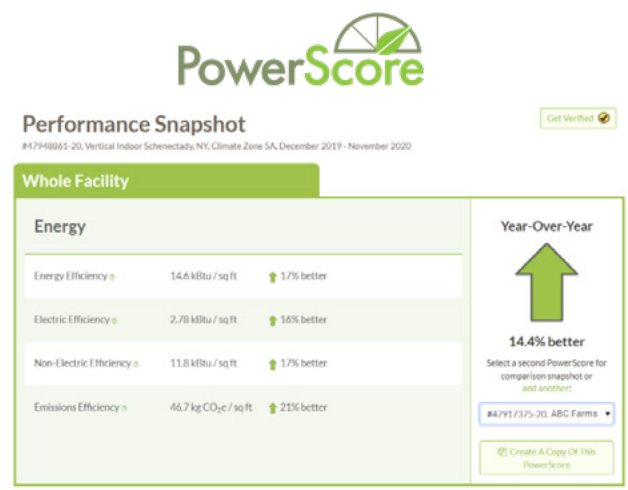
Get Utility Support - Share data periodically with your local efficiency programs to get recommendations for energy improvements and access financial support. By continuously monitoring energy performance, you can identify no- and low-cost savings opportunities and access technical assistance and financial incentives from your utility for your annual efficiency gains. Share your key performance targets for systems in your operation; these will differ based on your facility type and crop. Work with your local utility or efficiency program implementer to understand what kind of support you can get throughout operation to improve energy efficiency.

Retrocommissioning - Once your facility is up and running, you can work with efficiency programs to evaluate your operational data and assess performance of major energy-consuming systems. Some utilities and efficiency programs may offer financial incentives for ***retrocommissioning studies*** and pay you for improvements in performance. Technology and techniques are constantly evolving as well as incentive programs changing regularly to meet the efficiency needs of the industry. Stay in touch with your local utilities and efficiency program implementers to be aware of opportunities for greater operational efficiency.

Ask for Guidance - Talk with growers that have built or operate high-performance CEA facilities 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 RII's network of CEA producers to connect with other cultivators and collaborate.

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

Figure 10: PowerScore Performance Snapshot



Benchmark and Compare - Calculate key performance indicators (KPIs) 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 10 shows a Performance Snapshot for a vertical indoor facility, comparing two years of facility data. Examples of KPIs PowerScore calculations include Facility Energy Efficiency (measured in units of energy consumed per unit of canopy area per year) and Canopy Productivity (measured in units of biomass per units of canopy area). Create multiple years of Performance Snapshots to track your CEA facility key performance indicators and measure year-over-year performance trends.

Prepare for Reporting - Certification programs for CEA facilities are already available and more are being developed to recognize excellence in environmental categories like energy, water, and emissions performance. Knowing where your facility stands now can help prepare your organization to be a thought leader celebrated by your investors and consumers.

Resources

Organization	Resource	Description	Link
Resource Innovation Institute	**Catalog of Resources**	Catalog of RII's published curriculum and training.	https://catalog.resourceinnovation.org
	Workshops and Webinars	Library of RII's live and recorded Efficient Yields educational workshops for CEA producers.	https://catalog.resourceinnovation.org/category/efficient-yields-workshops
	Best Practices Guides	Library of RII's peer-reviewed and brand-agnostic best practices guidance on efficient technology and approaches.	https://catalog.resourceinnovation.org/category/best-practices-guide
	PowerScore	RII's specialized resource benchmarking platform for controlled environment agriculture production facilities. PowerScore generates KPIs for resource efficiency and productivity of energy, water, emissions, and waste.	https://resourceinnovation.org/powerscore https://powerscore.resourceinnovation.org/go-cea
American Society of Heating, Refrigerating, and Air Conditioning Engineers	**ANSI/ASHRAE/IES Standard 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings**	Provides minimum requirements for energy-efficient design of new buildings and their systems, new portions of buildings and their systems, and new systems and equipment in existing buildings, as well as criteria for determining compliance with these requirements.	https://www.ashrae.org/technical-resources/bookstore/standard-90-1
Greenhouse Lighting & Systems Engineering	**GLASE Lighting Short Courses**	Plant Lighting Short Course in partnership with Greenhouse Lighting & Systems Engineering (GLASE), OptimIA, and Lighting Approaches to Maximize Profits (LAMP)	https://glase.org/plant-lighting-short-course/
International Code Council	**International Energy Conservation Code**	Addresses building energy efficiency, energy usage, use of natural resources, and impact of energy usage on the environment.	https://codes.iccsafe.org/content/IECC2021P2
University of Arizona	**University of Arizona CEA Short Courses**	Greenhouse Production & Engineering Design Short Course presented by the Univeristy of Arizona Biosystems Engineering Controlled Environment Agriculture Center	https://ceac.arizona.edu/events/cea-short-course
University of Arizona, Ohio State University, Michigan State University, Purdue University	**OptimIA Indoor Ag Science Cafe**	Supported by USDA and NIFA	https://scri-optimia.org/cafe.php
U.S. Department of Agriculture ARS	**Virtual Grower**	Virtual Grower can help identify energy savings through different greenhouse and indoor farm designs, predict crop growth, assist in scheduling, make real-time predictions of energy use, and see the impact of lighting on plant growth and development.	https://www.ars.usda.gov/midwest-area/wooster-oh/application-technology-research/docs/virtual-grower/

Organization	Resource	Description	Link
U.S. Department of Energy	**50001 Ready for Utilities, Implementers, and Energy Service Providers**	50001 Ready recognizes facilities that implement an ISO 50001-based energy management system – a self-paced, no-cost way to build a culture of continual energy improvement. DOE partners with utilities and other organizations to support the program's implementation, often as part of an SEM offering.	https://betterbuildingssolutioncenter.energy.gov/iso-50001/50001Ready/50001-ready-program-utilities-admin-implementers https://betterbuildingssolutioncenter.energy.gov/sites/default/files/DOE_50001-Ready_Cohort.pdf

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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 performance benchmarking service, 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.