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Energy Analysis and Environmental Impact

Technology Catalog

For Controlled Environment Agriculture

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Technology Catalog for Controlled Environment Agriculture

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Acronyms and Abbreviations

AI	Artificial intelligence
BESS	Battery energy storage system
CAPEX	Capital expenditures
CEA	Controlled environment agriculture
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CST	Concentrated solar thermal
ECS	Environmental control system
kW	Kilowatt
kWh	Kilowatt-hours
HPS	High-pressure sodium
HVAC	Heating, ventilation, and air conditioning
LED	Light-emitting diode
MMBtu	Million British thermal units
MH	Metal halide (lighting)
MW	Megawatt
O&M	Operations and maintenance
OPEX	Operational expenditures
PPF	Photosynthetic photon flux
PPFD	Photosynthetic photon flux density
ppm	Parts per million
PV	Photovoltaic
RII	Resource Innovation Institute
USDA	United States Department of Agriculture
UV	Ultraviolet

Executive Summary

Controlled environment agriculture (CEA) offers a promising solution for reliable, high-yield food and floriculture production in the face of natural hazards, water scarcity, and land constraints. Yet, despite its potential, CEA can be hindered by high energy demands, elevated operational costs, and questions about its true environmental performance. To address these challenges and support informed technology selection and deployment across the CEA sector, this report presents a comprehensive CEA technology catalog designed to guide decision makers, developers, and policymakers.

This project aims to:

- Identify and characterize technologies that improve energy and water efficiency in CEA facilities.
- Support the efficient and accelerated adoption of CEA systems.
- Provide a standardized framework for comparing technologies across facility types, climate zones, and crop categories.

The catalog covers more than 80 technologies, spanning six major categories:

- **Energy Systems**: Including solar photovoltaics, combined heat and power, geothermal, energy storage, microgrids, and demand-side management.
- **Water Management**: Including reduction, recycling, filtration, and treatment strategies.
- **Building Envelope**: Featuring innovations such as smart glazing and transparent photovoltaics.
- **Hardware**: Focusing on heating, ventilation, and air conditioning, lighting, and other essential equipment.
- **Process**: Including environmental monitoring, predictive controls, and sensors.
- **CO_2 Utilization**: Covering sources such as combustion, fermentation, direct air capture, and advanced distribution systems for the purpose of increasing crop yields

Each technology is assessed using a combination of quantitative metrics and qualitative metrics (e.g., retrofit feasibility, spatial footprint, longevity).

This catalog provides a foundational framework for scaling CEA responsibly and cost-effectively. By offering a clear, data-informed roadmap of available technologies and their tradeoffs, the project helps pave the way toward a more efficient and accessible CEA future—one that meets food and floriculture demands while reducing operating costs and improving long-term business viability.

1. Introduction

Industry reports often describe controlled environment agriculture (CEA) as an effective approach to reducing production variability caused by weather, pests, and disease pressures, enabling more consistent year-round output (WayBeyond and Agritecture Consulting, 2021). Proponents also highlight benefits such as reduced pesticide use and improved food safety (RII, 2023a), as well as extended shelf life and reduced food waste through localized production (Agrilyst, 2017). Studies further emphasize the high water-use efficiency of CEA's closed-loop systems (Mohammed, 2017) and the potential for significantly higher yields per acre compared to field-based agriculture (Weidner et al., 2022). Some researchers also suggest that CEA can be viewed as a modern agricultural venture with the potential to attract younger generations to farming (WayBeyond and Agritecture Consulting, 2021).

Despite these promising attributes, the reality of CEA has not fully met these expectations, motivating this study. CEA presents a pathway for year-round food production under precisely managed conditions, but profitability is seldom achieved due to high energy and labor costs (Walker 2024). Electricity and heating requirements drive much of the operational burden, and while heating demands may be met with electricity, many facilities rely on natural gas, fuel oil, or district heating.

In fact, heating, ventilation, and air-conditioning (HVAC), lighting, and dehumidification constitute the largest share of energy use in CEA. Studies estimate that energy use accounts for up to 60% of a facility’s operational costs, with lighting alone accounting for about half of that usage (ACEEE n.d.). In some indoor farms, lighting may consume as much as 70% of total power, with humidity and temperature control using around 28% (Penuela et al. 2024). Consequently, energy expenses can make up as much as 40% of total production costs, posing a considerable challenge for the industry’s economic viability and scalability.

Several studies point to barriers to long-term scalability of CEA, including limited realized water savings, elevated capital costs, and high energy and material input requirements (Engler & Krarti, 2021; Dixon, 2023; Ehmke & Zuckerberg, 2022). Nevertheless, findings from the Resource Innovation Institute’s (RII) Energy & Water Benchmarking Report (RII 2023b) indicate that many CEA operations are successfully improving their resource efficiency. Against this backdrop, the aim of this technology catalog is to address these issues by identifying and promoting technologies that could help the CEA industry realize its potential in an efficient and cost effective manner.

2. Controlled Environment Agriculture Landscape

2.1 Crop Types

Several resources, such as the 2019 Census of Horticultural Specialties (USDA 2019) and 2022 Census of Agriculture (USDA 2022), cite the following specialty crops as the ones commonly grown under protection:

Floriculture
- Nursery crops
- Bedding and garden plants
- Cut flowers and florist greens
- Indoor foliage plants
- Potted flowering plants

Produce
- Leafy greens
- Microgreens
- Herbs
- Tomatoes
- Cucumber
- Peppers
- Mushrooms
- Strawberries

2.2 Facility Types and Growing Systems

CEA encompasses a wide range of facility types and growing systems. While the industry often uses different terms interchangeably (e.g., “indoor farm,” “vertical farm,” “plant factory,” etc.), for simplicity, this catalog groups CEA facilities into three main categories (Agrilyst 2017; Artemis 2020).

Hoop Houses (Low-Tech Plastic Hoop Houses)
Definition and Key Features: Semicircular, tunnel-shaped structures made of steel and polythene, often covering soil. Typically low-tech, with minimal or no automation (e.g., only simple heaters or fans, if any). Some operations refer to them as high tunnels.

Greenhouses
Definition and Key Features: Enclosed structures with transparent or semitransparent walls and/or roofs (glass, polycarbonate, etc.) that rely primarily on natural sunlight.
Subtypes:
Glass or Poly Greenhouse: Basic structure, transparent enclosure; moderate automation.
High-Tech Glass Greenhouse: Advanced structure with significant automation (e.g., integrated HVAC, environmental controls). These may also supplement natural sunlight with artificial lighting to extend day length or control light intensity.
Mid-Tech Greenhouse: More automation than a basic poly greenhouse but not as advanced as

a high-tech greenhouse. Some mid-tech greenhouses also use supplemental artificial lighting.

Indoor/Vertical Farms, Also Known as Plant Factories
Definition and Key Features: Fully enclosed, opaque structures (often called “indoor farms”) where environmental conditions—light, temperature, humidity, and CO_2—are almost entirely controlled. Artificial lighting is used instead of sunlight, and growing setups often involve stacked layers (i.e., vertical growing).
Subtypes:
Container Farms: Standardized, self-contained vertical farming units with built-in lighting and hydroponic systems.
Vertical Farms with Artificial Lighting: Highly controlled, multitiered environments using LED or other artificial lights, often referred to as “plant factories.”

While the facility types described above (hoop houses, greenhouses, indoor/vertical farms) are the central focus of this catalog, it is important to note that CEA production can be achieved using a variety of growing systems. These systems are independent of the type of structure and may be found across different facility types. Because this catalog concentrates on the facility-level aspects of CEA, the following systems are described here for reference only and will not be a focal point throughout the subsequent sections. Common CEA growing systems include:

- **Hydroponics**: Plants grown in water with dissolved nutrients rather than soil.
- **Aeroponics**: Plant roots suspended in air and misted with nutrient solution.
- **Aquaponics**: Plants grown in water shared with aquatic organisms (typically fish), creating a symbiotic ecosystem.
- **Soil-Based**: Plants grown directly in soil or soil-like substrates.
- **Hybrid**: Facilities that combine multiple approaches (e.g., a greenhouse with outdoor fields, or an indoor farm that includes aquaponics and hydroponics).

Throughout this catalog, we consistently refer to three primary facility categories: hoop houses, greenhouses, and indoor/vertical farms. While hoop houses are mentioned less frequently in the catalog because they tend to adopt technology at lower rates, they are included here to reflect their role in the broader industry landscape. The CEA industry and literature use a variety of terms and acronyms interchangeably to describe facility types. Below is a non-exhaustive list to help readers navigate the different names they might encounter:

- **Hoop Houses**: May also be called “high tunnels,” “low-tech plastic houses,” or “polytunnels.”
- **Greenhouses**: Sometimes referred to as “glasshouses,” “poly greenhouses,” or “controlled environment greenhouses.”
- **Indoor Farms**: Often described as “vertical farms,” “plant factories,” “vertical farms with artificial lighting,” “plant factories with artificial lighting,” or simply “indoor farms.”

Despite these many variations in terminology, our catalog **focuses on these three categories** to simplify discussions and maintain consistency across sections. Where possible, we clarify alternative naming to help readers build familiarity with the broader CEA landscape.
Although the majority of environmental footprint studies on CEA have focused on high-tech,

energy-intensive facilities like vertical farms and greenhouses, many CEA operations are low-tech hoop houses. Examples include open-air, soil-based systems with plastic covers, which currently constitute a significant portion of global food production spaces. In the United States, hoop houses account for 74% of the total number of operations and 75% of the total area of operations under protection. Medium- to high-tech greenhouse operations account for the other 26% of the total operations and 25% of the total area of operations (USDA 2019). Technology in these low-tech operations is likely to be very basic—simple heaters and fans—or not present at all. Medium- to high-tech operations are more likely to include more advanced technology such as lighting systems, HVAC, and controls. Throughout this catalog, we acknowledge the prevalence of these low-tech facilities and explore relevant technologies aimed at enhancing the adoption of CEA across our food system.

Further, the spread of crops grown in the U.S. CEA industry is important to note. For this catalog, the breakdown of the food and floriculture crop categories will be used to set context. Floriculture under protection accounts for 64% of the operations and 86% of the total area in the United States, while food crops only make up 36% of the operations and 14% of the total area (USDA 2019). Floriculture accounts for the majority of U.S. CEA in both operations and area, though this may not be the perception of people outside the industry.

3. System Definition, Scopes, and Boundaries

This CEA technology catalog has been meticulously developed to assist stakeholders in comprehensively understanding and deploying technologies that enhance the operational efficiency and long-term viability of CEA facilities. This work builds upon previous Lawrence Berkeley National Laboratory efforts, including the Precision Urban Agriculture Initiative (LBNL, n.d.), as well as best practice guides developed by RII. It also integrates peer-reviewed insights from a wide range of multidisciplinary experts. CEA facilities are composed of several components and inputs and are part of a much larger supply chain, both upstream and downstream. However, not all of those components are represented in this technology catalog. Figure 3.1 presents a simplified schematic of a CEA facility, highlighting the components that are and are not included in the catalog.

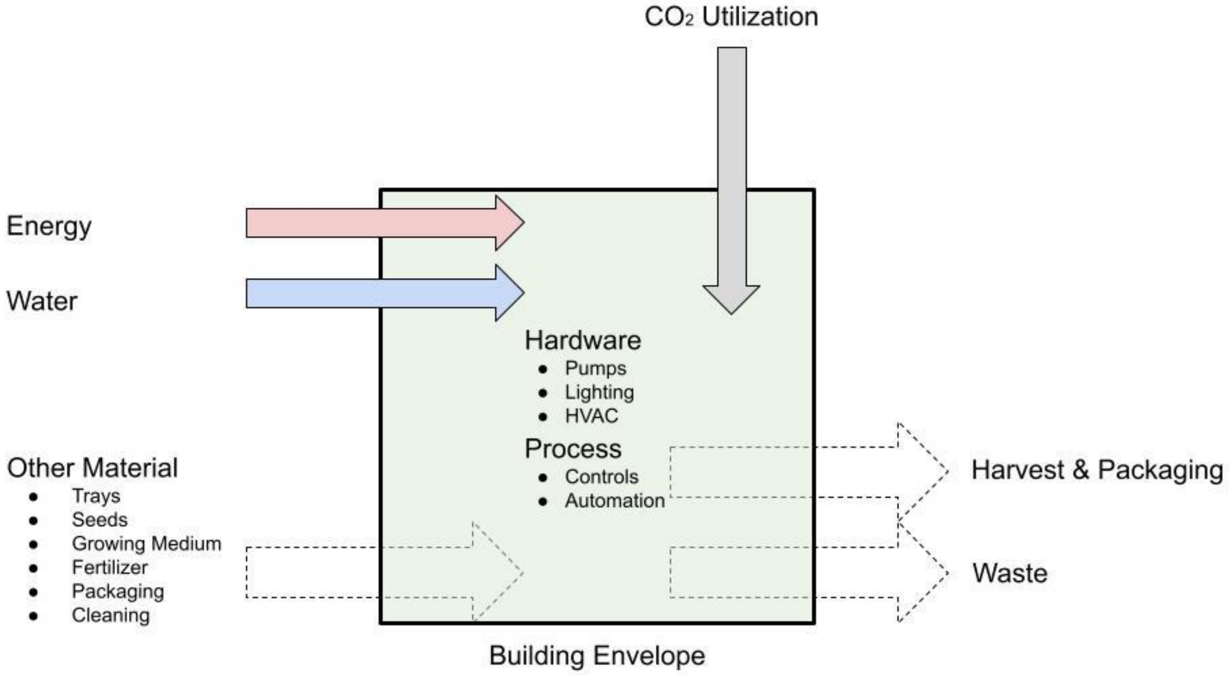


Figure 3.1. Scope of the technology catalog

A simplified schematic indicating major components of CEA facilities, with the green box and solid arrows indicating the scope of this catalog. Inputs and outputs at the bottom left and bottom right outside the green box are excluded from this technology catalog.

The technology categories selected for inclusion in this catalog encompass a broad spectrum of existing and emerging technologies that are pivotal for CEA operations. This catalog specifically focuses on water and energy technologies for input materials, building envelope, and essential hardware equipment such as pumps, HVAC, and lighting. It also covers processes such as climate control, along with the controls and automation associated with these processes. Given the critical role of carbon dioxide (CO_2) in enhancing plant growth within CEA facilities, sourcing, generating, and using CO_2 at CEA facilities is highlighted as a distinct technology category.

Colocation is also included in this catalog. It is viewed as a subset of energy technologies and is treated as a strategy rather than a technology. Its placement under the energy technologies umbrella reflects its close association with waste heat utilization and its role in improving overall facility energy performance.

These categories are shown in Figure 3.2, which illustrates the major CEA systems included in this technology assessment.

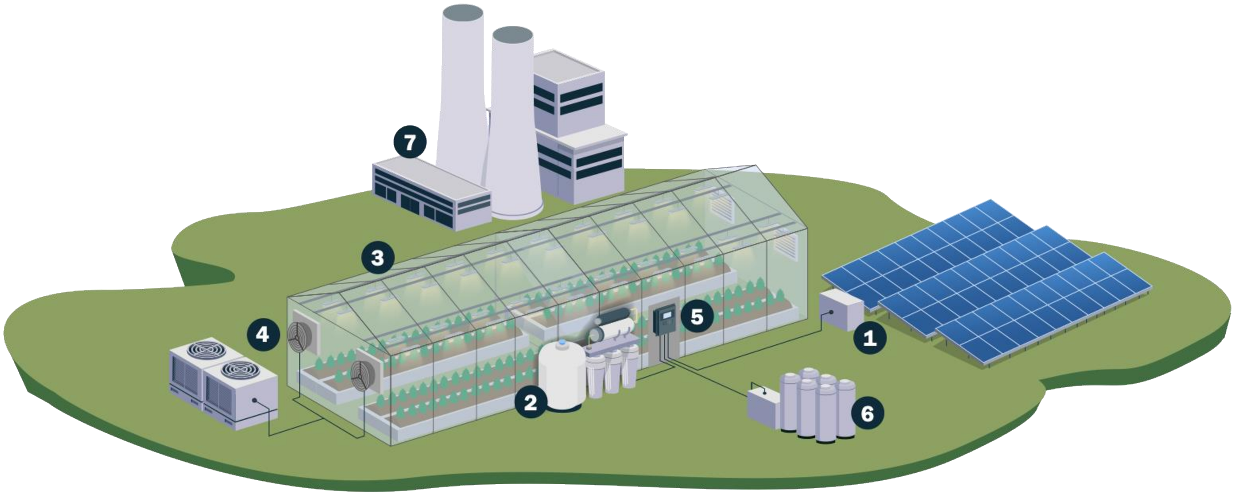


Figure 3.2. Major CEA systems included in this technology assessment
(1) Energy systems (e.g., renewables, combined heat and power, storage); (2) water technologies (e.g., recycling, filtration); (3) building envelope (e.g., glazing, insulation); (4) hardware systems (e.g., HVAC, lighting); (5) process and control systems (e.g., automation, sensors); (6) CO_2 utilization (e.g., recovery, enrichment); and (7) colocation opportunities with industrial infrastructure. Excluded elements include nutrients and other input, harvest and packaging, distribution and waste.

Although several inputs and outputs such as fertilizers, biologicals, waste, harvest, and packaging are critical for CEA facilities, they are not included in this catalog and may be addressed in future studies. Additionally, several processes occurring outside the growing area of the CEA, such as cold storage or processing and packaging, are also crucial but will not be part of the technologies mentioned in this catalog.

An overview of the technology categories included in this catalog is listed below, with comprehensive details in the next section of this catalog.

- **Energy Systems:** Includes onsite renewable generation and storage, combined heat and power (CHP) systems, integrated demand-side management, energy management, battery energy storage, colocation for waste heat utilization, and microgrids (based on both alternating current and direct current).
- **Water Management**: Includes technologies that ensure water recycling and efficiency, including CEA wastewater treatment and efficient irrigation systems.
- **Building Envelope:** Features technologies such as transparent photovoltaics (PV), retrofit films, and dynamic glazing, which are crucial for optimizing the energy efficiency of facility structures.
- **Hardware (e.g., HVAC, lighting, pumps, etc.):** Focuses on the electrification of HVAC

systems, incorporating innovations such as heat pumps and thermal energy storage. Custom-spectrum light-emitting diode (LED) lighting and sophisticated control mechanisms adjust lighting based on plant needs.

- **Process (e.g., controls and automation):** Focuses on advanced systems featuring model-predictive and demand-responsive controls that optimize various operational parameters for increased efficiency.
- **Carbon Dioxide (CO_2) Utilization:** Includes technologies related to CO_2 sourcing, generation, and utilization.

4. Assessment Metrics

4.1 Impact Categories

The technology catalog employs specific impact categories to systematically evaluate each technology's performance. These categories have been selected to provide a comprehensive understanding of the benefits and trade-offs associated with each technology. The research team's goal is to have primarily quantitative assessment metrics, offering precise data wherever available. In instances where quantitative data is not available, qualitative metrics are used to capture the technology's impact.

- **Energy Input:** Relative energy required to operate the technology.
- **Footprint:** Impact on land utilization, particularly relevant for technologies requiring significant physical space.
- **Capital Expenditure (CAPEX):** Initial investment required to implement the technology.
- **Operational Expenditures (OPEX):** Ongoing expenses associated with the operation of the technology.
- **Operation and Maintenance (O&M)**: Level of operational and maintenance effort required, reflecting factors such as specialized expertise, service frequency, and complexity of upkeep.
- **Lifespan:** Durability and operational lifespan of the technology.
- **Retrofit vs. New Build:** Suitability for integration into existing systems versus requirements for new infrastructure.

4.2 Quantitative Metrics

These include specifications such as capital and operating costs, system capacity (electrical and thermal output in kW), and expected lifespan. Cost data are presented in industry-standard units (e.g., $/kW, $/kWh, $/operating hour) to support technology comparisons and financial planning.

4.3 Qualitative Metrics

These involve descriptive evaluations where numerical data is lacking, providing insights based on expert opinions, case studies, and industry best practices. To structure these insights, the qualitative metrics will be categorized using simple scales such as small, medium, and large; low vs. high; or yes vs. no. Though these metrics lack precise quantification, they offer foundational insights into the associated technologies, aiding in general understanding and decision-making.

Table 4.1 offers a summary of quantitative and qualitative assessment metrics and indicators.

Table 4.1. Summary of Impact Categories, Metrics, and Qualitative Scales

Impact Category	Quantitative Metric	Qualitative Metric
Energy Input	kW, kWh, MWh (MMBtu)	Low / Medium / High
Footprint	m² (ft²), hectares (acres)	Small / Medium / Large
CAPEX	\$/kW, \$/kWh, \$/kWh$_e$, \$/kWh$_{th}$, \$/1,000 L (\$/1,000 gal)	\$ / \$\$ / \$\$\$ / \$\$\$\$
OPEX	\$/kW/yr, \$/operating hour, % of CAPEX, \$/1,000 L (\$/1,000 gal)	\$ / \$\$ / \$\$\$ / \$\$\$\$
O&M	N/A	Low / Medium / High
Lifespan	Years, operating hours	Short (<5 yrs) / Medium (5–10 yrs) / Long (>15 yrs)
Retrofit vs. New Build	N/A	Retrofit / New Build / Both

5. Energy

This section primarily focuses on ways of sourcing energy rather than the equipment that consumes it, which will be discussed in later sections. This section outlines various innovative energy technologies designed to effectively source, manage, and efficiently use energy in CEA facilities. This information is intended to guide the adoption of strategies that reduce energy and operational costs. Each technology discussed offers unique benefits for energy sourcing and demand management, contributing to more efficient and cost-effective operations in some or all CEA facilities. We will explore the integration of alternative energy sources like solar and wind, the utilization of microgrids and battery storage to enhance energy reliability, and innovative approaches such as colocation and waste heat utilization. This evaluation aims to demonstrate how CEA operations can optimize energy use to improve profitability and long-term competitiveness. Table 5.1 summarizes the energy technologies discussed in this section, complete with relevant metrics.

Table 5.1. Energy Technologies Summary

Technology	Purpose	Electrical Capacity (kW)	Thermal Capacity (kW)	Footprint	CAPEX	OPEX	O&M	Lifespan	Retrofit/ New Build
CHP – Natural Gas Reciprocating Engine	Electricity, Heat, CO_2	250–10,000[a]	50–3,500[b]	Medium	\$3,000– \$4,000/kW of electrical output[c]	\$0.029– \$0.05 per operating hour[d]	High	20–30 years (160,000–240,000 operating hours)	Both
CHP – Hydrogen	Electricity, Heat	115–750[g]	135–1,000[h]	Medium	About 15% more than natural gas CHP, additional equipment needed[i]	\$0.029–\$0.05 per operating hour[j]	High	20–30 years	Both
CHP – Biogas	Electricity, Heat, CO_2	164–1,960[k]	90–2,000[l]	Medium	Higher than other CHP systems due to hydrogen sulfide removal requirement[m]	Higher than other CHP systems due to hydrogen sulfide removal requirement[n]	High	20–30 years	Both
Solar PV	Electricity	Varies	N/A	Medium	\$1,600–\$3,400/kW[o]	\$13/kW dc/yr–\$25/kW dc/yr[p]	Low	30–35 years	Both
Floating Solar PV	Electricity, Reduced Evaporation	Varies	N/A	Medium	10–15% premium on ground solar PV[q]	\$15.5/kW dc/yr[r]	Medium	30 years	Both
Solar Thermal	Heat	N/A	Varies	Medium	\$550–\$700/kW[s]	1–3% of CAPEX (or \$5-\$21/kWth/year)[t]	Low	10–25 years	Both
Concentrated Solar Thermal	Electricity, Heat	Varies	Varies	Large	\$5,200–\$6,500/kW[u]	Fixed: \$55 /kW/yr–\$70 /kW/yr[v] Variable: \$0.02 /kWh–\$0.04 /kWh[w]	Medium	30 years	New Build
Wood-Fired Boilers	Heat	N/A	44–2,930[x]	Small	\$1,800/kW–\$4,500/kW[y] \$10,000–\$1,200,000[z]	\$0.15 /kWh–\$0.18 /kWh[aa]	Low	20–30 years	Both
Wind Turbines	Electricity	5–5,000[bb]	N/A	Large	\$3,500–\$5,700 (for distributed wind energy)[cc]	\$35/kW/yr[dd]	Medium	20–30 years	New Build

Technology	Purpose	Electrical Capacity (kW)	Thermal Capacity (kW)	Footprint	CAPEX	OPEX	O&M	Lifespan	Retrofit/ New Build
Direct Geothermal	Low Grade Heat	N/A	100–20,000[ee]	Medium	$381/kWth–$1,300 /kWth (Surface CAPEX only) $1,000/m–$3,200/m (Well drilling cost)[ff]	$50 /kW/yr - $400 /kW/yr[gg]	Low	25–50 years	New Build
Indirect Geothermal	Electricity, Heat	10,000–1,500,000[hh]	Varies	Large	$2,500/kW[ii]	N/A	High	15 years	New Build
Energy Management	Energy Reduction	3% annual savings[jj]	3% annual savings[kk]	N/A	$0.02/kWh of Energy Saved[ll]	Variable[mm]	Medium	1–5 years	Both
Demand Response	Cost Reduction	N/A	N/A	N/A	$0–$400/kW-year[nn]	5%–30% reduction in electricity cost[oo]	Low-Medium	N/A	Both
Battery Energy Storage	Cost Reduction, Reliability	0.3–3,000[pp] (1 kWh–10 MWh)	N/A	Small-Medium	$133–$700 /kWh[qq]	$10.8/kW/y[rr]	Medium	5–15 years	Both
Thermal Energy Storage	Cost Reduction, Energy Reduction	N/A	Variable	Medium-Large	$232/kWh[ss]	Data Not Found	Medium	Data Not Found	Both
Microgrids	Energy Reliability	2,000–60,000[tt] (Most microgrids are 2 - 10 MW of installed generation capacity)	N/A, unless CHP, boilers, or backup generators are part of the microgrid	Medium-Large	$2,000–$5,000/kW[uu]	Variable	High	20 years; some components require replacement at 5–10 years	Both

[a] INNIO (2023).

[b] INNIO (2023). This range represents the per-unit capacity of CHP systems commonly used in CEA facilities. These units can be stacked and combined to achieve higher total capacities. According to Jenbacher (2024a), the highest recorded installed CHP system for a CEA facility reaches 21,000 kW thermal output, achieved by integrating six 3,500 kW units in a single installation.

[c] Consultation with expert. Larger units have lower $/kW cost.

[d] Consultation with expert.

[e] SGIP: Self-Generation Incentive Program.

[f] IRA: Inflation Reduction Act.

[g] 2G (n.d.).

[h] Consultation with expert.

[i] Consultation with expert.
[j] Consultation with expert.
[k] DOE (n.d.-a).
[l] Consultation with expert.
[m] Consultation with expert.
[n] Consultation with expert.
[o] Feldman et al. (2024).
[p] Wiser et al. (2020).
[q] Consultation with expert and Ramasamy and Margolis (2021).
[r] Ramasamy and Margolis (2021).
[s] Akar et al. (2022). The reported CAPEX range of $550–$700/kWth (kilowatt-thermal) for flat-plate collectors is based on 2022 data for renewable thermal energy systems. While solar collector costs typically fall within this range, complete systems that integrate thermal energy storage, heat exchangers, and supporting infrastructure may exceed $1,000/kWth.
[t] Akar et al. (2022).
[u] NREL (2024). Values for the year 2024 are rounded and also capture the range between the advanced and conservative scenarios.
[v] NREL (2024). Values for the year 2024 are rounded and also capture the range between the advanced and conservative scenarios.
[w] Augustine et al. (2022).
[x] Expert consultation and various online resources.
[y] IRENA (2012).
[z] Cost estimate from various manufacturers including Crown Royal Stoves, Triple Green Products, The Log Boiler, and others.
[aa] Wang et al. (2019).
[bb] EPA (2013).
[cc] Stehly and Duffy (2022).
[dd] Stehly and Duffy (2022).
[ee] Robins et al. (2021).
[ff] Beckers et al. (2021) and Robins et al. (2021).
[gg] Beckers et al. (2021).
[hh] Wikipedia (n.d.)
[ii] University of Michigan (2023).
[jj] Fitzgerald et al. (2023).
[kk] Fitzgerald et al. (2023).
[ll] LBNL (n.d.)
[mm] OPEX for an EnMS varies widely depending on staffing (from a fraction of a full-time employee to a full team) and system complexity, with costs potentially ranging from tens to hundreds of thousands annually.
[nn] Alstone et al. (2017)
[oo] Arabzadeh et al. (2023); Avgoustaki and Xydis (2021).
[pp] Benson (2023).
[qq] Various sources.
[rr] CEC (2023).
[ss] Martucci (2024).
[tt] Giraldez et al. (2018)
[uu] DOE (2024a) and Giraldez et al. (2018).

5.1 Combined Heat and Power

Combined heat and power (CHP) systems provide substantial benefits for CEA, offering a solution to the high energy demands associated with lighting and space conditioning. By efficiently capturing and utilizing waste heat, CHP systems significantly enhance energy efficiency in CEA processes including heating water and conditioning spaces in vertical farms and greenhouses. Moreover, CHP systems can supply exhaust heat and CO_2, both crucial for enhancing crop yield. These systems offer fuel flexibility, operating on natural gas, biogas, or hydrogen, allowing facilities to optimize for cost and availability (DOE 2021). This versatility makes CHP an important component for CEA operations. A typical CHP set up for CEA is shown in Figure 5.1. Throughout this section, references to natural gas-fueled CHP refer primarily to reciprocating (gas) engines—the most common greenhouse CHP technology due to their flexible capacity, strong part-load performance, straightforward CO_2 injection, and robust vendor networks.

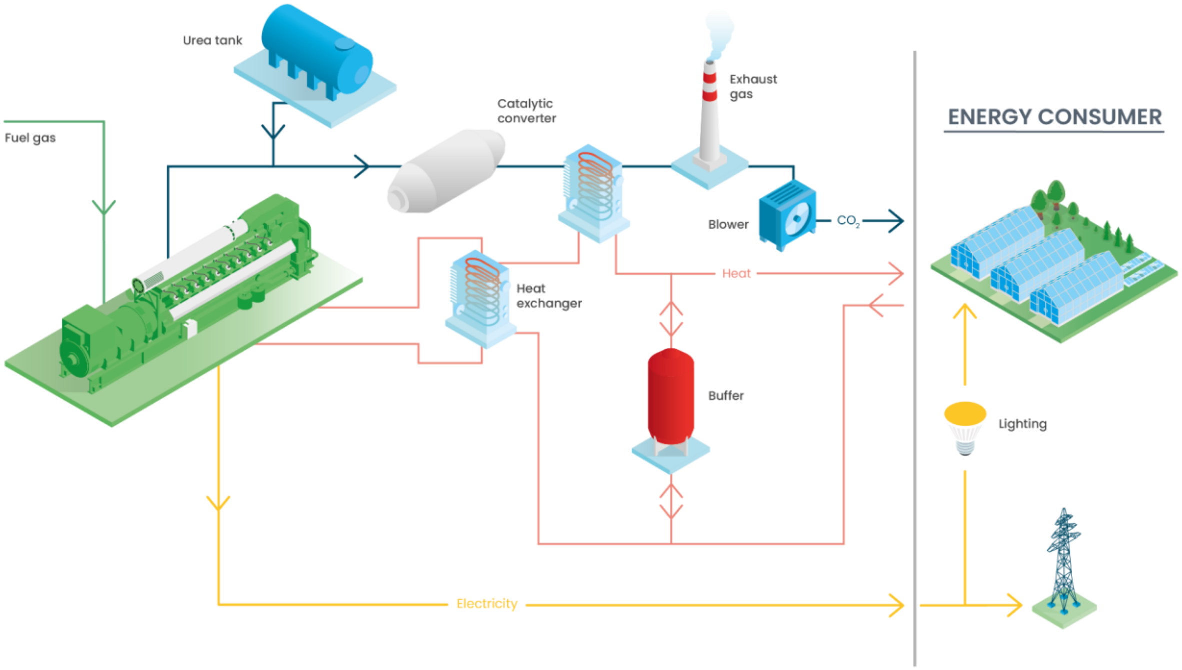


Figure 5.1. Combined heat and power schematic

A CHP system coupled with CO_2 fertilization to provide electricity, heat, and CO_2. Source: Jenbacher (2024a)

Integrating CHP systems into CEA facilities offers a multifaceted suite of benefits that enhance operational efficiency and economic viability. CHP systems provide a robust solution to energy management challenges by generating electricity onsite. This onsite generation enables continuous operations, especially during external power disruptions, safeguarding the precise environmental conditions necessary for optimal plant growth and increasing reliability. In regions prone to electricity supply issues, the ability of CHP systems to operate independently from the grid ensures that energy-intensive agricultural processes remain uninterrupted, enhancing the overall productivity and stability of CEA operations.

Beyond enhancing energy reliability, CHP systems can generate revenue for CEA facilities if excess electricity can be sold back to the grid. In some cases, this may also support local or regional grid stability and increase the benefits of participating in demand response programs, where CEA facilities can earn financial incentives by modulating their energy consumption and maximizing energy generation during peak periods, aligning economic benefits with energy conservation strategies. However, demand response participation can happen regardless of CHP or any other energy technology; refer to Section 5.2.9, Electricity Demand Management, for more information. Additionally, CHP systems can use a variety of fuels such as hydrogen and biogas, which can be sourced from colocation with wastewater treatment plants and agricultural activities like dairy farms. This flexibility not only reduces fuel cost but also equips CEA operations to adapt to variable energy and regulatory landscapes.

CHP systems offer the unique advantage of utilizing exhaust gases, including CO_2, to enhance crop growth—a topic discussed in detail in Section 10, CO2 Utilization. CO_2 is produced as a byproduct during the combustion process in a CHP system. This CO_2 can be captured from the exhaust gases instead of being released into the atmosphere. The captured exhaust needs to be cleaned to remove harmful components like nitrogen oxides, sulfur oxides, and other impurities that could be detrimental to plant health. This flexibility not only reduces fuel cost but also equips CEA operations to adapt to evolving energy and regulatory requirements.

For CEA facilities considering CHP systems, understanding the associated CAPEX and OPEX is crucial. The CAPEX for CHP systems primarily encompasses the costs of equipment such as engines and installation, ranging typically from $3,000 to $4,000 per KW of electrical output (Expert Consultation). This investment can be lower per KW for larger systems due to economies of scale. OPEX varies based on the size of the system and includes maintenance, oil changes, engine rebuilds, and other routine expenses. OPEX is often calculated based on operating hours and can range from $0.05 per hour for smaller engines to as low as $0.029 per hour for larger units. Notably, biogas-fueled CHP systems incur higher operational costs due to the additional processing required to remove contaminants such as hydrogen sulfide, which can significantly impact system components and efficiency, poison the CO_2 scrubber catalyst, and may degrade to sulfuric acid, a chemical harmful to plants.

The typical lifetime of CHP systems ranges from 20 to 30 years, depending on operational hours. Complete engine rebuilds are typically required twice in the CHP lifetime to ensure peak performance. Understanding these financial and maintenance aspects helps CEA operators evaluate the economic impacts and long-term viability of incorporating CHP technology into their operations, according to Aaron Tasin at Northeast-Western Energy Systems USA (Aaron Tasin, correspondence with author, June 12, 2024).

One major barrier to achieving a CHP system’s full potential is the misalignment between lighting (electricity) and CO_2 demand. The demand for CO_2 in greenhouses aligns with daylight hours when photosynthesis occurs. It does not coincide with the typical demand for electricity.

This misalignment highlights a critical paradox: While CHP systems are capable of generating both CO_2 and electricity simultaneously, their most efficient use occurs at different times. Ideally, greenhouses need to store CO_2 and sell surplus electricity back to the grid, both of which can be challenging. Adding CO_2 storage increases costs. Selling electricity back to the grid can be challenging due to complexities in U.S. electricity markets (Aaron Tasin, correspondence with author, June 12, 2024).

5.2 Onsite Generation

Costs for onsite or behind-the-meter energy sources like solar power have fallen cost are increasingly attractive for CEA facilities seeking to lower energy costs, improve reliability, and reduce dependence on the grid—particularly for power-intensive operations facing lengthy interconnection backlogs. However, onsite energy generation has its drawbacks. For context, a vertical farm producing 25,000 pounds of produce per month would need about 1.5 acres of solar panels to source all of its power needs (Ehmke and Zuckerberg 2022). While there is potential for onsite electricity generation in vertical farms, most onsite generation infrastructure (solar PV, wind turbines, geothermal) requires large upfront investments and vast amounts of land and comes with a unique set of siting and implementation challenges (Weidner 2022).

According to the *2021 Global CEA Census Report*, 37% of CEA facilities currently get their energy from renewable sources. Of these, roughly two-thirds generate energy onsite, and another one-third pay their utility provider explicitly for renewable energy (WayBeyond and Agritecture Consulting 2021). Purchasing renewable power from the grid falls outside the scope of this catalog. Such arrangements typically involve renewable energy certificates and interactions with utility providers which are not covered here. This section focuses on energy generation technologies that CEA facilities can implement onsite or access through colocation arrangements.

Energy sources that require specific geographical conditions and a large land footprint—such as geothermal fields, solar thermal plants, and hydroelectric dams—are discussed in Section 5.2.12, Colocation. This distinction ensures that CEA operators understand and evaluate different approaches to sourcing energy: direct installation or strategic colocation. By delineating these options, we aim to help operators evaluate options for reducing energy costs and improving energy security.

5.2.1 Solar Photovoltaic

Solar PV systems are increasingly prevalent in CEA, particularly for vertical farms that require substantial energy for lighting and climate control. Integrated PV panels can offset a facility's electricity demand and, in some cases, generate surplus power to sell back to the grid (Martin and Molin 2018; Zeidler et al. 2017). In contrast, for solar PV systems at greenhouses (Figure 5.2), the primary challenge lies in the shading effect caused by static, conventional PV modules, which reduce the photosynthetic efficiency of crops. Research has shown that 1% of fixed PV module coverage can decrease a tomato crop’s yield by about 0.66%. Two potential solutions to this issue—dynamic shading and concentrating solar technologies—are explored later in this section (Kumar et al. 2022).

Figure 5.2. A greenhouse using solar PV
Source: Hortinergy (n.d.)

By integrating PV panels directly onto or near the building, these systems provide a local energy source that can significantly reduce electricity costs while bypassing grid interconnection bottlenecks. The initial installation of solar PV is cost-intensive, but the long-term benefits include the potential to sell excess electricity back to the grid, enhancing the facility's economic viability. Despite their advantages, the effectiveness of solar PV in CEA depends heavily on geographic location and solar resource availability. Additionally, the large space required for solar panels may be a limiting factor in urban settings. Roof loading capacity, particularly on brownfield sites (e.g., abandoned, underused, or idled properties), may further restrict their use. However, decreasing costs due to solar technology advancements makes PV a compelling option for CEA facilities aiming for energy independence. Onsite solar PV integration can be enhanced if it is part of a microgrid, discussed further in Section 5.2.11, Microgrids.

5.2.2 Floating Solar Photovoltaic

Floating solar PV offers a synergistic solution for greenhouses by generating energy onsite while conserving water and improving water quality in agricultural operations (Figure 5.3). These systems are strategically placed on water-holding ponds, where they minimize evaporation, reduce algae, and use underexploited space efficiently. The proximity to water significantly cools the PV panels, enhancing their electricity production efficiency; research indicates that a decrease in panel temperature by 1.8°F can improve efficiency 0.3%–0.5%

(Solar N Plus 2024). This cooling effect can increase overall electricity production by up to 5% (Ramanan et al. 2024). The systems also significantly reduce water evaporation by as much as 42% when compared to uncovered reservoirs, especially in hot, arid regions (Farrar et al. 2022). Such conservation is critical when water scarcity impacts both agriculture and human consumption. Floating solar PV will have limited applicability to vertical farms and container farms, as they do not typically use water-holding ponds.

Figure 5.3. Floating PV

Floating solar PV panels on water reservoirs at Zwinkels bell pepper nursery in Wervershoof, Netherlands. The floating PV ensures high water quality and consistent supply, which is vital for bell pepper cultivation. Source: Genap (2024)

However, the implementation of floating solar PV is not without challenges. The electrical output of PV modules is direct current and necessitates the use of inverters to convert this into more usable alternating current. The placement and scaling of these inverters on floating structures poses design challenges and raises safety concerns. Moreover, fluctuating water levels in reservoirs can impact the structural integrity of the installations; extremely low levels may cause the panels to contact the reservoir bed, leading to potential damage.

Despite these challenges, the ecological impacts of floating solar farms, particularly on reservoir ecology, are an area of active research. The shading provided by the panels could reduce algal growth and improve water quality (W. Li et al. 2011). Floating solar PV systems offer a practical solution for CEA facilities with existing water infrastructure, generating electricity while making use of otherwise underutilized space and reducing water loss from evaporation.

5.2.3 Solar Thermal (Heat Only)

Solar thermal technology captures sunlight and converts it into heat, which can be used for various CEA applications (Figure 5.4). For greenhouses and other CEA facilities, solar thermal systems can provide an efficient and cost-effective heat source for space heating, water heating, and soil warming. These systems typically consist of solar collectors, such as flat-plate or evacuated tube collectors, that absorb solar energy and transfer the heat to a working fluid using a heat exchanger. The fluid is then circulated to distribute heat throughout the facility.

By using solar thermal systems, CEA operations can reduce heating costs, hedge against fuel price volatility, and improve overall energy efficiency. This approach is particularly effective in regions with high solar insolation and where the heating demand aligns well with the availability of solar energy. The amount of heat energy captured per square meter of collector surface area varies with design and location but typically can range from 300 to 800 kWh/m^2/y (Varbanov and Klemeš 2011). Moreover, integrating a thermal energy storage system (buffer tanks) can further enhance these benefits by capturing excess solar heat for later use. This method maximizes solar energy utilization and reduces dependency on external fuel supplies.

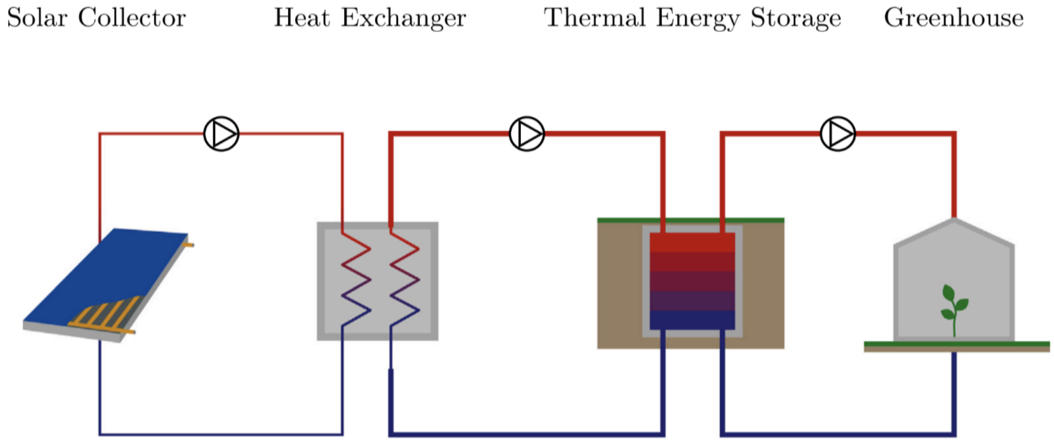


Figure 5.4. Solar thermal collector

Schematic of collectors, heat exchanger, buffer tank, and CEA heating system. Source: Adapted from Tafuni et al. (2023)

5.2.4 Concentrated Solar Thermal Electricity (Electricity and Heat)

Concentrated solar thermal (CST) technology uses mirrors or lenses to concentrate sunlight onto a small area to produce the high temperatures needed to generate both electricity and heat (Figure 5.5). In the context of CEA, CST systems offer a dual benefit: they provide onsite electricity for lighting, HVAC systems, and other electrical needs, while also supplying heat for maintaining optimal temperatures within the growing environment. Integrating CST into CEA facilities can significantly reduce energy costs by leveraging abundant solar energy. Furthermore, CST systems can store thermal energy, enabling them to provide continuous power and heat even during cloudy periods or after sunset. This makes them an ideal solution for CEA operations located in sunny regions that require reliable, energy sources for both electrical and thermal demands.

Figure 5.5. Solar thermal at a CEA facility

Aerial image of Sundrop Farms in Australia, which uses CST to generate electricity, heat, and desalinated water for a greenhouse growing tomatoes. Source: Kiernan-Stone (2022)

Key CST technologies such as parabolic troughs and molten-salt power towers optimize efficiency and can reduce both capital and operational costs. These systems often incorporate dual-tank thermal energy storage, facilitating continuous power supply for CEA operations. In terms of space requirements, CST systems can generate 5 to 7.75 kWh/m²/day, or 1,825 to 2,829 kWh/m²/year (Murphy et al. 2019). For a facility requiring 1,000 MWh/year, this translates to around 350 to 550 m² of collector area, depending on the local solar resource. Zoning concerns may limit the large land area needed, making CST more suitable for rural or spacious regions with high solar exposure.

Notably, Sundrop Farms in Australia uses CST not only for energy but also for desalination, supporting their production of 17 million kilograms of tomatoes annually with a system that integrates electricity, heat, and freshwater production (Figures 5.5 and 5.6). Power plants such as Crescent Dunes in the United States and Noor III in Morocco showcase CST's capabilities in providing sustained energy output and high operational efficiencies. Looking ahead, technological advancements and economic evaluations suggest significant cost reductions, with future developments potentially lowering CAPEX by up to 30% by 2030. Such advancements could make CST increasingly cost-competitive for CEA operations in high-solar regions. (Aalborg CSP n.d.; NREL 2024).

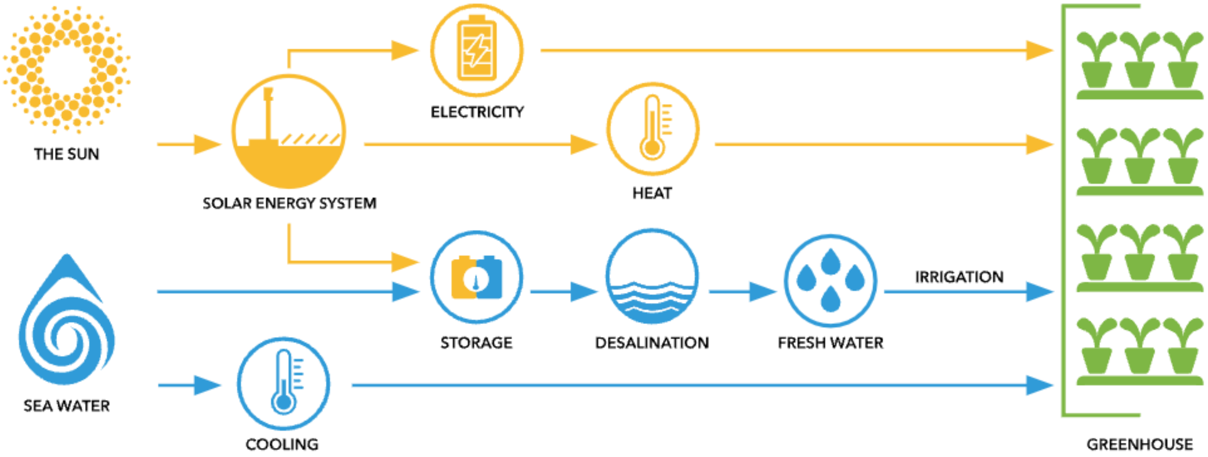


Figure 5.6. Schematic of the Sundrop Farms CST system
Source: Sundrop Farms (n.d.)

5.2.5 Wood-Fired Boilers

Wood-fired boilers may offer an economical heating option for CEA facilities by utilizing biomass such as fuel wood, waste wood, and agricultural waste (Figure 5.7). As biomass power plants are phased out in some regions, agricultural and forestry waste streams are becoming a disposal challenge—CEA facilities can turn this liability into a low-cost fuel source while generating onsite heat.

Efficient combustion requires a balance of fuel, air, and heat to ensure proper burning and meet air quality requirements. The energy content of the fuel depends on moisture and density, and advanced boilers are designed to maximize heat generation while meeting local air quality regulations (Bartok 2007). The long-term viability of these systems depends on reliable, cost-effective fuel sourcing and permitting requirements, which vary by region (EPA 2022).

Wood-fired boilers are particularly effective in colder climates where they can significantly reduce heating costs. These systems can be integrated with existing heating infrastructure to manage base loads; buffer tanks can store excess heat for peak demands, improving overall cost-effectiveness (Säätötuli 2018).

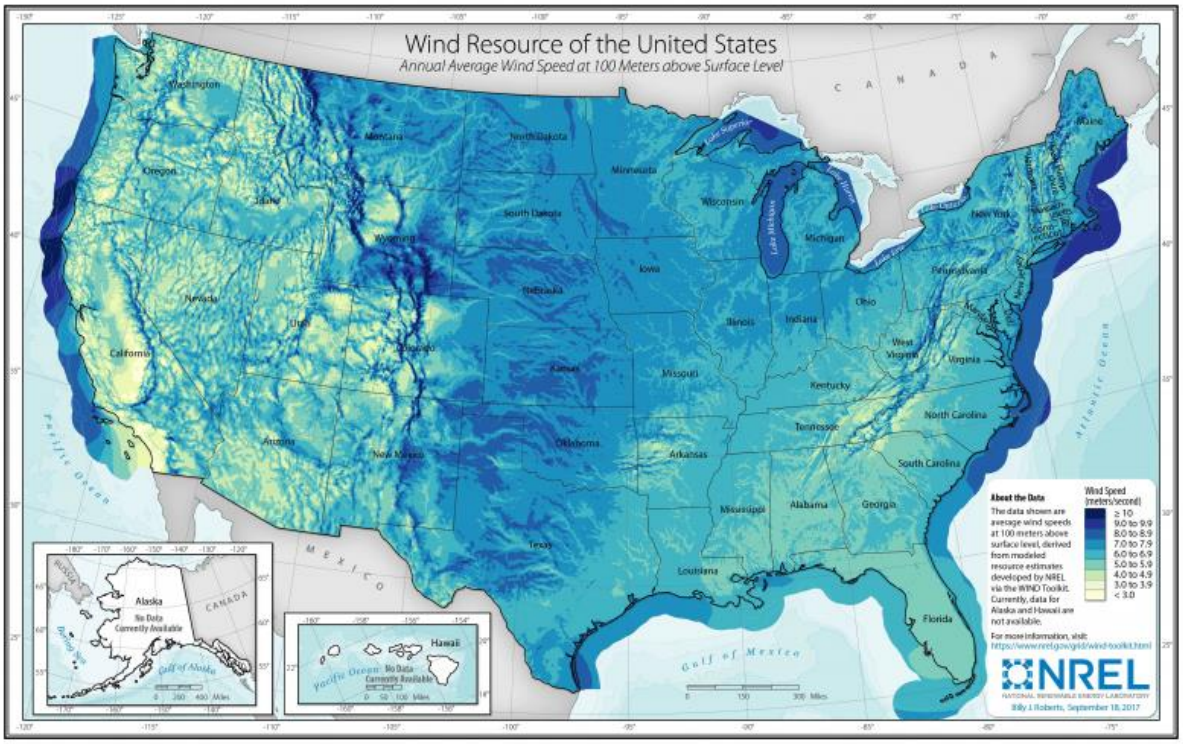
Figure 5.7. Greenhouse heating with biomass in Canada
Source: Säätötuli (2018)

A case study from Blais Farm in Vermont demonstrates the economic and operational aspects of wood-fired boilers in a CEA setting. Blais Farm replaced approximately 2,500 gallons of heating oil annually, reducing heating costs by up to $7,000 per year with a payback period of 3.5 years—assuming fuel costs of $50/cord and heating oil at $4/gallon (Grubinger 2008). However, the system is labor-intensive, requiring frequent feeding during colder periods. Poor insulation in parts of the underground piping led to significant heat loss, highlighting the need for proper installation and system design.

5.2.6 Wind Turbines

While less common in CEA due to geographic and infrastructure requirements, wind energy can be a viable option in rural or coastal settings with strong wind resources (Figures 5.8 and 5.9). Facilities such as Nordic Harvest in Denmark have successfully integrated wind power, demonstrating its potential for onsite energy generation in CEA (Jordan 2023).

Figure 5.8. Example of wind turbines being used for a greenhouse in Spain
Source: Enair (n.d.)



About the Data

The data shown are average wind speeds at 100 meters above surface level, derived from modeled resource estimates developed by NREL via the WIND Toolkit. Currently, data for Alaska and Hawaii are not available.

For more information, visit: https://www.nrel.gov/grid/wind-toolkit.html

Figure 5.9. Wind resources in the United States
Source: NREL (2017)

For CEA facilities in high-wind areas, turbines can diversify energy sources and reduce electricity costs. However, successful implementation requires thorough site assessments, and ongoing maintenance is essential to maximize operational lifespan and ensure reliable power supply.

5.2.7 Geothermal Energy

Geothermal energy is heat from the Earth. Geothermal energy resources range from shallow ground to hot water and hot rock found a few miles beneath the Earth's surface, and deeper to the extremely high temperatures of molten rock (Crowe 2014). Geothermal resources for the United States are shown in Figure 5.10. When considering using geothermal energy, the availability of geothermal resources is a critical issue.

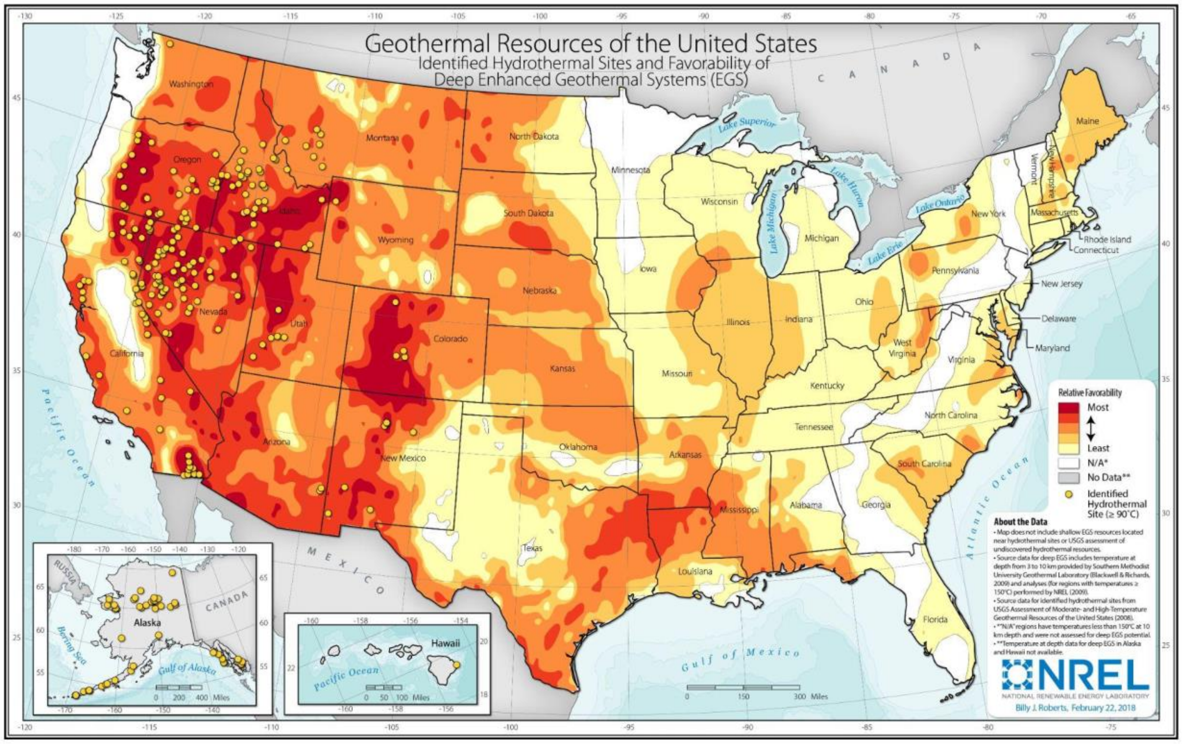


Figure 5.10. Geothermal resources in the United States

Source: NREL (2018)

Geothermal heating systems harness the Earth's vast underground thermal energy, offering cost-effective greenhouse heating through direct and indirect methods. These systems exploit shallow ground temperatures which can provide a consistent source of electricity, as well as low- to high-temperature heat, despite variations due to depth and season. Low-temperature (50°F) systems, often paired with heat pumps, efficiently manage air temperature for crop production. Medium- (140°F–300°F) and high-temperature (>300°F) geothermal sources supply direct heat or steam, widely used in regions with natural thermal wells or geysers. Geothermal heat pumps and closed-loop systems use the ground or water bodies as thermal banks, providing both heating and cooling and reducing operational costs. These systems, alongside robust energy conservation practices, offer stable long-term OPEX and reduced exposure to energy price volatility, making them increasingly attractive for CEA operations (Bartok 2007).

Direct-Use Geothermal

Direct-use geothermal means that the heat from geothermal energy is not converted into electricity but rather used directly to heat a greenhouse using various configurations including geothermal heat pumps. In direct-use applications, a well (or series of wells) brings hot water to the surface; a mechanical system—piping, heat exchanger, pumps, and controls—delivers the heat to the space or process. Often, direct-use applications use lower-temperature geothermal fluids that are not hot enough for electricity generation. To improve efficiencies, water used in geothermal power plants can be 'cascaded' down for lower-temperature uses, including greenhouses or aquaculture (Green and Nix 2006).

Most direct-use applications including greenhouse heating require geothermal fluids in the low- to moderate-temperature range between 122°F and 302°F, which are typically much more abundant and located at shallower depths than the high-temperature resources needed for power generation (Crowe 2014).

Geothermal heat pumps, also known as ground-source heat pumps, leverage the Earth's consistent underground temperature to efficiently provide heating, cooling, and hot water for buildings. These systems use conventional vapor compression heat pumps to extract low-grade heat from the ground, ground water, or surface water sources, depending on the season. In the winter, the system extracts heat to warm spaces. During the summer, this system reverses, using the Earth as a heat sink to cool spaces (Figure 5.11). This dual capability not only meets diverse thermal needs but also significantly reduces the OPEX associated with traditional heating and cooling methods (Chai et al. 2012; Gorjian et al. 2021; Green and Nix 2006). Heat pumps used for cooling may not meet the dehumidification needs of some facilities. Widely used across all 50 U.S. states, geothermal heat pumps show immense potential for market growth and energy savings, underscoring their importance in building practices.

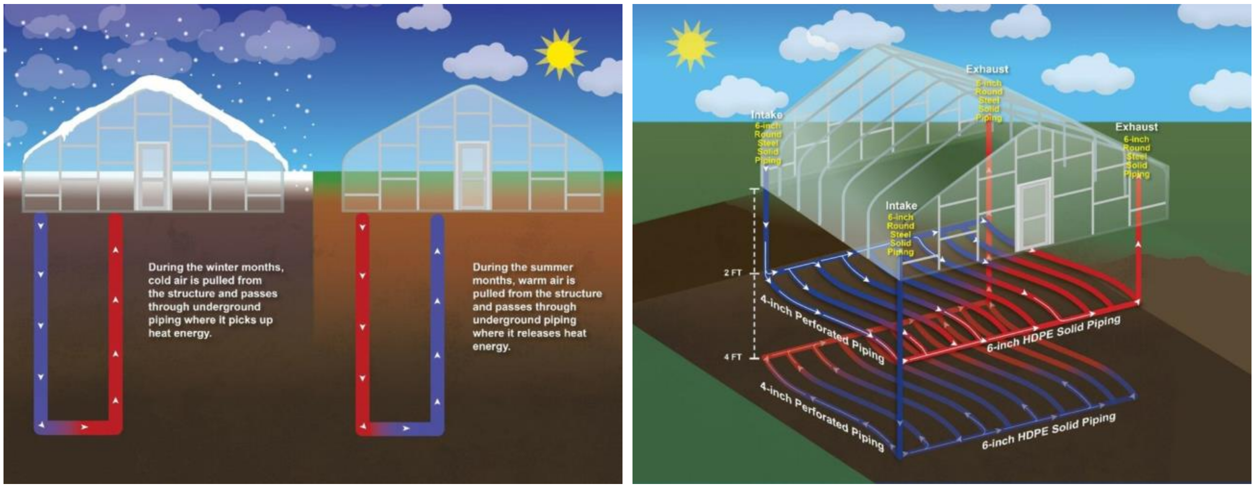


Figure 5.11. Examples of direct-use low-grade geothermal energy for CEA

Ground source heat pump flow of energy (left). Passive geothermal energy for greenhouse cooling and heating (right). Source: Smart et al. (2021)

A notable example is Coveyou Scenic Farm in Petoskey, Michigan. A geothermal heat pump both chills produce coolers and heats the farm's greenhouse floor. By circulating heat out of the walk-in coolers in summer—storing it in the ground below a parking lot—and recovering it in winter to keep seedlings warm, the farm minimized its energy costs. The system's dual-layer horizontal piping field under the parking lot makes efficient use of the available land area, while the greenhouse floor heating ensures crops flourish during cold Michigan winters (DOE 2024b).

Indirect Geothermal

Indirect use of geothermal resources includes using high-grade heat for generating electricity first and then using the waste heat from the geothermal plant (Figure 5.12). Given the high cost of drilling geothermal wells for electricity production, CEA facilities are more likely to colocate with geothermal fields rather than integrating a geothermal power plant into CEA operation.

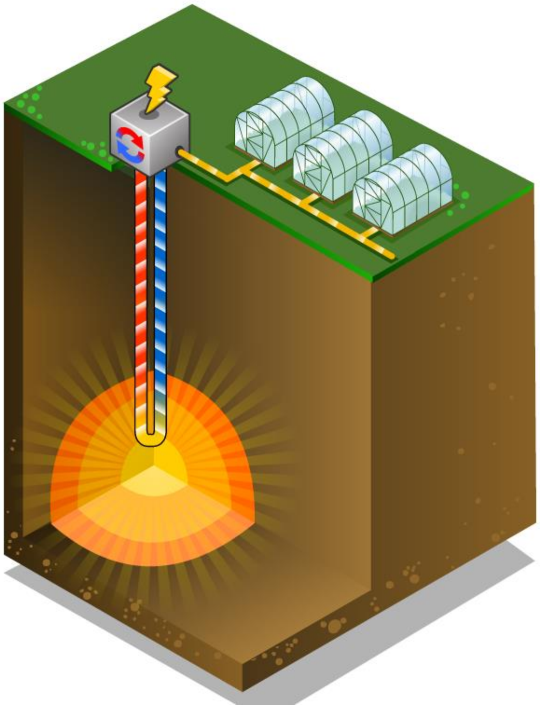


Figure 5.12. Indirect use of geothermal energy to provide electricity and heat to CEA facilities
Source: Freshbay (2023)

5.2.8 Energy Management

Energy management is essential for CEA facilities aiming to reduce operating costs and embed energy efficiency into their operations. It involves a systematic approach to monitor, control, and reduce energy use across all aspects of CEA operations. Implementing energy management systems like those based on ISO 50001 (Figure 5.13) has led to persistent annual energy performance improvements of around 3% (Fitzgerald et al. 2023).

Key components of energy management in CEA extend beyond adopting advanced technologies such as variable speed pumps, energy-efficient HVAC systems, and LED lighting. Achieving full energy efficiency requires optimizing operations and maintenance (O&M) practices, such as setting proper equipment controls, addressing sensor malfunctions, and fostering better habits among employees. Simple energy best practices such as preventative maintenance, leak audits, and timers are low-cost strategies that can yield substantial savings (EPA 2016). Tools like the U.S. Department of Energy's 50001 Ready Navigator (DOE n.d.-c) and the ENERGY STAR Portfolio Manager (ENERGY STAR n.d.) help identify and prioritize opportunities for continuous improvement.

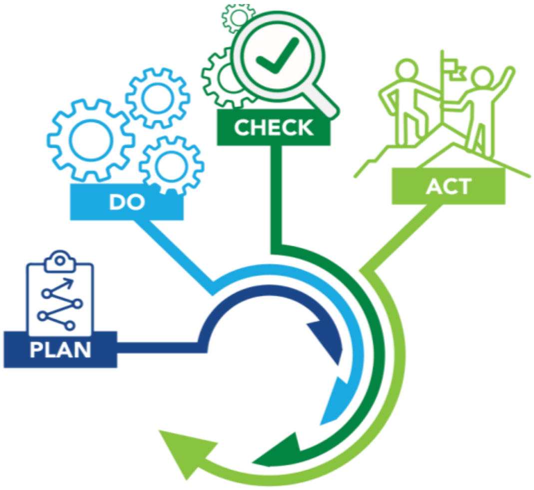


Figure 5.13. ISO 50001 energy management systems process
ISO 50001 energy management systems follow a Plan, Do, Check, Act cycle that fosters continual improvement of energy performance. Source: DOE n.d.-b

Studies highlight the significant impact of strategic energy management. Engler and Krarti (2021) found that changes to a facility's envelope, HVAC, lighting, and incorporation of onsite generation can reduce electricity consumption by up to 75% in several CEA case studies. Overall, adopting a proactive energy management strategy in CEA achieves immediate energy savings and also ensures long-term productivity and operational excellence.

5.2.9 Electricity Demand Management

Electricity demand management includes strategies to reduce energy costs by shifting or reducing electricity use during peak pricing periods. Demand response programs allow CEA facilities to adjust operations—such as dimming lights or delaying non-critical equipment—during high-cost periods in exchange for lower rates or direct financial incentives from utilities. For energy-intensive operations like vertical farms (where lighting accounts for up to 70% of electricity use), these strategies can significantly reduce electricity bills without compromising crop quality (Penuela et al. 2024). Figure 5.14 shows a greenhouse in Finland participating in a utility demand response program.

Load-shifting strategies in vertical farms can reduce lighting costs by 16% to 26% annually without negatively affecting plant growth or harvest-ready size (Avgoustaki and Xydis 2021). This flexibility allows operators to schedule lighting around peak pricing periods while maintaining crop outcomes. However, operators should weigh these savings against potential labor impacts—shifting lighting schedules may require adjusted work hours or overtime.

Figure 5.14. Demand response at a CEA facility

Greenhouse in Finland working with the local utility to do demand response. The greenhouse acts as a flexible resource for the grid while receiving financial incentives. Source: Sympower (n.d.)

5.2.10 Energy Storage

Onsite energy sources such as solar and wind are increasingly attractive for CEA, but their intermittent nature poses challenges for consistent power supply. Similarly, thermal generation from sources like solar thermal, geothermal, or wood-fired boilers may not always align with heating demand. For example, peak solar heat is available midday, while heating demand often peaks at night. Energy storage solutions address these challenges. Battery systems can store excess electricity for later use, while thermal storage (such as buffer tanks) capture heat for release during cooler periods. Utilizing these strategies ensures that CEA operations maintain reliable power and heat supply, optimizing growing conditions and reducing operational costs (Walker 2024).

Battery Energy Storage

Battery energy storage systems (BESS) enhance grid independence and reliability for CEA facilities, particularly where selling back to the grid is not viable or in microgrid configurations (see Section 5.2.11, Microgrids). BESS store surplus electricity during periods of high onsite generation and discharge it during peak demand or low production periods. This optimizes the use of onsite generation and can significantly reduce costs associated with peak electricity pricing. BESS are most commonly paired with solar PV systems (Benson 2023). They can improve operational reliability during grid outages.

BESS also enable participation in demand response programs, allowing facilities to respond quickly to utility signals and earn financial incentives. Integrating BESS with microgrid configurations offers CEA facilities greater operational autonomy and protection against grid vulnerabilities.

Thermal Energy Storage (Buffer Tanks)

Thermal energy storage, more commonly referred to in CEA as "buffer tanks" (Figure 5.15), are typically large, insulated tanks that store thermal energy in the form of hot water. This stored thermal energy is crucial for effectively managing greenhouse microclimates. Stored heat is released during cooler nights or cold weather to maintain growing temperatures without running heating equipment continuously. This results in lowered operational costs and enhanced energy efficiency, optimizing resource use within the facility (J Huete Greenhouses 2022). Additionally, in setups with electric heat pumps, the surplus heat can be harnessed to warm water stored in thermal tanks, providing an effective heating solution for greenhouses during cooler nighttime hours (Walker 2024).

Figure 5.15. Example of buffer tanks at a greenhouse facility

Source: J Huete Greenhouses (2022)

Integrating buffer tanks maximizes the utilization of thermal energy generation (e.g. solar thermal or geothermal systems) and decreases reliance on external energy sources. For longer-term storage needs, underground thermal energy storage can retain heat across seasons, while systems such as phase change materials handle daily fluctuations. Greenhouses using thermal storage typically recoup costs within 5 to 8 years (Amir and Viktoria 2013; Tafuni et al. 2023).

5.3 Microgrids

Microgrids have a broad definition. A microgrid could be one or a combination of several technologies, including many that have already been mentioned in this catalog. Figure 5.16 shows an example of a CEA facility connected to a microgrid made up of a combination of onsite energy sources, as well as BESS and thermal energy storage.

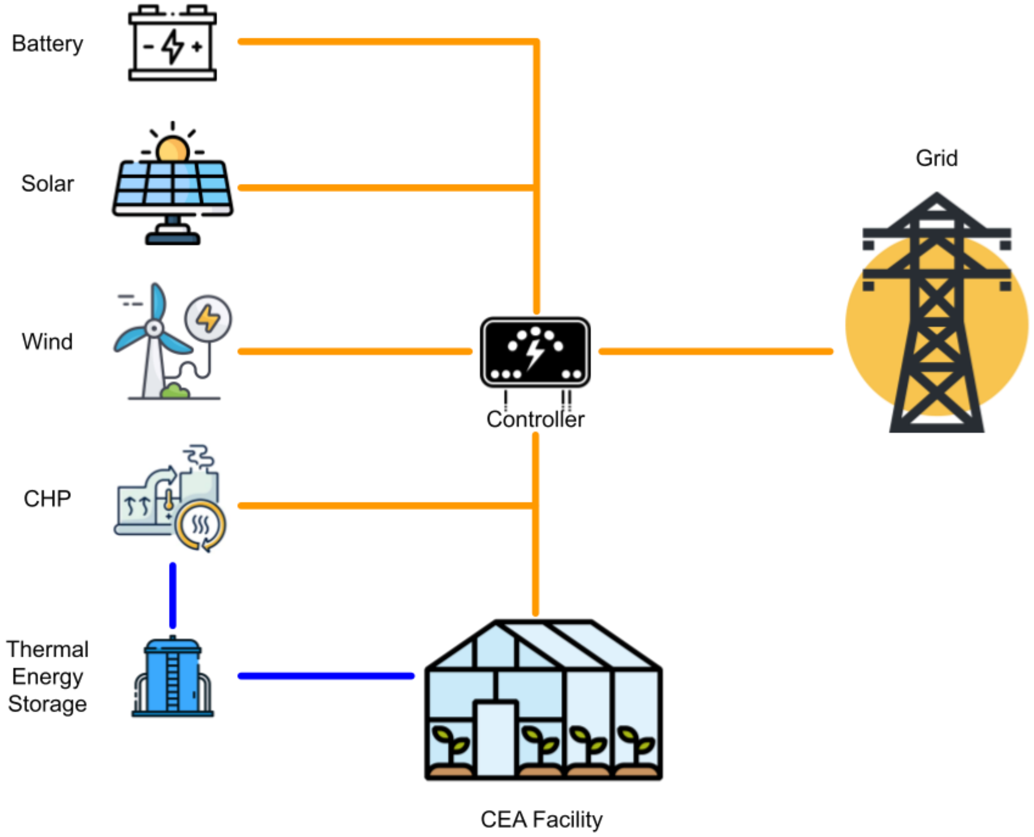


Figure 5.16. Schematic diagram of a microgrid for CEA

The primary challenge in integrating microgrid technology in CEA facilities is economic, notably the financing of these systems. Microgrids typically exhibit a payback period of 15–20 years, posing a significant initial financial burden that can deter facility owners from adopting this technology. This long payback period necessitates innovative financing solutions to enhance the attractiveness of microgrid investments in the CEA industry, according to the vice president of business development at Scale Microgrids (Shea Hughes, correspondence with author, May 30, 2024).

There is a growing recognition of the necessity for onsite power generation within CEA facilities. The surge in electricity demand has placed considerable strain on existing grid infrastructures, complicating access to reliable and cost-effective power for CEA operations. This is particularly acute for new CEA sites or repurposed warehouses, which often lack the power capacity for CEA operations—leading to potential delays and increased costs due to utility upgrades such as substation enhancements.

Despite their high upfront costs and long payback periods, microgrids represent a strategic solution to circumvent the limitations of existing grid infrastructures. By enabling onsite power generation, microgrids can significantly reduce the time and financial investment associated with grid upgrades. Additionally, implementing demand side management strategies within microgrids can further improve their cost-effectiveness, especially when these systems operate across multiple energy markets. Microgrids also enhance disaster preparedness, enabling CEA facilities to operate independently, or in 'islanded' mode. For instance, during Hurricane Sandy, Gotham Greens was the only fresh food supplier operating in New York, demonstrating the critical role of onsite power generation (Al-Kodmany 2018).

5.4 Colocation

Colocation focuses on identifying spaces that are amenable to CEA and are also close to inputs needed for CEA facilities (e.g., waste heat, compost, wastewater, and CO^2 from compatible sources). Gains in efficiency could be realized through the colocation of CEA operations with what may be waste streams in other sectors, potentially increasing yields and offsetting life cycle energy demands relative to conventional approaches (Mohareb et al. 2017). In this section, we look at a few possible colocation opportunities for CEA and other industries.

While colocation offers substantial benefits, it also poses several logistical and technical challenges that require careful consideration. Significant capital investment is needed to establish the necessary infrastructure for colocation, including modifications and installations to effectively handle and process industrial byproducts. Additionally, the continuous operation of colocation systems incurs ongoing expenses, highlighting the importance of efficient management to control costs. Regulatory compliance is another crucial aspect, as adherence to environmental regulations regarding energy reuse often involves complex permitting processes and stringent standards. The success of colocation heavily depends on the proximity to suitable industrial facilities and the feasibility of integrating their byproducts into CEA operations without compromising CEA operations.

Capturing heat and CO_2 from power plants and industrial facilities and transferring it to an enclosed growing chamber is not costless. Upfront costs are involved, but the operating costs of pumping warm water through a heat exchanger will be less than the costs incurred to generate heat through conventional systems powered by gas or electricity (Li, H. et al. 2023).

Power Plants

Power plants are significant sources of both heat and CO_2, byproducts that can be harnessed to enhance the efficiency and productivity of CEA facilities. Colocating CEA operations with power plants can provide several strategic benefits. Power plants often produce large amounts of excess heat that is typically released into the environment as waste. By colocating CEA facilities near these power plants, waste heat can be captured and used directly for heating greenhouses or other growing areas, especially during colder months. This process requires installing heat exchangers and thermal piping systems to transport the heat from the power plant to the CEA facility.

In Samsun, Turkey, the local metropolitan municipality harnesses 46 gigawatts of waste heat from its power plant to cultivate 1.7 million flowers annually (Figure 5.17). This initiative exemplifies how waste heat can be repurposed effectively in urban CEA applications (Denge 2024).

Figure 5.17. CEA colocation with a power plant
Flowers produced in Turkey's first flower greenhouse heated with waste heat from Samsun powerplant. Source: Samsun Metropolitan Municipality (2024)

In the case of combustion power plants, CO_2 is a major byproduct and, when captured, can enrich the CEA environment, promoting faster plant growth and yield. Implementing CO_2 capture involves the use of technologies like exhaust gas scrubbers. The absorbed CO_2 can then be piped directly into greenhouses. This process provides a cost-effective CO_2 source for CEA operations, as discussed further in Section 10, CO2 Utilization.

Data Centers

Data centers are among the fastest-growing facilities worldwide, driven by an increasingly digital economy. Data centers are expected to consume more than 20% of the global electricity supply in 2025. Compared to pre-COVID-19 lockdown levels, internet services have increased by 40%–80%, further increasing their energy demands. At least 40% of this energy is dedicated to cooling the servers (Borland et al. 2023). As major consumers of electricity, these centers produce substantial amounts of waste heat as a byproduct of their operations. For data centers, this waste heat is a liability requiring additional energy to dissipate; for CEA facilities, it's a potential low-cost heat source. Colocating CEA facilities with data centers creates a mutually beneficial arrangement—data centers offload excess heat while CEA operators reduce heating costs.

One example is the Equinix PA10 data center in Saint-Denis, Paris, which includes a 4,600-square-foot greenhouse that uses heat exchangers linked to the data center's chilled water system to capture waste heat (Judge 2023). Another example is the Windcloud data center in

Enge-Sande, Germany, which has a 2,600-square-foot greenhouse on its roof growing microalgae (Weiss Klimatechnik GmbH 2021).

Industrial Facilities

Similar to power plants, some industrial processes (e.g., ammonia production) have both waste heat and CO_2 in their exhaust. Both could be used for CEA if farms are colocated with these facilities. One example is a project called WarmCO_2 in Zeeland, Netherlands. Heat and CO_2 from a fertilizer plant (Yara Sluiskil) is diverted to a greenhouse complex. The Yara plant emits 1,700 terajoules of heat and 60,000 metric tons of CO_2 per year. Providing these resources to 16 million square feet (150 hectares) of growing space avoids combusting 55 million cubic meters of primary natural gas annually and provides the farmers with 50% savings on their energy bills (Van Keer 2017). Another example is a 1 million square foot greenhouse located next to the Billerud paper mill in Frövi, Sweden. The greenhouse, designed by WA3RM, uses 35 gigawatt-hours per year of waste heat from the mill. The greenhouse is expected to produce 8,000 metric tons of tomatoes a year (WA3RM 2024).

Ethanol Plants

In regions with large corn and ethanol production, colocation with ethanol plants can present a significant opportunity. Ethanol plants generate a substantial amount of heat in the corn-to-ethanol conversion process. CO_2 is a byproduct of the fermentation process. One kilogram of ethanol produced from corn produces one kilogram of biogenic CO_2 from fermentation process. When efficiently captured, the heat and CO_2 can be used in the CEA facility. One example is Truly Green Farms in Chatham, Ontario. Located next to a Greenfield Global ethanol plant, the 90-acre farm gets waste heat and CO_2 from the plant and grows tomatoes on the vine, cocktail tomatoes, and grape tomatoes (Truly Green Farms n.d.). The Greenfield Global plant produces up to 30 megawatts of heat, which is all available to Truly Green (Chatham-Kent This Week 2018) and allows the farm to cut heating costs by up to 40% (Cowen 2013). They also produce 65,000 metric tons of CO_2 which Truly Green uses to boost plant production (Zajac 2023).

Waste Streams

CEA facilities can benefit from colocation with sites that produce organic-rich waste streams, such as dairy farms. Biogas derived from manure can replace natural gas in boilers and CHP systems with exhaust gases used for plant CO_2 fertilization. A practical example of this integration is seen in dairy farms where waste is converted into energy through anaerobic digestion (Figure 5.18). The generated energy supports both dairy and greenhouse operations. Instead of selling excess energy back to the grid, greenhouse operations can use it directly, lowering operational costs (Scott et al. 2005). However, digesters should be checked for leaks regularly—methane is both a safety hazard and represents lost fuel.

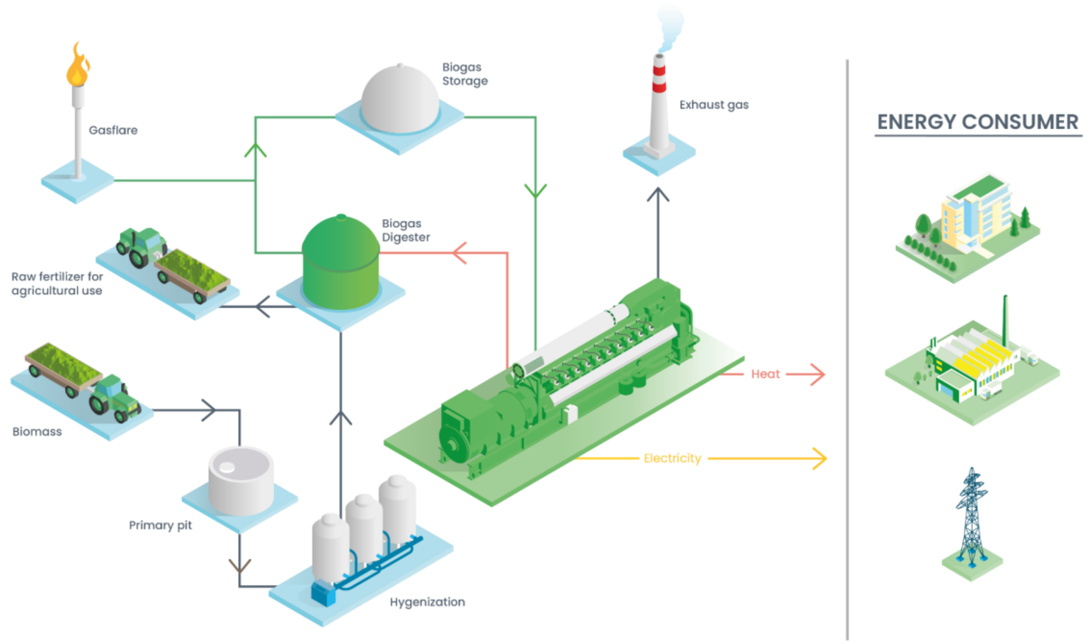


Figure 5.18. A schematic of colocation with animal waste streams

Biogas is generated using a digester and is burned in a CHP system to generate electricity, heat, and CO_2. Source: Jenbacher (2024b)

Beyond agricultural waste, municipal waste streams also offer colocation opportunities. The Econotre facility outside of Toulouse, France burns 192,000 metric tons of trash annually to produce 25 gigawatt-hours of thermal energy, heating a 24.7-acre greenhouse that produces 6,000 metric tons of tomatoes per year (SUEZ n.d.; Ô Toulouse n.d.). Another example is the Modern Landfill's site in Model City, New York (now offline), where waste heat from seven CHP generators powered by landfill gas heated a 7.5-acre hydroponic tomato greenhouse (NYSERDA 2004; Rivera 2015).

Colocating CEA facilities with wastewater treatment plants offers another avenue for resource recovery, leveraging waste streams like low-grade heat, biogas, or processed sludge. For instance, The Green House Growers UK in Norwich and Ely uses waste heat from nearby wastewater treatment plants to heat large-scale greenhouses growing tomatoes and cucumbers (Lattimore 2019; The Green House Growers n.d.).

5.5 Technologies on the Horizon

Transparent Infrared Collecting Solar Panels

These panels allow for the simultaneous generation of electricity and provision of light suitable for plant photosynthesis, which can reduce the internal temperature of greenhouses, thereby lowering cooling energy requirements.

Agrivoltaics

Agrivoltaics involves the simultaneous use of land for both agriculture and solar energy production. By installing solar panels above crops, this approach provides partial shading, which can reduce water evaporation—a critical benefit in arid regions. The generated solar energy can power CEA operations, decreasing reliance on external energy sources (USDA n.d.).

6. Water Management

Water use, scarcity, and pollution are often among the key issues affecting agricultural systems globally. The agriculture sector is estimated to account for up to 85% of water consumption in the United States and, with the growing amount of pollution from nutrient and chemical runoff, water is a pivotal resource for farmers to manage (Schaible 2017). Like traditional agriculture, CEA operations use water for irrigation, but these facilities also use water for climate control (e.g., evaporative cooling and humidification) and process activities (e.g., sanitation of growing areas and materials). By deploying efficient irrigation technologies, closed-loop systems, and capture or recapture of water, CEA operations can use water more efficiently than traditional agricultural systems. CEA can achieve greater than 90% water savings compared to traditional agriculture, but this comes at an energy cost (RII 2023b).

The water treatment process, whether for irrigation, climate control, reuse, or disposal, requires energy for treatment technologies, hardware such as pumps, or fertilizer mixers. This relationship between energy and water is referred to as the energy-water nexus and should always be considered in both the pre- and post-construction phases of a CEA operation. In the pre-construction phase, testing the water source is the key first step in understanding the treatment and, therefore, energy requirements. The more impaired a water source is, the more remediation—and, therefore, energy—is required to achieve the desired quality and avoid damage to the plants, workers, or equipment. Understanding daily water demands is also pivotal for an operation’s water management planning, equipment selection, and sizing. Irrigation, when factoring in pumping, fertigation systems, heating and cooling water, and treatment, can range from about 5% to 7% of an operation’s energy requirements (Sabeh et al. 2022). Energy requirements for water management are much lower compared to other CEA systems, but recovering and reusing water could affect OPEX.

Besides energy, other considerations for choosing a closed-loop system include regional policy and operational cost. In water-scarce regions, CEA operations can be required to reduce water use and waste. However, in all regions, closed-loop water systems can lower water and fertilizer consumption and therefore operational costs. In fact, closed-loop irrigation systems in CEA operations can lower water consumption by 20%–40% and reduce fertilizer costs by 40%–50%, resulting in payback periods as low as two years (Beytes 2021; Mohammed 2017).

Most facilities should select and install a combination of treatment technologies described in the following sections to achieve the necessary water quality for closed-loop water systems to ensure the health of equipment, workers, and crops. This section will focus on physical, chemical, and biological water treatment technologies that are used in CEA operations to achieve water reuse, reduce water related energy demands, and manage costs.

6.1 Water Reduction and Recycling Strategies

Strategies can range from simple, such as regular maintenance on irrigation equipment, to more complex, such as staggering irrigation events or reclaiming water from pathways or equipment (e.g., recycled irrigation water or HVAC condensate). All can achieve sufficient water savings.

Efficient irrigation equipment such as drip irrigation can reduce water and nutrient use compared to traditional irrigation methods and can achieve 80% water savings and 25%–75% energy cost savings (NYSERDA 2022). According to the 2018 Irrigation and Water Management Survey, drip and subirrigation were used in 61% of CEA operations and account for 61% of the square footage irrigated under protection in the United States (USDA 2018). Up 20% from 2013, these efficient irrigation systems are likely a significant majority in CEA operations.

The CEA industry is moving toward water reuse (designing the elimination of water waste), which includes a combination of strategies and technologies to reduce, remediate, and recycle water. While strategies and efficient irrigation technologies can provide high water savings, to unlock the water savings potential of CEA (i.e., 95% water savings compared to traditional field agriculture), the remediation technologies component of closed-loop systems and their associated energy and cost considerations are the focus of this technology catalog.

6.2 Physical Water Treatment Systems

Physical water treatment systems primarily filter suspended solids, but some technologies may also filter pathogens, agrichemicals, salts, and even some nutrients. These systems are often used for prefiltration before water enters irrigation lines or other treatment systems to prevent blockage and limit damage (Figure 6.1). Some membrane filtration options can also be used for compliance purposes, such as food safety criteria by providing log removal credits for target organisms. Energy requirements, operating costs, and other considerations (e.g., managing rejected water or brine) can vary and depends on factors such as the quality of the water, volume of water, target contaminants, and the level of desired filtration. Physical water treatment systems are summarized in Table 6.1 and is described a section following the table.

Figure 6.1. Example of physical filtration

Sediment cartridge filters in blue colored casings. Source: RII (2023a)

Table 6.1. Physical Water Treatment Systems Summary

Technology	Purpose	Treatment range	Energy Input	Footprint	CAPEX	OPEX	O&M	Lifespan	Retrofit/New Build	Notes
Coarse Filtration	Prefiltration	Solids/organic material	Low	Small–Medium	$–$$	$	Low	Short (1+ years)	Both	Assume freque replacement.
Rapid Media Filters	Prefiltration	Solids/organic material	Low	Small	$–$$	$	Low	Medium (5+ years)	Both	Backwash wastewater will be directed to the sewer.
Membrane Filtration	Pretreated source water and closed-loop water systems	Solids/organic material; Pathogens; Nutrients; Agrichemicals	Medium	Medium	$$–$$$	$$	Medium	Short (2+ years)	Both	Requires proper pretreatment, source pressure, temperature and water quality.
UV-C Light	Pretreated source water and closed-loop water systems	Pathogens	Medium	Small	$$$	$	Medium	Short (1+ years)	Both	Requires proper hydraulic conditions and water quality.

Sources: Raudales et al. 2017; West et al. 2018

6.2.1 Coarse Filtration

Coarse filtration includes screen filters, cartridge filters, disc filters, paper filters, or fabric filters to remove particulates. All irrigation systems require some form of particulate filtration to avoid clogging or damage to other irrigation equipment. Screen filter systems cost $0.02–$0.17 per 1,000 gallons of water treated. Capital costs account for the majority of the total cost. Energy requirements are minimal and account for most of the OPEX. Fabric filters are another option, but costs can range greatly depending on material, $0.08–$2.97 per 1,000 gallons. In some cases, cloth filter costs are similar or more expensive than membrane systems (Raudales et al. 2017). Coarse filtration, with its low upfront and operating costs, makes it a viable alternative for low-tech operations seeking to pursue water reuse or for medium- to high-tech facilities as prefiltration before water reaches other filters described in this section.

6.2.2 Rapid Media Filtration

Rapid media filtration includes technologies that treat water by passing it through a specific medium or set of media such as sand, granulated activated carbon, and/or ion exchange resin (West et al. 2018). These systems filter solids and, depending on the media, may be ale to filter specific contaminants through physical and/or chemical means. A common example of a rapid media filtration system for CEA application would include granular activated carbon (GAC), which can filter solids, as well as key contaminants such as chlorine and fluoride (common in municipal source water); agrichemicals (pesticides, herbicides, and plant growth regulators); and other sanitizers (Fisher, P. et al. 2019; Grant et al. 2018). Considerations around selecting rapid media filters include water quality needs, operating costs related to recharging and/or disposing of media to maintain removal efficiency, required prefiltration with a coarse filtration system, and contact time (i.e., required treatment time to achieve desired removal).

6.2.3 Membrane Filtration

Membrane filtration includes pressurized membrane purification systems that range in pore size of the membrane and the pressure applied. Options, listed in order of decreasing pore size and increasing pressure, include microfiltration, ultrafiltration, and nanofiltration. Reverse osmosis is another form of membrane treatment but it is not a purely physical filtration process (i.e., dependent on pore size to prevent crossing the membrane). In reverse osmosis, the excess applied pressure reverses the usual osmotic process, allowing clean water to flow across the membrane while blocking impurities. Of the membrane filtration systems, reverse osmosis is widely selected for its ability to remove solids, pathogens, nutrients, and agrichemicals. The ability to remove salts with reverse osmosis is increasingly relevant, as groundwater and surface water salt concentrations are increasing in the United States (USGS 2018). Ultrafiltration and nanofiltration can also remove salt, though not to concentrations as low as reverse osmosis. Both are less effective for nutrient removal and ultrafiltration has a limited ability to remove agrichemicals (West et al. 2018). Total costs of membrane filtration can be high. Capital and installation ($1.22 per 1,000 gallons) and labor costs ($0.49 per 1,000 gallons) account for the majority of the total $1.75 per 1,000 gallons for reverse osmosis systems (Raudales et al. 2017).

Another important consideration for membrane filtration is the wastewater, referred to as reject water, concentrate, or brine, a byproduct containing high concentrations of contaminants that can create disposal complications. In some inefficient cases, nine gallons of brine can result per one gallon of water treated, or a 10% recovery rate (RII 2023a). High-efficiency or high-performance reverse osmosis may require multiple passes of the source and reject water that can result in a 85% recovery rate and lower energy consumption, but systems can be costly.

6.2.4 Ultraviolet Light Disinfection

Ultraviolet light (UV) disinfection refers to using UV-C light (240–280 nanometers) to disinfect water through photooxidation. This wavelength of light controls pathogens (algae, bacteria, or fungi) by breaking through cell walls, genetically damaging the cell and rendering it inactive. It prevents spread through the irrigation system. These systems have a relatively small footprint and treat water as it flows through a steel tube containing the UV lamp. The pathogen removal depends on the lamp characteristics, clarity of the water, and flow rate (West et al. 2018). UV-C has no residual effect on water that would lead to phytotoxicity downstream, so it may be combined with select chemical treatment processes to increase the sanitizing effects (Fisher, P. 2009). More detail on these technology pairings will be discussed in the next section. Key considerations for UV disinfection include: the high capital cost, lamp selection tradeoffs between energy consumption and pathogen removal efficiency, prefiltration systems, and high maintenance requirements, much of which can be done onsite (West et al. 2018).

6.3 Chemical Water Treatment Systems

The chemical treatment category refers to the processes responsible for water quality adjustments (e.g., pH) and disinfection of water (Figure 6.2; Table 6.2). These may be used to treat source water and, in closed-loop systems, to ensure water properties are adequate and any damaging constituents like pathogens, biofilms, and agrichemicals are not present to harm plants, workers, and equipment. Chemical treatment systems require appropriate personal protective equipment and procedures in place for operation, maintenance, and service, as authorities will inspect to ensure compliance. Systems can have high CAPEX and OPEX, especially when combining multiple processes, which is commonly done to optimize treatment.

Figure 6.2. Chemical water treatment system

Source: University of New Hampshire (2017)

Table 6.2. Chemical Water Treatment Systems Summary

Technology	Purpose	Energy Input	Treatment Range	Footprint	CAPEX	OPEX	O&M	Lifespan	Retrofit/ New Build
Chlorine	Pretreated source water and closed-loop water system	Low	Solids/organic material; Pathogens; Nutrients; Some agrichemicals; Biofilm	Small	\$–\$\$	\$	Low	Instant reaction, with residual byproducts	Both
Peroxyacetic Acid	Pretreated source water and closed-loop water system	Low	Solids/organic material; Pathogens; Nutrients; Some agrichemicals; Biofilm	Small	\$	\$\$–\$\$\$	Low	Instant reaction, with no residual byproducts over time	Both
Ozone	Pretreated source water and closed-loop water systems	Medium to High	Solids/organic material; Pathogens; Nutrients; Some agrichemicals; Biofilm	Medium	\$\$\$	\$\$	High	Instant reaction with no residual byproducts over time	Both
Electrochemical Activation	Pretreated source water and closed-loop water systems	Low	Solids/organic material; Pathogens; Nutrients; Biofilm	Small	\$–\$\$	\$	Low	Instant reaction with no residual byproducts over time. Biodegradable, environmentally safe	Both

6.3.1 Chlorine Disinfection

Chlorine is a low-cost disinfectant ($0.17 per 1,000 gallons of treated water) that is effective on most pathogens, such as *Pythium*, as well as algae and bacteria that can clog irrigation equipment. It is commonly used in CEA operations growing in container substrates. The effectiveness of chlorine disinfection can be affected by pH, temperature, organic debris, and presence of biofilm (Fisher, P. et al. 2008). Additionally, chlorine is less effective when it reacts with ammoniacal nitrogen, which is present in most water-soluble fertilizers. With the variable effectiveness and the damage chlorine can cause to hydroponic crops, chlorine disinfection is less common in hydroponic growing systems (McGehee and Raudales 2023). Chlorine dioxide can also be used for disinfection with relatively low phytotoxicity, no reaction to nitrogen compounds, and effectiveness over a wide range of pH (West et al. 2018). Using a chlorine dioxide generator, a stock solution can be created and used to treat irrigation systems throughout a facility. However, these generators are generally more costly than other options and more commonly used for high-value crops or in large facilities.

6.3.2 Peroxyacetic Acid Disinfection

Peroxyacetic acid, a combination of acetic acid and hydrogen peroxide, is a low-capital treatment option for algae, bacteria, and fungi. Unlike chlorine, peroxyacetic acid does not damage crops at low concentrations, but can also be used to shock systems in higher concentrations. It can also be combined with UV or ozone disinfection to achieve increased effectiveness through their synergistic effects. Considerations for peroxyacetic acid are that prefiltration is required. Compared to other chemicals, this is a more expensive option (West et al. 2018).

6.3.3 Ozone Disinfection

Ozone treats pathogens and biofilm, and it can break down organic chemicals such as pesticides and plant growth regulators. Pairing ozone with UV or peroxyacetic acid can improve disinfection and oxidation. Ozone disinfection system CAPEX and OPEX are high compared to other options and are more suited for large operations (West et al. 2018). Other considerations include required safety precautions and expertise when producing onsite, phytotoxicity, and prefiltration requirements, as high levels of organic matter can reduce effectiveness or increase electricity consumption (West et al. 2018).

6.3.4 Electrochemically Activated Water

Electrochemically activated water is created by passing a current through water that contains salts (potassium chloride or sodium chloride) to form hypochlorous acid, a disinfectant. Electrochemically activated water treats bacteria, viruses, and fungi, and controls common contaminants such as biofilm and pythium (Heungens et al. 2015). It is biodegradable and compatible with biological treatment systems, which makes it a good option for operations with constructed wetlands and similar systems (See Section 6.4, Biological Water Treatment Systems). If not managed correctly, higher concentrations of hypochlorous acid can cause phytotoxicity.

6.4 Biological Water Treatment Systems

The biological category refers to systems that use microorganisms to break down organics in the water (Table 6.3, Figure 6.3). In addition to microbial treatment, biological treatment can also involve physical filtration, sedimentation, vegetative uptake, and sorption to another media to remove pollutants from water. Biological systems are often used for wastewater and stormwater treatment. The most common examples in CEA are retention ponds and constructed wetlands. This method also can be used for closed-loop water systems. These systems are chosen for their limited to nonexistent energy requirements. Barriers include large land area requirements, high upfront cost, susceptibility to shocks that disrupt the microbial community and lead to system downtime, and lower treatment efficiency in winter months in cooler climates.

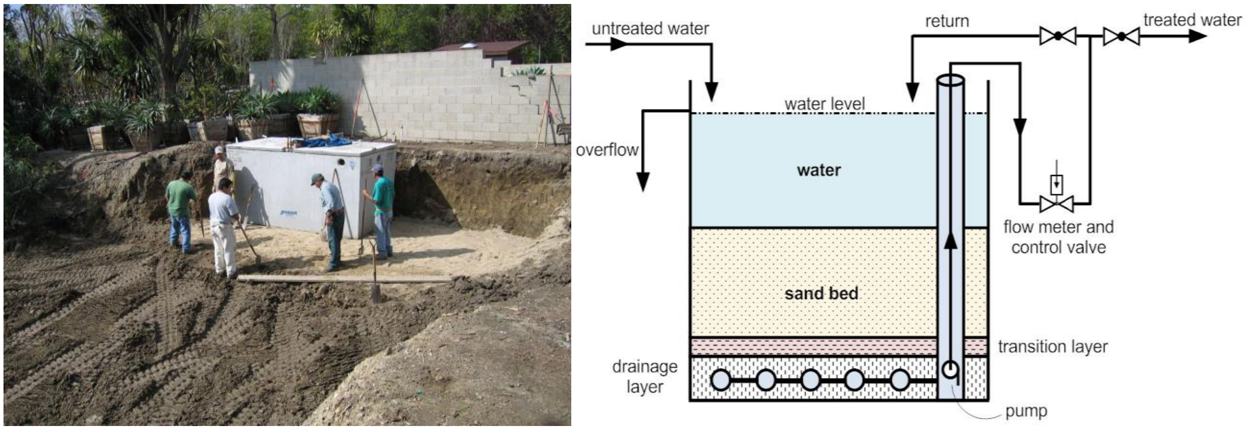


Figure 6.3. Containerized slow sand filter (left) and schematic (right).
Source: Oki et al. (2017)

Table 6.3. Biological Water Treatment Systems Summary

Technology	Purpose	Energy Input	Treatment Range	Footprint	CAPEX	OPEX	O&M	Lifespan	Retrofit/ New Build
Constructed Wetlands	Pretreatment prior to discharge	Low	Solids/ Organics, pathogens, nutrients, agrichemicals	Small– Large	\$\$–\$\$\$	\$	Medium	50+ years	Both
Hybrid Treatment System	Pretreatment prior to discharge	Low	Solids/ Organics, pathogens, nutrients, agrichemicals	Medium	\$\$–\$\$\$	\$	Medium	10+ years	Both
Slow Sand Filters	Pretreatment prior to discharge	Low	Solids/ Organics, pathogens, agrichemicals	Medium	\$\$	\$	Medium	1–10 years	Both

6.4.1 Constructed Wetlands

Constructed wetlands are engineered systems designed to mimic natural wetlands. These systems often are used as a final treatment before the water used in the facility reenters the surrounding ecosystem. They can be coupled with stormwater management systems onsite. Closed-loop water systems may also use constructed wetlands, though water exposed to the outdoor environment will likely need a filtration step before reuse. Constructed wetlands are chosen for their ability to remove the key pollutants or contaminants in agricultural wastewater. Studies have shown removal success for nutrients (50%–99% for nitrogen; 25%–98% for phosphorus), pesticides (84%–97%), and heavy metals (60% for copper; 86% for zinc) (Cheng et al. 2002; Gill et al. 2017; White et al. 2011). Barriers include the capital costs (e.g., design and construction process; land requirements) which depend on the volume and quality of water. Wetlands are generally not a viable option for urban operations due to limited space. A 2016 study determined a 1-acre constructed wetland designed to treat 100 acres of drainage would cost around $10,000 for design and construction, which amounts to about $800 per acre of growing area per year (Tyndall and Bowman n.d.).

6.4.2 Slow Sand Filter

Slow sand filters are containerized biological treatment systems in which water is dispersed over the top media (medium-size grains of sand less than 0.6 millimeters in diameter). Water is treated as it flows down through the sand, providing physical filtration of solids and pathogens while also promoting the growth of microbial communities for biological treatment (Horticultural Development Council 2004). Slow sand filters have a limited impact on nutrient concentrations, pH, and conductivity, which makes them viable in closed-loop systems. Their energy and operational cost requirements are relatively low when compared to other filtration technologies and are associated primarily with influent/effluent pumping (Horticultural Development Council 2004). Sizing these systems depends on the water quality and quantity needs of an operation, but generally, a 1-acre facility requires a surface area of 25 square meters (~270 square feet) with a flow rate of 2.5 cubic meters/hour (~660 gallons/hour) (West et al. 2018).

6.5 Technologies on the Horizon

Hybrid Treatment Systems

Hybrid treatment systems are relatively new technologies, especially in the CEA industry. They consist of multiple cells, one or more filled with woodchips (i.e., a woodchip bioreactor) and others filled with mineral media such as sand or gravel. Size, number of cells, and media selection are all determined by the quantity and quality of water to be treated (West et al. 2018). Similar to constructed wetlands, hybrid treatment systems require a large land area. However, treatment systems can be buried below the ground surface, so potted production can occur on top of the system, limiting unproductive land (Huber and West n.d.). Designed to target pathogens, nutrients, pesticides, and solids, hybrid treatment systems have potential for CEA operations due to their custom nature and flexibility. They may particularly appeal to low- to medium-tech CEA operations (plastic film structure, minimal climate control, and simple controls) that are looking to implement closed-loop water systems.

7. Building Envelope

Indoor facilities are somewhat simple when it comes to envelope design. Without worrying about clear overhead materials for light transmission, indoor facilities can focus on basics of good building design and construction principles such as insulation, air sealing, and designing for use. The remainder of this section, therefore, focuses on greenhouses.

Some growers use the general rule that 1% more light equals 1% more growth. With that in mind, greenhouse glazing is especially important. Glazing materials fall into one of three types: glass, rigid plastic, and plastic film. Figure 7.1 summarizes the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service 2019 Census of Horticultural Specialties (USDA 2019). It shows the dominant material is plastic film (75% of greenhouse area), followed by rigid plastic at 13% and glass with 12%. Many considerations go into material selection, and there is no clear best material for every application (Table 7.1).

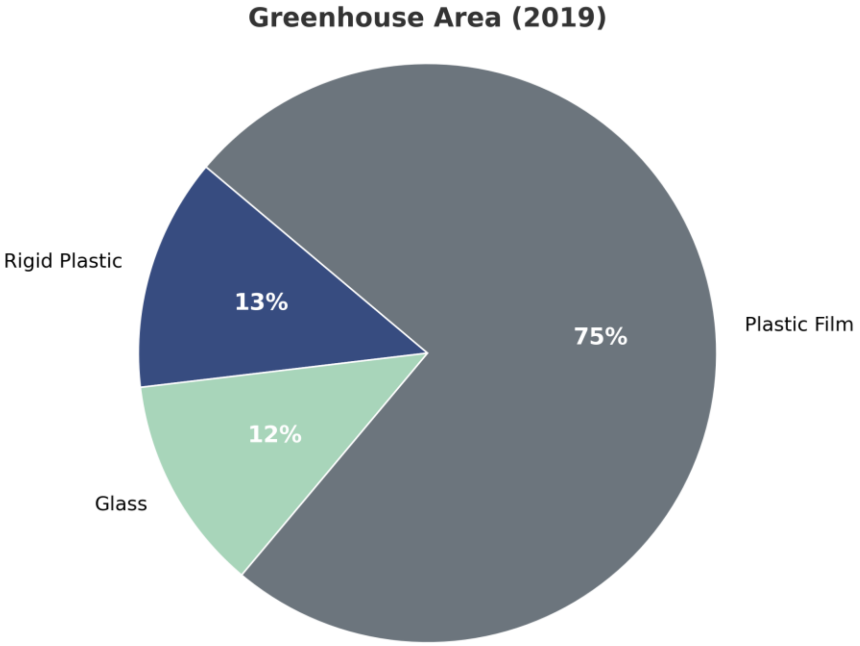


Figure 7.1. Breakdown of greenhouse material by growing area
Source: Graphic based on USDA (2019)

7.1 Plastic Film

Plastic film is a very inexpensive material, contributing to its popularity. Plastic film greenhouses are typically lower-tech than their glass and rigid plastic counterparts, though there are some higher-tech plastic film greenhouses. The film used is typically polyethylene and can be installed in a single layer or a double layer with an air gap, where a small fan inflates the space between layers to act as an insulator between layers. Double-layered plastic film greenhouses can reduce heat losses by 40% compared to a single layer. Some films are manufactured with infrared treatments to further reduce heat loss. There is, however, some reduction in light transmission when moving from single layer to double and when adding infrared blocking. Sunlight, weather, and certain pesticides are harsh on polyethylene. According to manufacturers, these coverings only have a 2–4 year lifespan. Plastic films will continue to be popular due to low cost. Due to the relatively short lifespan, as improvements to films continue to come on the market, new technology can be quickly adopted.

7.2 Rigid Plastics

Rigid plastics are typically polycarbonate and acrylic. Less expensive than glass, these materials have good light transmission, although polycarbonate can yellow over time in sunlight, reducing its transmission. UV coatings can help polycarbonate extend its useful life and are quite popular, since polycarbonate is less expensive than acrylic. While acrylic is desirable for its long-term transmission capabilities, as it does not yellow over time, it is flammable, which can be a risk. Both types of rigid plastic sheets weigh less than glass, requiring less structural support in the greenhouse. Rigid plastics don't last as long as glass but are more resistant to hail damage. Fiberglass was previously a popular material and may be seen in older greenhouses or in areas where high corrosion resistance is important. However, fiberglass ages and yellows quickly and has fallen out of favor compared to improved polycarbonate and acrylic options.

7.3 Glass

Glass is the most expensive of the three materials but has the longest lifespan. It has high light transmittance through its full lifespan and allows many different coatings to be applied both before and after installation. Glass also means a heavier roof and thus a more expensive and extensive support structure. Coatings and cleanings are common with large greenhouses that use chalk application to reduce heat gain in hot months and roof cleaning machines to make sure as much light as possible makes it through. Glass is not as insulating as rigid plastic materials or even double-layered plastic film coverings. While double-paned glass panels improve insulation, they come at a higher price.

Table 7.1. Building Envelope Alternatives Summary

Covering Type	Imperial R-Value ($h\ ft^2\ F/Btu$)	Imperial U-Factor ($Btu/h\ ft^2\ F$)	Light Transmission (%)	Cost	Lifespan
Polycarbonate, Five Wall, 25 mm	3.26	0.31	60%	$$$$	10–15 years
Polycarbonate, Triple Wall, 8 mm	2.0	0.50	74%–78%	$$	10–15 years
Double-Pane Storm Windows	2.0	0.50	78%	$$$$	25–30 years
Polyethylene Film, Double, with Infrared	2.0	0.50	78%	$	2–4 years
Polycarbonate, Double Wall, 10 mm	1.87	0.53	80%	$$$	10–15 years
Acrylic, Double	1.79	0.56	84%	$$$	15–30 years
Polycarbonate, Double Wall, 8 mm	1.60	0.63	80%	$$	10–15 years
Polycarbonate, Double Wall, 6 mm	1.54	0.65	82%	$$	10–15 years
Polycarbonate, Double Wall, 4 mm	1.43	0.70	83%	$$	10–15 years
Glass, Double Pane	1.43	0.70	75%–80%	$$$$	25–30 years
Polyethylene Film, Double	1.43	0.70	85%	$	2–4 years
Acrylic, Single Wall	0.88	1.13	90%	$$$	15–30 years
Glass, Single Pane, 3 mm	0.95	1.05	88%–93%	$$$	25–30 years
Polyethylene Film, Single Wall	0.83	1.2	77%–87%	$	2–4 years
Polycarbonate, Corrugated Single Wall	0.83	1.2	90%–91%	$$	10–15 years

Source: RII (2022a)

7.4 Technologies on the Horizon

Ethylene Tetrafluoroethylene

The field of material science is rapidly innovating, with new materials entering research and market phases. One of these new materials is ethylene tetrafluoroethylene, a translucent polymer glazing. This material is touted as having high transmittance (95%), strength, and repairability without yellowing or the flammability issues associated with other non-glass coverings. This material is well established in Asia. U.S. greenhouses are starting to test it out commercially (CERES 2024).

Smart Glazing

Smart glazing is an emerging technology that is still in the early research and development phase. Glazing with solar PV energy generation and transparency is possible; several technologies to achieve this. A notable one uses quantum dots, or semiconductor nanocrystals, which already have a greenhouse product on the market. Other examples include organic solar cells, thin-film solar cells, and wavelength selective semitransparent solar cells, each with their own advantages. Currently there are still challenges in applying these technologies to commercial greenhouses including performance, longevity, durability, and light reduction; experimentation and innovation are ongoing. Dynamic glazing, or electrochromic glazing, is a rapidly developing field with potential greenhouse applications in energy storage, thermal regulation, energy harvesting, and sensing. Still in early research applications, this is another area to watch as it develops (Beytes 2021; Maraveas et al. 2021; RII 2024a).

8. Hardware

8.1 Lighting

Light fuels plant growth and a key element of any CEA design. Repeated research into a variety of crops supports the common rule of thumb: 1% more light means 1% more crop yield. It is understandable that growers are very serious about their light. This section is designed to provide an overview for those outside the world of CEA to gain a basic understanding of light in the world of CEA. RII's *Best Practices Guide: Lighting for Controlled Environment Agriculture Operations* and similar publications go into greater depth to understand light in CEA (RII 2022b).

For plants, useful light received is measured as photosynthetic photon flux density (PPFD) in units of micromoles of photons per second (µmol/s). For supplemental light fixtures, the rate of light that can be produced is measured as photosynthetic photon flux (PPF). These are slightly different because not all light coming from a fixture will reach the plant. PPFD should be measured at multiple locations within the plant canopy to understand how much light the plants receive. A fixture's photosynthetic photon efficacy, measured in micromoles per joule, defines how efficiently the fixture can translate electric energy into PPF for the plants.[1]

8.2 Lighting in Facilities

The most basic greenhouses, or those in climates with high solar insolation year-round, often depend entirely on light passing through the glazing overhead to fuel the photosynthesis of their crop. The amount of light, or certain desirable spectrums of light, can be reduced substantially by the material overhead (for more on glazing, see Section 7, Building Envelope). There are many reasons a greenhouse may install supplemental lighting, including boosting low winter light levels, boosting certain spectrums, supporting crops that require high light levels, or adjusting the timing of crop maturity. For greenhouses that run year-round, it is common to skip supplemental lights during summer months when enough sunlight is available but to use them in darker months. Indoor facilities depend entirely on electric lighting to fuel photosynthesis.

Though it is tempting to declare LED lights the new baseline for greenhouse supplemental lighting, this may not be true. Many facilities use high-pressure sodium (HPS) lights. Only recently have LED horticultural lights become competitive enough in pricing and applicability to become a significant part of the lighting market. Among new facilities, some manufacturers estimate that 30%–40% of the market for new lights is HPS; the rest are LED. Existing facilities with HPS lights installed may not be able to afford to buy all new lights all at once. Especially for facilities with low margins, the replacement of HPS with LEDs is very slow, often occurring only with the failure of HPS fixtures themselves, not just when bulbs are replaced. It is not uncommon for facilities to checkerboard a mixture of LED and HPS lights as they make the

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[1] While a commonly known measurement of light, lumens are for humans. Humans and plants use different spectrums of light in different ways. Plants can use a wider spectrum of light, into far red and UV, but some of the spectrum that is useful for human sight is not particularly effective for plants. PPF is the plant equivalent. Lumen measurements should never be used when discussing CEA grow spaces.

financial and training investment into using LEDs. Some growers value the additional radiant heat provided by HPS lights during colder months and remain reluctant to switch technologies.

While CEA can be technology-packed space, the agriculture world is often conservative about new technologies. HPS are much less energy-efficient than LED lights. However, if HPS lights are preferred, efficiency may be improved by switching from single-ended to double-ended HPS lighting fixtures.

Some facilities are still using metal halide (MH) lights, sometimes alone but often in combination with HPS lights. MH light is heavier on the blue end of the spectrum. Combining them with HPS, which are on the red end of the spectrum, can produce a more complete lighting spectrum for plants. The upfront costs of MH lights are higher and they are much less efficient than HPS lights. While few growers are likely buying new MH lighting systems, they are still in use today because they expand the spectrum for HPS lighting. One of the major drawbacks of MH lights is how long they take to warm up to full brightness. In some literature, HPS and MH lights are grouped under high-intensity discharge lighting.

LED costs have come down significantly in just a few years to be competitive with HPS lights. Innovation within the LED industry is extremely fast-paced. There have been significant improvements in PPF, photosynthetic photon efficacy, cooling, durability, size, cost, controls, and the logistics of installing and operating LEDs. LEDs can be purchased in many different spectra, depending on the needs of the facility. It can be possible to change lighting spectrum recipes after installation. Energy cost savings estimates for a switch from HPS to LED lighting range from 40%–75% (Dannehl et al. 2021; Katzin et al. 2020).

Advanced and integrated lighting controls offer opportunities for energy savings and energy management strategies. Modern LED lights are increasingly dimmable, using less energy to put out less light when it is not needed. This is particularly advantageous in regions where time-of-use electricity charges are common. Plants require sufficient light but can receive it anytime within their photo period (i.e., typical daylight hours for outdoor plants). That means lights can be at full brightness outside of peak hours, then dimmed during peak hours. Advanced and integrated controls also allow a level of flexibility and efficiency to the grow space, allowing watering and HVAC systems to work in concert with lighting as well.

Incentive programs to encourage LED adoption in CEA are becoming more common, especially in states with a cannabis market. These programs are very effective in increasing adoption of LEDs, because manufacturers, retailers, and growers become natural advocates. However, there has been some learning curve from swapping out the high-heat-emitting HPS and MH lights. Not all LEDs are created equal, and marketing claims must be verified. Still, as innovation continues and growers learn to harness the capabilities of new LED lighting technology, the advantages of LED horticultural lighting are expected to grow.

8.3 The Light Spectrum

Research is ongoing to understand how the light spectrum affects CEA. Some manufacturers sell LED lights that can be tuned to a desired spectrum easily and repeatedly after installation. This allows growers to adapt their facilities when new lighting research emerges. With the new LEDs on the market, spectrums can be fine-tuned, allowing unprecedented research opportunities in academic, manufacturer, and commercial settings on lighting needs for specific crops. Table 8.1 summarizes current widely accepted research on the impact across the light spectrum at the time of publication. Figure 8.1 shows an example of the intensities of spectrum available from different lighting sources including sunlight, LED lights, and HPS lights. While these are only examples, they illuminate the differences between LED, HPS, and the fuller spectrum of sunlight. This can be compared to the absorption spectrum of plants shown in Figure 8.2.

The lighting types covered in Table 8.1 include:

- UV-C: Useful for protecting fruit and vegetables from spoiling after harvesting, pathogen control, and air and surface disinfection.
- UV-A and UV-B: Useful for protecting fruit and vegetables from pathogens (powdery mildew) and from spoiling after harvesting. Affects (often increases) metabolites and defensive compounds; high levels disrupt growth.
- Blue: Some level necessary for optimal photosynthesis (inhibit stem extension and plant height). Blue level of 5%–30% is typically desirable. Regulates stomata opening.
- Green: Able to penetrate further through canopy than blue/red. Regulates plant architecture. Absorbed by photochemicals other than chlorophyll.
- Yellow/Orange: Using these wavelengths can increase growth and metabolites; results vary between species. Antagonistic to some blue light responses including phototropism, hypocotyl, and flowering inhibition.
- Red: Highest action spectrum for photosynthesis; photosynthetically efficient. Consider ratio of red to far-red (R:FR).
- Far-Red: Enhances photosynthesis; consider R:FR and phytochrome photo-stationary state. Increases extension growth (stem length, plant height, leaf size).
- Infrared: Not photobiologically active; heat radiation affects plants by affecting leaf temperature.

Table 8.1. Effects of Wavelength Ranges on Plant Growth

Technology[a]	Purpose	Wavelength	CAPEX	OPEX	O&M	Lifespan (hours)
LED, Fluorescent	Secondary Metabolism	UV-C (100–280 nm)	$$$ (LED); $ (fluorescent)	$$$ (LED); $$ (fluorescent)	Medium	~5,000–10,000
	Secondary Metabolism, Shade Avoidance	UV-B (280–315 nm)	$$$$ (LED); $$ (fluorescent)	$$ to $$$	Medium	~5,000–10,000 (LED); ~10,000–24,000 (fluorescent)
	Secondary Metabolism, Photomorphogenesis	UV-A (315–400 nm)	$$ (LED); $ (fluorescent)	$$	Low-Medium	~10,000–15,000
	Photosynthesis, Shade Avoidance, Metabolism	Blue (400–500 nm)	$ (LED); $ (fluorescent)	$ (LED); $$ (fluorescent)	Low	~50,000 (LED); ~10,000–20,000 (fluorescent)
	Photosynthesis, Shade Avoidance, Metabolism	Green (500–530 nm)	$$$ (LED); $ (fluorescent)	$ to $$	Low	~15,000–50,000
HPS, LED	Photosynthesis, Secondary Metabolism	Yellow/Orange (530–600 nm)	$ (HPS); $$ (LED); $ (fluorescent)	$$$ (HPS); $–$$ (others)	Low-Medium	~10,000–50,000
LED, Fluorescent	Photosynthesis, Shade Avoidance, Photoperiodism	Red (600–700 nm)	$ (LED); $$ (fluorescent)	$ (LED); $$ (others)	Low	~15,000–50,000+
LED	Photosynthesis, Shade Avoidance	Far-red (700–800 nm)	$ to $$ (LED)	$	Low	~50,000
LED, HPS	None / Unknown	Infrared (800+ nm)	$ (LED); Inherent in HPS	$ (LED); $$$ (HPS)	Low	~10,000–50,000

[a] Table information sources: RII (2022b), IESNA (2021), and University of Arizona (2022).

[b] REAP: Rural Energy for America Program

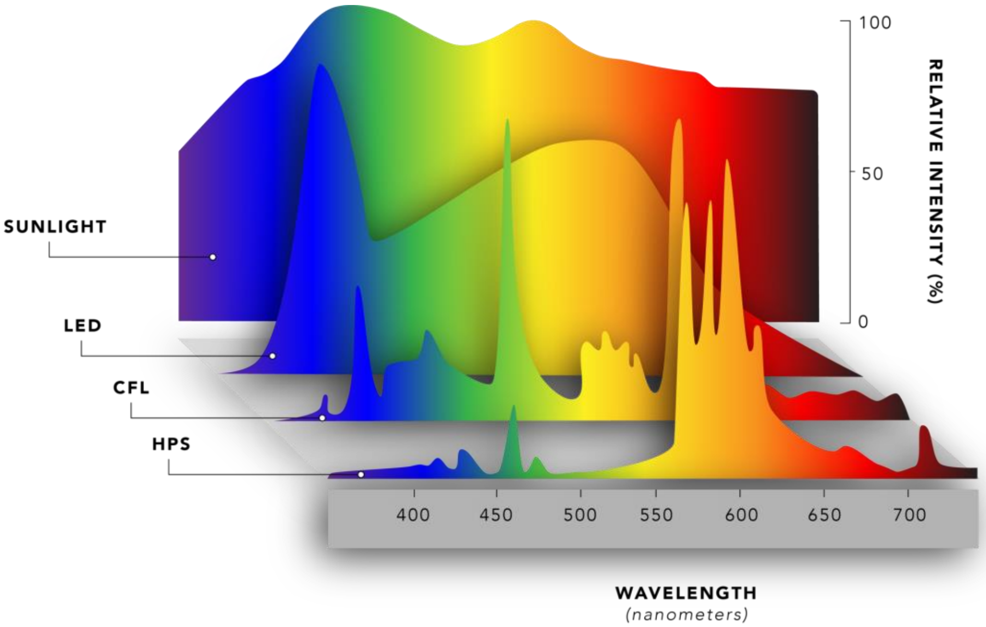

Figure 8.1. Wavelength prevalent in common lighting sources
Source: Schaffer (2020)

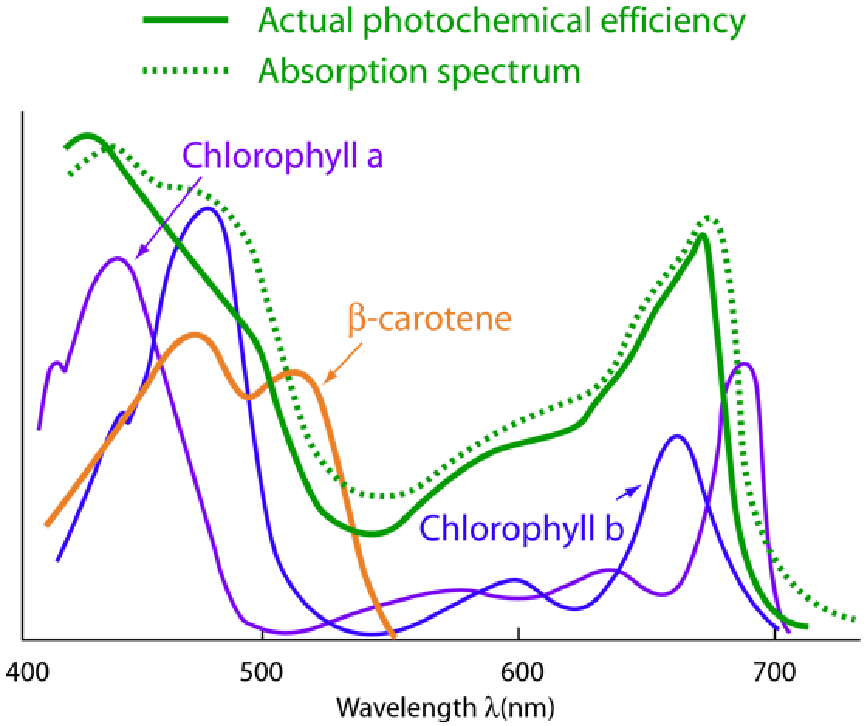

Figure 8.2. Relationship of wavelength and photochemical efficiency
Source: Nave (n.d.)

The DesignLights Consortium is a nonprofit organization that qualifies the performance of high-performance lighting technology. This third party measures the performance of horticultural lighting products and maintains a qualified product list of over a thousand high-efficiency horticultural lighting products. The threshold for qualification for this list advances with the technology over time. Lighting regulation often reflects the guidance of this group.

For links to the DesignLights list and other resources related to lighting, see Appendix A.

8.4 Heating, Ventilation, and Air Conditioning

HVAC systems are made up of a combination of different HVAC technologies (Table 8.2). Heating, cooling, ventilation, and dehumidification are the most common functions, which are used in concert to create ideal conditions within the facility. An HVAC system serves as a plant life support system. CEA facilities place high demands on HVAC systems, resulting in increased maintenance needs, unplanned system failures, and shortened lifespans of some systems—especially equipment in the grow area, which has higher temperatures and humidity than would be ideal for equipment. Many CEA HVAC experts recommend designing systems with maintenance, both planned and unplanned, in mind. This may mean designing systems with multiple smaller units rather than one large one, despite increased upfront costs. This redundancy allows the facility to maintain set points while maintenance is being performed on a unit.

Table 8.2. HVAC Technologies Summary

Technology	Purpose	Energy input	Footprint	Application	CAPEX	OPEX	O&M	Lifespan	Retrofit /New Build	Major Advantages	Major Concerns
Natural ventilation	Ventilation & Cooling	N/A (passive)	Small	Low-tech greenhouses	$	$	Low	30+ years	New build	Passive technology	Contaminants, low control
Convection tubing	Ventilation	Low	Medium	Low- to high-tech greenhouses	$	$	Low	1–5 years	Both	Reduction of microclimates	Frequent replacement
Unit heaters	Heating	High	Small–Medium	Low- to high-greenhouses & indoor	$	$$–$$$	Low	~ 15 years	Both	Low upfront cost & availability	Depends on size and fuel source
Hot Water systems	Heating	Medium	Small	Mid - High Tech Greenhouses & large indoor	$$$	$$	Medium	Boiler 15–25 years	New build	Long-term precise controls, system flexibility, chiller integration	Availability of expertise
Root zone heating	Heating	Low	Small	Low- to high-tech greenhouses	$–$$	$	Low	Depends on system	Both	Targeted heating	High upfront cost; complex installation; uneven heating and slower response than air systems
Heat pumps	Heating & Cooling	Low	Small–Large	Mid- to high-tech greenhouses & indoor	$$–$$$	$	Medium	10–25 years	Both	Heat & cool with one system, energy efficient	Design expertise for CEA applications
Curtains	Cooling	N/A (passive)	Medium	Low- to high-tech greenhouses	$	$	Low	7–12 years	Both	Energy efficiency from other system savings	Not always applicable
Evaporative pads	Cooling	N/A or Low	Small–Medium	Low- to high-tech greenhouses	$	$	Low	Pads 3–5 years	New build	Inexpensive cooling	High water use & adds humidity
Misting	Cooling	Low	Small	Low- to high-tech greenhouses	$	$	Low	System 25 years	Both	Inexpensive cooling	Frequent maintenance of nozzles or water treatment needs

Technology	Purpose	Energy input	Footprint	Application	CAPEX	OPEX	O&M	Lifespan	Retrofit/New Build	Major Advantages	Major Concerns
Chillers	Cooling	Low–High	Medium–Large	Mid- to high-tech greenhouses or indoor	$$$	$$	Medium	15–30 years	New build	Long-term precise controls, system flexibility, hot water integration	Availability of expertise
Commercial mechanical cooling	Cooling	Medium–High	Small–Large	Mid- to high-tech greenhouses or any indoor	$–$$$	$–$$	Medium	5–15 years	Both		
Standalone/portable	Dehumidification	Low–Medium	Small	Indoor	$	$	Low	3–5 years	Retrofit	Quick to install to add capacity	Can add heat to the grow area
Desiccant	Dehumidification	Low	Medium–Large	Indoor	$$	$	Medium	System 5–15 years	New build	Low energy use	Initial costs and setup challenges
Integrated	All HVAC Functions (Heating, Cooling, Ventilation, Dehumidification)	Low–High	Medium–Large	High-tech greenhouses or indoor	$$$	$$	High	Depends on specific equipment selected	Both	Integrated systems can make all equipment more efficient by having them work together to meet set points while reducing microclimates and improving productivity	Can be time-intensive and expensive up front, experienced technical design expertise can be hard to find

8.4.1 Ventilation Technologies

Natural Ventilation

In lower-tech facilities, HVAC systems typically focus on the movement of air through the facility, often called natural ventilation. Rolling up the bottom edges of a hoop house or opening windows close to the ground while opening vents located near a peak of the structure will naturally move hot air out the top and cooler air in from the base. Adjusting how open those vents are will dictate how much outside air will flow through the facility. These facilities may also use simple circulation fans to reduce microclimates in the space. Simple vent systems (Figure 8.3 and Figure 8.4) are easy to operate and maintain but only offer rudimentary control of the climate in the facility. They can also expose the plants to outside contaminants and pests.

Figure 8.3. Greenhouse ventilation view from outside

Source: Rob Eddy, RII

Exhaust Fans (Active Ventilation)

The next level of HVAC technology is adding exhaust fans for active ventilation. Vents are opened simultaneously and typically located on opposite sides of the grow area to facilitate air movement across the crop. This allows the greenhouse to maintain temperatures similar to the outdoor environment. Reducing greenhouse air below ambient outdoor temperatures most often involves the installation of an evaporative pad on the intake vents (see Section 8.4.3, Cooling). When additional filtering is needed, more surface area for intake can be needed for the same airflow, because the filters are restricting airflow through their area. Common solutions often include adding cages around a piece of equipment or having rooms with filter material built out around one wall that serves as the intake point into the facility.

Convection Tubing

Convection tubing, which is plastic tubing with precise holes, is increasingly common in low- and high-tech facilities for air distribution, either above or below benches. Conditioned air is blown in through one end of the tube and distributed at an even, low velocity to prevent microclimates.

Figure 8.4. Greenhouse ventilation view from inside
Source: Rob Eddy, RII

Semi-Sealed Greenhouses

Semi-sealed greenhouses have more advanced air management and distribution systems with vestibules for mixing both outdoor and recirculated air prior to distribution. CO_2 enrichment may also take place in these vestibules. These spaces house electrical and mechanical systems for easy access in large, open hallways along the air intake side of the greenhouse. These vestibules may feed into convection tubing below the grow tables or more conventional ventilation systems. Interior vents on the top of the vestibules may be used to draw greenhouse air back in for reconditioning rather than exhausting it outdoors, as occurs in standard greenhouses. This reduces energy required for heating or cooling the air and positively pressurizes the room to prevent pest contamination.

Advanced Zoned Ventilation

The most advanced greenhouses have precise zoning capabilities within different areas of the facility. For example, ventilation could be customized for every bay of a greenhouse or for overhead hanging crops relative to benchtop crops. These zoned controls can allow tuning for different stages of growth, crops, or varietals.

8.4.2 Heating Systems

Unit Heaters
In lower-tech facilities, portable unit heaters are common, designed to heat and move air. Many combust delivered fuels like propane within the grow space. Portable electric resistance versions are also on the market. Electric resistance heating is expensive per unit of energy so it is not popular for large users of heat but can be an easy solution for hobbyists. Combustion heaters have the added benefit of generating some CO_2, but they also generate less desirable gases. They have limited control capabilities and can present a danger when left unsupervised overnight, when they are most neeed. However, they are easy to operate, inexpensive, and low maintenance.

Advanced Unit Heaters
Advanced unit heaters are used in high-tech greenhouses across the United States, with some advertising efficiencies of around 90% by recapturing exhaust heat. Large-scale unit heaters for CEA typically use combustion fuels like natural gas, but there are electric and hot water systems on the market. While larger systems produce more CO_2 to promote plant growth, problematic combustion products are also more prevalent and must be managed. These systems tend to be cheaper per unit of heat than less advanced heating systems and easily integrate within air distribution and zoned systems. CEA environments are harsh for equipment placed within the grow room. There can be more rapid wear and tear on unit heaters, requiring frequent but not necessarily expert maintenance.

Hot Water Systems (Hydronics)
Hot water systems, often called hydronics, are extremely common in CEA facilities globally with significant penetration into the U.S. market, primarily for larger and higher-tech facilities. Heat can be easily controlled and tuned for many different applications around the facility by managing the flow of hot water through pipes. Greenhouse builders have advanced this technology for a myriad of applications, from slab heating to snowmelt management. Initial installation costs for hot water systems can be high. Specialized knowledge is needed to install, operate, and maintain them properly. Nonetheless, there are significant advantages in ease of conversion of a boiler fuel source, as well as integration with many heat recovery and thermal storage strategies.

Boilers
Boilers (Figure 8.5) are the heart of a hot water system and can use many fuel sources, including delivered fuels such as propane and heating oil, natural gas, biofuels, and electricity. Newer demand-type boilers, or low-mass boilers, are being increasingly adopted. Demand-type systems are most often designed modularly for multiple smaller units to combine to meet demands of the facility. This redundancy increases the reliability of the system and makes it easier to adapt the boiler system in an expanding facility. Boilers are removed from the harsh

environment of the grow room and do not experience the rapid wear and tear that much of the other HVAC equipment faces. While the systems using the hot water are often purpose-built for CEA, the boilers do not need to be, allowing for economy of scale for boiler installation, operation, and maintenance.

Figure 8.5. Boiler system in the mechanical room of a greenhouse facility
Source: Rob Eddy, RII

Root-Zone Heating

Root-zone heating is localized and targets the crops themselves more directly at the bench or on the floor around the roots, versus heating the air in the whole greenhouse. There are multiple strategies for this type of targeted heating including electric pads and hot water systems installed in or on the floor and on plant benches. This strategy can be especially efficient and cost-effective at night, when warm air rises in the greenhouse and outside temperatures outside the glazing are especially low with no solar heat gain inside. In New York, estimated energy cost savings from root-zone heating are 15%–30% (NYSERDA 2022).

Heat Pumps

Heat pumps are expanding in use across residential and commercial HVAC applications. They are only recently beginning to be used in CEA facilities. With their extremely high energy efficiencies and ability to both heat and cool, they will likely be more widely adopted for CEA. Air-source heat pumps are the most common type used for residential and commercial applications, but they have challenges when it comes to more extreme heat and cold. Geothermal heat pump technology has piqued the interest of the CEA community (See Section 5.2.7, Geothermal Energy). These systems continue to perform efficiently in more extreme temperatures. Heat pumps also easily combine with other heat recovery and thermal storage methods. However, heat pumps, when cooling, may struggle to meet the dehumidification needs of some facilities. Growers operating indoor facilities seem to be the most comfortable installing air-source heat pumps, using the new and highly efficient technology alongside older conventional heating and cooling systems. Indoor facilities are often adapting off-the-shelf HVAC solutions to meet the bespoke needs of CEA, especially facilities with smaller operations that can use inexpensive, commercially available equipment with easy maintenance needs. Though heat pumps are operating in greenhouses, their use currently involves a custom approach requiring a high level of expertise to design, install, and maintain.

Heat Recovery

Heat recovery is possible from many systems within a greenhouse or indoor operation. Nearly every piece of machinery generates heat. The decision to adopt heat recovery depends on how logistically and economically viable it is to harvest and use that heat.

8.4.3 Cooling

Shade, Diffusion, and Thermal Curtains

Shade curtains, as well as thermal and diffusion curtains, are a legacy technology more frequently adopted in greenhouses as improved materials come on the market. There are many options, often fulfilling multiple purposes, with extensive technical specifications available to help growers select the right product for their location and desired conditions. Shade curtains are designed to reflect light, and thus heat, back out of the greenhouse to reduce cooling loads and protect crops from too much direct light and high temperatures. Diffusion curtains are designed to allow reduced light through. These curtains create a more uniform light distribution to crops and reduce the impacts of harsh shadows from overhead structures such as lights, equipment, and beams. Diffused light has been shown to increase overall yields by 5%–8% with no additional energy consumption outside of motors to deploy the curtains (Li et al., 2014; Baystar, 2024). Modern combination curtains designed for shade and diffusion are often designed with a weave that freely allows airflow for use with ridgeline ventilation. Thermal curtains are designed to help growers maintain optimal temperature and avoid humidity swings. They are most often deployed at night to keep daytime heat near plants and prevent loss through rooftop glazing as well as to manage condensation from overhead structures as air cools. All of this can significantly reduce the demands on heating and cooling systems, resulting in energy efficiency savings. Facilities in New York estimate they can produce 20%–60% energy cost savings, and Michigan State University has reported 26% energy savings using thermal curtains (Getter 2015).

Evaporative Cooling (Pad and Fan Systems)

For greenhouses, the most common form of active cooling is an evaporative pad and fan, known in residential and commercial applications as “swamp coolers.” These systems consist of a pad made of an absorbent material with water pumped to flow through it. Air flows through the pad and cools as water evaporates. These systems can be standalone but are commonly built into a greenhouse wall. Evaporative cooling adds humidity to the air, making it a poor fit for facilities with high evapotranspiration loads. Evaporative pad and fan cooling systems are extremely common in greenhouses of all sizes but are rare in indoor facilities. While they are not a significant energy draw, they are a major water use in a greenhouse. Maintenance is extremely important because leaks are common. The pad can get a buildup of mineral deposits, algae or, if incoming air is not filtered, seeds and pollen, requiring pad replacement.

Fogging Systems

Another evaporative technology is fogging systems, using nozzles that spray a fine mist either where fresh air enters the grow area or distributed throughout the grow area. These systems are very common across the United States. They can be easily tuned for a specific grower’s needs with nozzle flow rates. Filtration, water quality, and maintenance are vital to prevent clogging and keep systems in good working order.

Chillers

Chillers may be used in facilities that already use a hot water system. Because they can use the same distribution systems and equipment (e.g., air handlers), chillers can avoid an investment in two separate systems. Chillers may be fueled by either natural gas or electricity. Similar to hot water systems, the distribution equipment is purpose-built for CEA. Chillers, however, are a common HVAC technology in other building types and may be used in greenhouse or indoor facilities that do not have a hot water system.

Commercial Mechanical Cooling Systems

There are a variety of commercial mechanical cooling systems for CEA facilities, especially as indoor and sealed facilities experiment with cost-effective solutions for high transpiration crops. Understanding operational set points and sizing these pieces of equipment is extremely important. They are often used in combination with additional equipment like dehumidifiers to achieve ideal growing conditions. Direct expansion systems are a common choice but can less effective when it's cold outside. Unit cooling systems are standalone equipment that are not typically ducted and tend to require additional dehumidification unless used to achieve cool temperatures of 55°F or below. While these commercial systems—and the expertise to install and maintain them—are widely available in the United States, expertise to design and operate the system for CEA is crucial. They can be sensitive to relatively small changes in temperature and humidity set points.

Heat Recovery

Heat recovery is a common offering for many types of cooling systems. This is especially useful for indoor, sealed, or high-transpiration CEA facilities that are working with high humidity. Heat recovery improves energy efficiency and balances dehumidification and cooling.

8.4.4 Dehumidification

Within CEA, dehumidification plays such a large role that the acronym “HVACD” is often used in place of the more traditional “HVAC” to indicate that additional dehumidification capacity has been integrated. Plants retain less than 5% of water absorbed (McElrone et al. 2013). The other 95% eventually makes its way into the air around the plant, most commonly as transpiration during photosynthesis. Any water added into the grow area that is not taken up by the plant adds to the humidity levels with evaporation. That results in a lot of water in the air. It also means large differences between the plant's day and night cycles, with high humidity in the day when they are using light for photosynthesis and thus rapidly adding moisture to the air.

For some facilities, demand for dehumidification surpasses other HVAC loads, especially in high-tech sealed facilities with high-transpiration crops. The added humidity loads can present unique load profiles for CEA facilities, requiring CEA-specific HVAC technical expertise in system design and commissioning. Dehumidification may not be a concern for facilities that take in a significant amount of outside air, operate in more arid climates, or have lower-transpiration crops. While many cooling equipment technologies also dehumidify, using only equipment purpose-built for cooling can result in too much cooling and not enough dehumidification. Equipment focused specifically on dehumidification rather than cooling was adapted for CEA from the aquatic center industry. There are still only a few purpose-built CEA solutions. HVAC equipment is increasingly regulated at a state level.

Standalone (Portable) Dehumidifiers

Standalone, or portable, dehumidifiers are direct expansion units designed to dehumidify but, in this application, will reject heat back into the space. This may increase cooling demands overall. Portable dehumidifiers are typically used in indoor facilities to supplement primarily cooling systems, but they may also be brought into a space during a crucial point in the grow cycle of a plant to reach a less humid set point.

Desiccant Systems

Desiccant systems use a solid or liquid hygroscopic substance to remove moisture from air without the cooling requirements of other technologies. Unlike other technologies, the absorption capacity of solid desiccant systems is not reduced by lower temperatures. Operations working to achieve very cool temperatures or very low humidity may find desiccant systems desirable. Solid desiccants must be heated to reactivate the material, reducing energy efficiency. Liquid desiccant systems can use the specific mixture of the liquid to tune the humidity by increasing or decreasing the concentration of salts within. Some liquid desiccant systems spray the liquid into incoming air prior to filtration to avoid contamination of supply air.

Integrated HVAC and Dehumidification Systems

Integrated HVAC and dehumidification systems are becoming more popular, especially for indoor facilities. A nonintegrated system can mean multiple systems working against each other to dehumidify, heat, and cool. Integrated systems manage temperature and humidity under one single control source with a purpose-built combination of systems designed to work in harmony. These systems typically combine non-purpose-built technology into a CEA-specific system designed for the set conditions of that facility. These systems require expertise in design and commissioning. Often, nonexpert facility employees can conduct regular maintenance.

Emerging Standards
For indoor facilities, the American National Standards Institute, the American Society of Agricultural and Biological Engineers, and the American Society of Heating, Refrigerating and Air-Conditioning Engineers have recently developed a new standard, EP653: Heating, Ventilating, and Air Conditioning (HVAC) for Indoor Plant Environments Without Sunlight. This represents the first HVAC standards for indoor CEA environments. Greenhouses have a variety of standards globally designed to guide decision making.

For links to this and other resources related to HVAC, see Appendix B.

8.5 Technologies on the Horizon

Low-Energy Salt Water Cooling Systems
Low-energy salt water cooling systems use the abundant sea water in Middle East and North Africa regions to cool agricultural setups efficiently, which is vital in hot climates where traditional cooling methods would be energetically costly (Lefers et al. 2020).

Hybrid Systems
Hybrid systems combine greenhouses and vertical farms. Crops are grown vertically with some of the daily light integral provided by natural sunlight and the rest supplemented through artificial lighting.

Growing in the Dark (Electro-Agriculture)
Electro-agriculture, or electro-ag, enables vertical farms to grow crops without sunlight by feeding gene-edited plants with acetate produced from CO_2 using renewable electricity. This method achieves four times greater energy efficiency than photosynthesis. It also reduces land use by up to 94% and could allow cultivation of high-calorie staple crops like grains and tubers in controlled environments. Key challenges include the required complex metabolic engineering to rewire plant metabolism for acetate utilization. There is also uncertainty in plant development without light (long-term physiological effects). Further improvements in the efficiency of CO_2-to-acetate conversion are needed. Although implementing these technologies is costly, preliminary studies suggest that the modest increases in CAPEX for such CEA systems are partially offset by reduced OPEX (Crandall et al. 2024; Ralls 2024; ScienceDaily 2024).

9. Process

9.1 Controls and Automation

CEA facilities use controls and automation for (1) crop improvement by optimizing climate conditions, (2) climate-smart operation by optimizing resource use through programming, (3) maintaining optimal systems by tracking equipment data, and (4) streamlining management and labor through remote operation or augmentation of labor. This catalog will focus primarily on how controls and automation (Figure 9.1) can be deployed to improve resource use efficiency and maintain optimal systems of the technologies discussed in this catalog.

CEA operations in the United States range from low- to high-tech with regard to building envelope (plastic film to glass) and the hardware within (portable heaters to fully integrated HVAC). Controls to achieve crop production and processing goals vary as well, from basic to advanced. Control selection should be determined based on an operation's budget, complexity, and goals for both the present and the future. Table 9.1 displays the range of technologies.

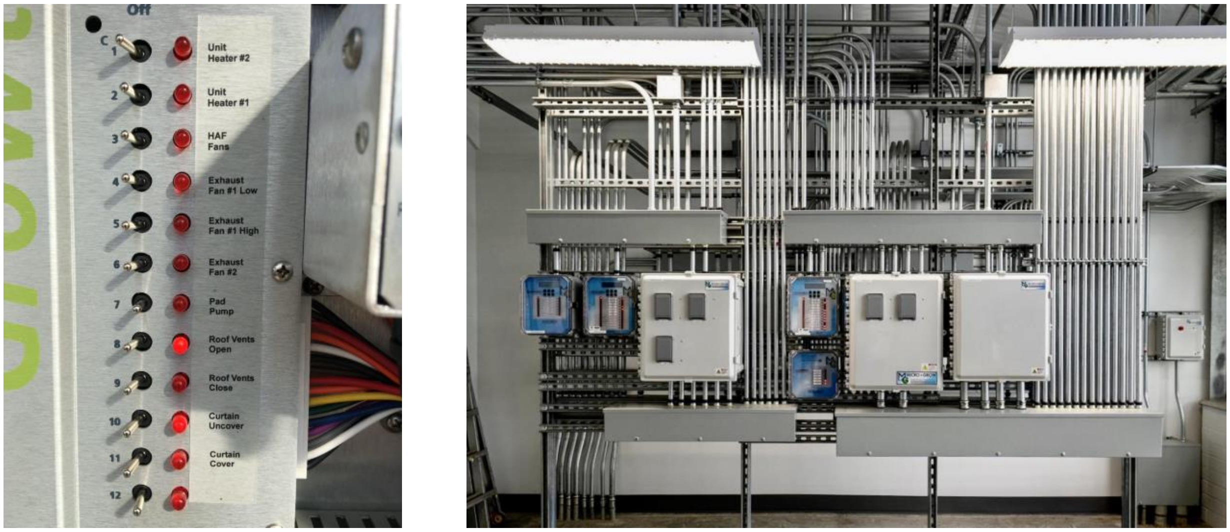

Figure 9.1. Images of CEA control systems

Left image shows a manual control panel, and the right image shows an automated-precision control system. Sources: RII Staff, left; Texas A&M Agrilife Research (n.d.), right.

Table 9.1. Controls Technology Summary

Technology[a]	CAPEX	OPEX	Energy Efficiency	Benefits
Manual Operation	Low – Typically involves basic equipment such as manual vents, fans, and heaters.	Relatively Low – Can be labor-intensive. Ongoing costs may include occasional equipment repair or replacement.	Generally Low – Lacks the precision and adaptability of automated systems.	Limited – Less efficient and may result in suboptimal growing conditions.
Thermostatic Control	Moderate – Involves the installation of basic temperature-triggered devices such as thermostats.	Moderate – Requires occasional calibration or replacement of thermostats.	Generally Low – Improved efficiency compared to manual control but still limited in adaptability.	Moderate – More automated approach but lacks sophistication. Reduces crop loss from excessive stress.
Step Controller	Moderate–High – Involves more advanced equipment capable of adjusting settings in discrete steps.	Moderate – Requires periodic calibration and maintenance.	Moderate – More efficient than manual and thermostatic controls but may still be limited in precision.	Moderate – Increased control over climate parameters, resulting in improved crop consistency and quality. Efficiency is not as high as more advanced systems.
Microprocessor Control with Feed-Forward Algorithms	High – Requires advanced equipment and sensors.	Moderate – Requires regular maintenance and occasional software updates. Some control system providers operate on a subscription model.	High – Precise control and the ability to anticipate changes contributes to energy savings.	Significant – Provides optimal conditions to reduce resource usage and enhances overall greenhouse productivity.

[a] Listed from simple to complex and adapted from RII's best practices guide for controls and automation (RII 2024b)

9.2 Sensors and Data Collection

Sensors and the data they collect are crucial for monitoring and controlling the environmental conditions of the growing environment. Specific sensor types and configurations will depend on an operation's goals and vary from facility to facility, but sensor placement, maintenance, calibration, and data management are crucial across all operations to accurately inform the controller. For example, if a temperature sensor is located next to heating equipment, the data feeding into the controller will not be representative of the crop canopy. Further, to account for variance in temperature in a CEA operation, sensors in the center of the growing zone can be set to have more weight compared to sensors on the perimeter. A grower should follow the manufacturers' recommendations on placement and maintenance of sensors.

Note that more sensor data is not always better. A grower should plan to only collect data that is useful to optimize their operation.

9.3 Environmental Control Systems

Environmental control systems (ECS) for CEA facilities comprise sensors, actuators, controllers, communication systems, and software. These systems interface with equipment to regulate environmental conditions with the goal of optimizing plant growth and improving resource efficiency (RII 2024b). Environmental conditions these systems are tasked to monitor and control include temperature, humidity, airflow, lighting, shading, irrigation, and CO_2. Within each environmental condition, there are a range of simple to complex strategies growers can implement with their controls systems to achieve energy, water, and cost savings (Table 9.2). A New York State Energy Research and Development Authority study found that implementing an ECS can result in 5%–10% total energy cost reduction with a payback period of 1–5 years (NYSERDA 2022). The following section will cover climate-smart controls strategies for (1) temperature, humidity, and airflow (2) lighting and shading; (3) irrigation; and (4) CO_2 enrichment.

Table 9.2. Environmental Controls Systems Summary

Technology	Energy Savings	CAPEX	OPEX	O&M	Retrofit/New Build	Notes
Environmental Control Systems	15%[a]	$500–$15,000+[b]	$	Low	Both	Upfront costs depend on complexity of the system, ranging from thermostatic to advanced integrated controls.

[a] Posterity Group (2019) estimated energy savings of about 15% from replacing a standalone control system with an integrated environmental controller in Ontario greenhouses. Actual savings will vary by facility

[b] See NYSERDA (2022) and Beytes (2021).

9.3.1 Temperature, Humidity, and Airflow Control

Staging Equipment

CEA operations, both greenhouse and indoor, often use multiple technologies for heating and cooling. Controls are often programmed to stage these systems, activating the least energy-intensive option first rather than all the cooling or heating technologies turning on at once. For example, staging cooling in a greenhouse would begin with passive ventilation by opening vents, followed by fans and ultimately evaporative pad and fan. This can provide energy savings and assist a grower with efficiency goals by staging passive or electric technologies before natural gas, for example.

Anticipatory Controls

ECS can use predictive data such as weather forecasts to optimize the growing environment by preparing for changes in environmental conditions (Shelford et al. 2022). Integrating weather forecasts into a greenhouse ECS could inform anticipatory controls for lighting, HVAC, and CO_2 enrichment equipment. For example, if cold temperatures are forecast for the night, the system can initiate the thermal curtain to close, retaining heat gained throughout the day and reducing heating requirements. Such strategies can reduce energy consumption by 20% in cold climates (Boyacı et al. 2023).

9.3.2 Lighting and Shading Control

Ramped Starts and Stops

Similar to staging equipment, ramped starts or stops refer to staggering the activation or deactivation of the lighting system. Rather than all the lighting turning on at once, resulting in a spike in peak demand load, the lighting can be staggered by growing zone or room, or the dimming controls can be used over a programmed period of time (10–45 minutes) through ECS.

Off-Peak Electricity Pricing Control of Lighting

Shelford et al. (2022) offer an example of off-peak control. They developed a lighting control algorithm that uses day-ahead market data from utilities and weather forecasts to estimate whether supplemental lighting will be needed on a given day and how many hours lights will need to run. Based on the day-ahead market pricing, the algorithm could determine the least expensive time to run the lights and achieve simulated energy cost savings up to 80% compared to other controllers operating on a similar peak rate schedule algorithm.

9.3.3 Irrigation Control

Using ECS can control variable frequency drives on irrigation pumps to better control flow, lowering water use while also lowering the energy requirements of the irrigation system. This precision can be taken one step further by measuring water content for irrigation and crop steering. By using sensors measuring the water content of the substrate, such as weight scales or volumetric water content sensors, a grower can increase the precision of irrigation events, reducing water and fertilizer waste (Nederhoff and Houter 2009).

9.3.4 CO_2 Enrichment Control

CO_2 enrichment can lower the lighting requirements for crops, provide energy savings, and increase yields (Zhang and Kacira 2022). Monitoring light intensity and CO_2 concentrations closely through ECS can allow operations to fine-tune the relationship to optimize crop growth while reducing energy requirements associated with lighting proactively or in response to changes in the environment. For example, if a greenhouse operation forecasts ahead of time or is responding to a sunny day, the ECS could leave or switch the lights off, increase CO_2 concentrations, and achieve similar plant growth with reduced light levels.

For an operation to use CO_2 enrichment effectively, environmental controls are used to monitor and optimize concentrations. An example of this is programming maximum set points to allow for temperature to reach slightly above average during the morning and late afternoon. This practice would reduce the cooling demand of the operation and therefore limit the ventilation or pulling in of fresh air, which results in diluted CO_2 concentrations.

More information on how CO_2 enrichment is used in CEA operations is discussed in Section 10, CO2 Utilization.

9.4 Technologies on the Horizon

Artificial intelligence (AI), a branch of computer science, imitates human intelligence by using algorithms to perform tasks such as learning, perception, decision-making, and reasoning. AI and advanced robotics are emerging technologies in CEA that are advancing to address key problems in the industry such as energy consumption and labor shortages. Adoption of these technologies by growers in the United States is currently low and reserved for larger operations that can afford the high capital costs. However, adoption of AI and robotics in CEA is expected to increase gradually, driven by persistent labor challenges. A recent survey found that more than 80% of U.S. growers struggled to recruit, train, and retain workers (GPN 2024). In another survey, 28% of growers reported that over 20% of ripe produce could not be harvested due to insufficient labor, and 45% planned to address this by reducing production (IUNU 2023).

Artificial Intelligence
In a CEA operation, AI can be used to advance ECS, crop and pest/disease monitoring, and yield prediction. Currently, some ECS manufacturers are building systems that integrate AI solutions. Additionally, some are building integration capabilities for third-party AI systems, making for a more seamless adoption in CEA operations. A leading challenge for AI adoption in CEA is the cost of advanced control systems, which can range from about $8,000 to over $15,000 depending on complexity (Beytes 2021, NYSERDA 2022), with additional costs for other components such as sensors, software, and IT infrastructure. Other challenges include data availability to train AI systems and knowledge barriers for smaller operations.

Advanced Robotics
Automation has been widely adopted in CEA from conveyance (e.g., trolley systems for hanging plants or mobile benches and gutters) to pre- and postharvest activities (e.g., seeders and packaging systems). Recent innovation in automation comes with the development and

use of advanced robotics to augment specific tasks such as harvesting, de-leafing, spraying and sanitation, and transport to help ease the industry’s labor shortage. Currently, harvesters constitute the majority of commercialized advanced robots in CEA, with a primary focus on tomatoes; however, harvesters for other vine crops, floriculture, and mushrooms are either available or under development. High costs limit the adoption of advanced robotics in CEA. Initial investments can range from $30,000 for simpler tasks to hundreds of thousands for more advanced robots such as harvesters, but economic viability is possible (Eddy et al. 2025).

10. CO_2 Utilization

In CEA, optimal CO_2 levels are crucial for maximizing photosynthesis, leading to thicker leaves, faster growth, and increased production. Studies indicate that elevated indoor CO_2 concentrations, typically maintained between 800–1,000 parts per million (ppm) or about two times higher than ambient CO_2 concentrations (Wang et al. 2022), significantly enhance plant growth compared to the ambient atmospheric levels. The ideal CO_2 range for many CEA crops is between 450 and 1,200 ppm, depending on specific crop requirements (Dixon 2023). Given the rising costs of commercially sourced CO_2 and its critical role in boosting crop yields, efficient CO_2 utilization technologies (Table 10.1) are becoming a pivotal aspect of CEA operations. This reliance on CO_2 enrichment, often referred to as CO_2 fertilization, underscores the need for innovative solutions to manage CO_2 supply effectively and economically (Li, H. et al. 2023). As such, this technology category warrants significant attention to ensure efficient and cost-effective production in vertical farms and other CEA facilities.

Table 10.1. CO2 Fertilization Technologies Summary

Technology[a]	Purpose	Footprint	CAPEX	OPEX	O&M	Lifespan (years)
Compressed CO_2	CO_2 supply	Medium–Large	$$$	$$	Low	40+
Fuel-Based CO_2 Supply Unit	Electricity, heat, CO_2	Small	$	$	Low	20
Natural Gas Boilers	CO_2 (heat)	Small	$$	$$	Medium	20
CHP Systems	CO_2 (electricity/heat)	Medium	$$$	$$	Medium	20
Decomposition & Fermentation	CO_2 supply	Small	$$	$$	Medium	5–10
Chemical Method	CO_2 supply	Small-Large	$$	$$	Low	5–10
Direct Air Capture	CO_2 supply	Medium	$$$$	$$$	Low	20–25
CO_2 Injection	Crop management	Small–Medium	$$	$$	Medium	20+
CO_2 Distribution (Air Circulation)	Crop management	Small-Large	$$	$$	Medium	Data Not Available
CO_2 Control	Crop management	Small	$	$	Low	10+
Exhaust Gas Scrubber	CO_2 supply	Large	$$$	$$$	Medium	40+

[a] The information presented in this table is based on data sourced from multiple references, including product pricing details from SkyTree, expert consultation, and publicly available data on CO_2 supplementation from the Ontario Ministry of Agriculture, Food, and Rural Affairs (2002).

CO_2 can be purchased in containers or created using gas-fired equipment. As discussed in Section 5.4, colocation with electricity generation or industrial facilities that produce CO_2 can provide access to low-cost CO_2 and eliminate the need for onsite fuel use or transport and delivery of CO_2 (Mohareb et al. 2017). CEA heavily relies on a CO_2 supply chain mainly powered by hydrocarbon resources, either captured at emitting industries based on combustion processes or by burning natural gas onsite and capturing the CO_2 from the exhaust (Skytree n.d.).

Purchased CO_2 is used in various industries, including food and beverage production, greenhouse operations, and enhanced oil recovery in the oil and gas sector. The CO_2 is typically purified, compressed, and transported to end users via pipelines, trucks, or rail cars, depending on the distance and quantity required. The sources of purchased CO_2 in the United States are diverse: ethanol production (36%),[2] natural CO_2 wells (25%),3 ammonia production

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[2] During the fermentation process of converting corn or other biomass into ethanol, CO_2 is produced as a byproduct. This CO_2 is captured, purified, and sold for industrial use.

[3] Natural CO_2 reservoirs are natural geological formations with trapped CO_2.

(22%),[4] hydrogen production (13%),[5] cogeneration (4%),[6] and others such as chemical manufacturing[7] and natural gas processing.[8] Regional distribution varies significantly: The U.S. West relies on hydrogen production and CO_2 wells, the South depends on CO_2 wells and ammonia production, and the Midwest and Northeast primarily use ethanol (SkyTree 2024). Recently, the North American Liquid Carbon Dioxide market experienced mixed trends with rising prices (Figure 10.1) due to high natural gas costs, demand driven primarily by the carbonated drinks and food packaging industries, and stable yet strained supply due to limited inventories. The demand for CO_2 in the United States is substantial, totaling approximately 10.4 million tons per year. The food industry accounts for 70% of that demand, primarily driven by prepared foods (17%) (SkyTree 2024).

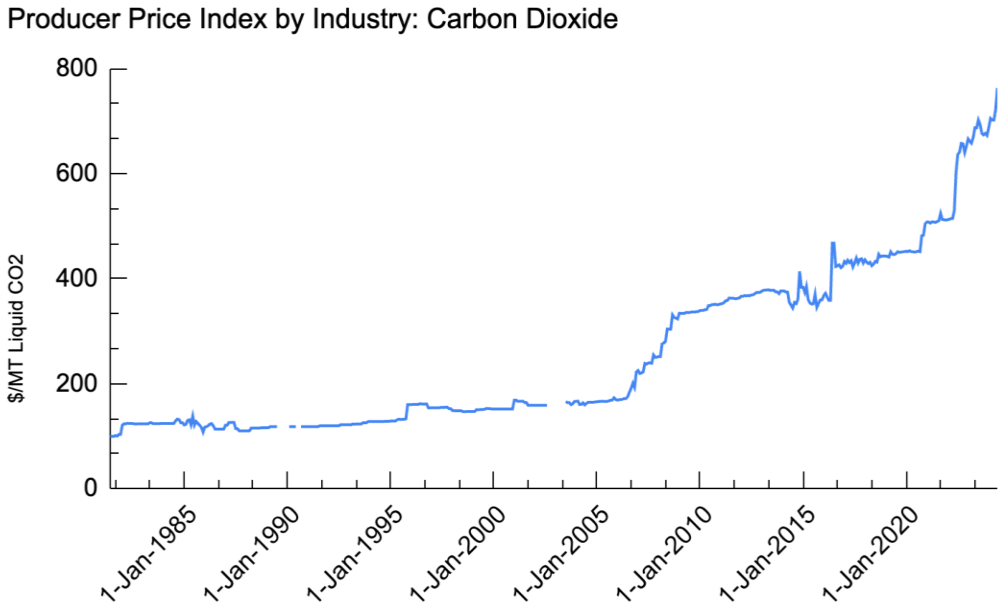

Figure 10.1. CO_2 cost over time based on U.S. Producer Price Index

Source: U.S. Bureau of Labor Statistics (2024)

CO_2 utilization is a critical yet often underestimated component of CEA. CO_2 is essential for enhancing yield, and CEA growers typically obtain it from onsite combustion of natural gas or through external suppliers. However, traditional purchasing of CO_2 is declining due to increased

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[4] The production of ammonia, a key component in fertilizers, generates significant amounts of CO_2 as a byproduct. This CO_2 is often captured and purified for use in various industries.

[5] The steam methane reforming process used to produce hydrogen also generates CO_2 as a byproduct. This CO_2 can be captured and used in various applications.

[6] Power plants and other large industrial facilities that burn fossil fuels produce CO_2 as a result of combustion. While not all of this CO_2 is captured, some facilities are equipped with carbon capture technologies to collect and purify the CO_2 for industrial use.

[7] Certain chemical processes, such as the production of sodium carbonate (soda ash), release CO_2 that can be captured and purified for industrial use.

[8] When natural gas is extracted from wells, it often contains CO_2 that needs to be removed before the gas can be used. This separated CO_2 can be captured and utilized for industrial purposes.

demand across various industries, including food production and emerging carbon capture and storage startups. While emerging direct air capture technologies present an alternative, their high energy requirements and costs currently make them less viable. Combustion remains the most economical option, though it involves fuel procurement, exhaust treatment, and potential permitting considerations. CHP systems offer a more efficient solution by generating both electricity and heat, but regulatory challenges and grid integration issues complicate onsite CO_2 generation. As a result, some CEA facilities resort to burning natural gas solely for CO_2 production, underscoring the need for integrated and efficient solutions in the sector.

Given that the boundary of this technology catalog is the CEA facility itself, we will focus only on the CO_2 technologies that are onsite and will not focus on different methods of CO_2 generation offsite. Offsite-generated CO_2 is only discussed as part of the opportunities in Colocation, Section 5.2.12.

10.1 Compressed CO_2

Compressed CO_2 is a widely adopted method for enhancing plant growth in CEA by providing an easily controllable and consistent source of CO_2. Compressed CO_2 is stored in high-pressure cylinders or tanks and is released into the growing environment in precise amounts (Figure 10.2). The system is often integrated with ECS, such as sensors and automated ventilation, to ensure that CO_2 levels are maintained within the desired range, optimizing conditions for plant health and productivity. Unlike other sources of CO_2, compressed CO_2 is clean and free from contaminants, reducing the risk of introducing harmful pollutants into the growing environment. This method is also flexible and scalable, making it suitable for both small and large-scale operations. Although considerations related to cost, storage, and safety must be managed, using compressed CO_2 remains an effective and reliable approach to enhancing crop production in CEA.

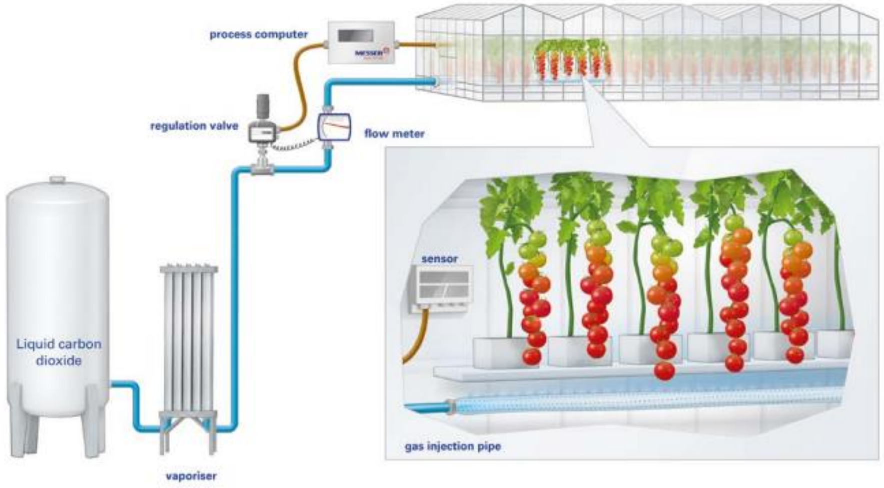

Figure 10.2. An illustrative example of how compressed CO2 is used in a greenhouse
Source: CBMTEC (2024)

10.2 Fuel-Based CO_2 Supply Unit

Greenhouse operators often use small CO_2 generators (Figure 10.3) that burn propane or natural gas to enhance plant growth. Combustion of hydrocarbon fuels typically produces CO_2, water, and heat, with 1 pound of fuel generating approximately 3 pounds of CO_2. These generators are ideally placed just above the plants, covering an area of about 4,800 square feet each. They are capable of producing significant amounts of CO_2, up to 8.2 pounds per hour. However, adequate ventilation is crucial, as incomplete combustion can generate harmful impurities. The operational costs of these systems are relatively low, making them a viable solution for maintaining optimal CO_2 levels in greenhouses (Dunn and Poudel 2023).

Larger greenhouse operations may opt for more robust systems that use gas engines to produce flue gas, which after purification provides CO_2, as well as heat and electricity. This not only ensures a steady supply of CO_2 but also helps in heating the greenhouse and reducing energy costs. These comprehensive systems, though more expensive—potentially costing up to $8,000 per acre—offer the dual benefits of CO_2 generation and significant operational cost savings through integrated heat and power production (Dunn and Poudel 2023).

Figure 10.3. Carbon dioxide generator manufactured by several different manufacturers

The generator operates with either propane or natural gas and has a pressure gauge to control the size of the burner. Sources, from left: Shandong Jienuo Thermostat Equipment (n.d.), Dunn and Poudel (2023), FarmTek (n.d.)

10.3 Boilers and CHP Systems

Boilers and CHP systems, which are commonly used within CEA settings, produce exhaust gases that are rich in CO_2. This CO_2 can be captured and repurposed effectively for CO_2 fertilization in greenhouse operations (Figure 10.4). The integration of these energy systems with CEA allows for the direct utilization of CO_2 from exhaust gases, either directly or after treatment with exhaust gas scrubbers to remove impurities. This process not only recycles waste byproducts but also reduces the need for external CO_2 procurement, offering an efficient and cost-effective solution to boost photosynthesis and optimize crop production in CEA facilities.

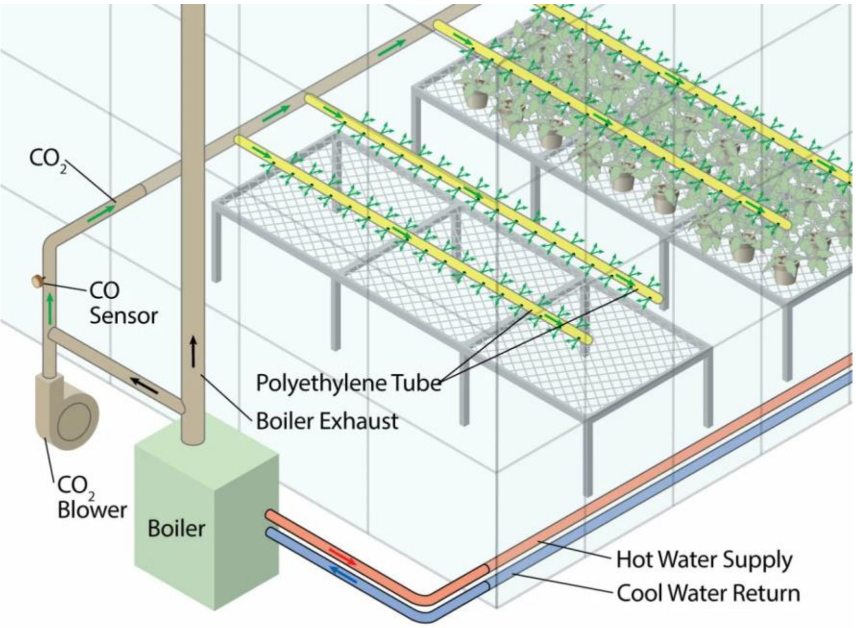

Figure 10.4. CO2 fertilization using the exhaust gas from a boiler system
Source: BioTherm Solutions (n.d.)

10.4 CO_2 from Decomposition and Fermentation

Decomposition and fermentation are organic methods to produce CO_2. Decomposition involves the microbial breakdown of organic waste, releasing CO_2 that plants can use. While cost-effective and useful for waste utilization, this method can be challenging to manage in terms of space, CO_2 concentration control, and odor management. Fermentation, another organic method, produces CO_2 and ethanol from a sugar and yeast solution. Although this method generates CO_2 more quickly than decomposition, it shares similar challenges, including odor management and maintaining precise CO_2 levels. Additionally, it requires more space and careful sealing of the production container. The ethanol produced can be used as an organic fuel, potentially increasing the CO_2 yield when burned (Dunn and Poudel 2023).

10.5 Chemical Method

The chemical reaction of baking soda with acid (mostly acetic acid) can produce CO_2, but a large quantity of materials is required to produce adequate CO_2. The reaction of about 2 pounds of baking soda with 10 to 12 liters of 5% acetic acid just produces 1 pound of CO_2. Thus, this is considered an expensive method of CO_2 production. The acetic acid is dripped on baking soda, and CO_2 is generated. Slow release of acetic acid by drip increases the life of the reaction. The reaction takes a long time to generate enough CO_2, and it is difficult to control the CO_2 concentration (Dunn and Poudel 2023).

10.6 Direct Air Capture

Direct air capture is an innovative technology that enables closed-loop CO_2 utilization within CEA. It captures CO_2 directly from ambient air, eliminating the need for integration with industrial emission sources or reliance on external CO_2 supply chains. Direct air capture is most often categorized into two groups: solid sorbent (low temperature) and liquid solvent (high temperature) (SkyTree 2024). These systems are energy-intensive, so electricity costs are a significant factor in overall operating economics.

10.7 Exhaust Gas Scrubbers

Exhaust gas scrubbers are essential technologies for CEA facilities that use exhaust gas from CHP systems or are colocated with industrial operations, such as power plants, ammonia plants, and ethanol production facilities (Figure 10.5). These scrubbers play a critical role in capturing and purifying CO_2 from the exhaust gases of these colocated facilities. The captured CO_2, which would otherwise be released into the atmosphere as a waste product, can be redirected to enrich the growing environment in greenhouses or indoor farms, thereby enhancing photosynthesis and promoting crop growth.

The process involves directing exhaust gases through scrubbers that remove sulfur oxides, nitrogen oxides, particulates, and other contaminants. The resulting purified CO_2 can then be safely introduced into the CEA environment. Colocation with industrial facilities that produce exhaust gases offers a cost-effective CO_2 source, eliminating the need for separate CO_2 generation or procurement. This arrangement can also benefit the industrial partner by providing an outlet for exhaust gases that might otherwise require treatment for regulatory compliance.

Figure 10.5. Exhaust scrubber (left) and CO_2 piped into the CEA facility after scrubbing (right)
Source: Hug Engineering (n.d.)

Whether integrated with onsite CHP systems or colocated industrial facilities, exhaust gas scrubbers offer CEA operators flexibility in sourcing CO_2 based on local partnerships and infrastructure.

Figure 10.6 shows a greenhouse facility that uses a CHP as well as a scrubber to generate food-grade CO_2 for CO_2 fertilization in the greenhouse.

Figure 10.6. CHP exhaust capture and cleanup system for use inside the greenhouse
Source: Frames Group (2019)

10.8 CO_2 Injection, Distribution, and Control

Besides generation of CO_2, controlling the concentration and making sure uniform distribution of CO_2 across the entire grow area is also important. CO_2 concentrations within greenhouses and vertical farms are regulated manually or via automated computer systems, depending on facility size and system sophistication. CO_2 sensors monitor greenhouse air, providing data on CO_2 concentrations along with temperature and humidity, which aids in crop management. In manual setups, these sensors inform when to activate CO_2 generators. In contrast, automated systems adjust CO_2 levels based on preset parameters established by growers.

CO_2 diffuses slowly. To ensure even CO_2 distribution, effective air circulation strategies are critical. Figure 10.7 provides an overview of the primary equipment used for CO_2 injection and distribution in CEA facilities. Small greenhouses might use fan jets or horizontal airflow fans, while larger facilities often employ perforated plastic tubes positioned under benches close to the crop level. This method enhances CO_2 delivery directly to the leaf boundary layer — crucial in densely planted areas — ensuring optimal growth conditions (Dunn and Poudel 2023).

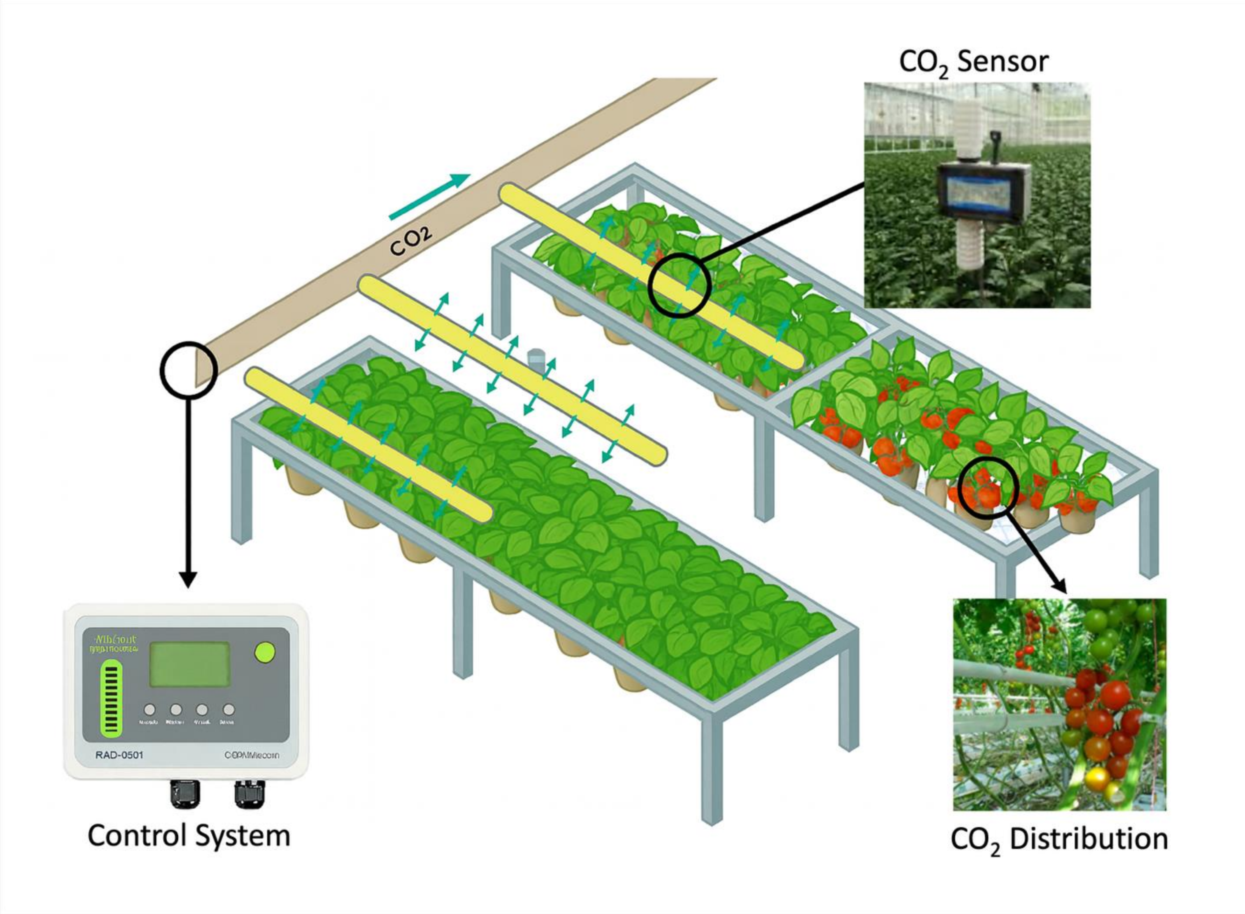

Figure 10.7. Overview of CO$_2$ injection, distribution, and control in a CEA facility

Source: Figure created by the author, adapted from BioTherm Solutions (n.d.), Johnson CO$_2$ (n.d.), Bilim (2022), and Enertec Engineering (n.d.).

10.9 Technologies on the Horizon

Advanced CO$_2$ Sensor Technologies

Modern CEA facilities can adopt advanced CO$_2$ sensing networks to monitor and optimize enrichment. Wireless sensor arrays placed throughout a facility can give real-time, high-resolution CO$_2$ readings at the canopy level (Hortica 2025). These innovations include ultra-sensitive optical sensors and low-cost IoT devices that enable growers to maintain ideal CO$_2$ concentrations with precision. By improving spatial monitoring, these sensors help prevent CO$_2$ stratification and ensure uniform distribution, ultimately reducing waste and energy use (Almawgani et al. 2023).

Targeted CO$_2$ Micro-Injection Systems

Instead of diffusing CO$_2$ uniformly through an entire greenhouse, emerging systems deliver CO$_2$ directly to the plant canopy in a targeted manner. Research on crop-localized CO$_2$ enrichment has shown dramatic efficiency gains. Injecting CO$_2$ at the crop level raised the in-canopy CO$_2$ concentration by about 264 µmol/mol and boosted leaf photosynthesis rates, all while using CO$_2$ far more efficiently than traditional methods (Zhang et al. 2022). This means

Local Enrichment methods can be four times more CO_2-efficient than flooding an entire growing area (Zhang et al. 2022). This innovation could allow growers to achieve the same growth promotion with a fraction of the CO_2 input, reducing costs.

AI-Driven CO_2 Dosing Control

As discussed earlier sections of this catalog, AI and advanced control systems are already being explored for optimizing broader environmental conditions such as temperature, humidity, and lighting. A similar approach is now emerging for CO_2 enrichment. To maximize benefits from CO_2 enrichment while minimizing waste, growers are turning to smart control algorithms. Advanced greenhouse climate software now uses AI and machine learning to dynamically adjust CO_2 dosing in concert with ventilation, lighting, and plant needs. Research has shown that computational models coupled with machine learning can optimize CO_2 distribution and maintain ideal concentrations more precisely than manual control (Li et al. 2018). These systems account for factors such as plant growth stage, time of day, occupancy of the space, and even energy pricing to dose CO_2 only when and where it's most effective. For instance, algorithms may reduce CO_2 flow before a ventilation cycle to avoid losses or increase dosing during peak photosynthesis hours for maximum uptake. This trend toward data-driven CO_2 management complements the new hardware (sensors and injectors) and could significantly reduce CO_2 waste and improve cost-efficiency of CO_2 fertilization in CEA (Li et al. 2018).

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Appendix A: Lighting Resources

- Controlled Environment Agriculture Lighting Best Practices Guide (RII)
- Energy Best Practices for Agriculture: Greenhouses (NYSERDA)
- Ball Red Book Volume 1: Greenhouse Structures, Equipment, and Technology (pp. 123–128) (Independent Publishers Group)
- A critical review of ultra-violet light emitting diodes as a one water disinfection technology (*Water Research X*)
- The Robustness and Reliability of Mercury Lamps in Healthcare (UV academy)
- 2022 Solid-State Lighting R&D Opportunities (U.S. Department of Energy)
- How Long Does a UV Light Last? (BSC Bulbs)
- UV LEDs for UVA, UVB & UVC (Opsytec Dr. Gröbel)
- DesignLights Consortium Qualified Product Lists (DesignLights Consortium)

Appendix B: HVAC Resources

- Ball Red Book Volume 1: Greenhouse Structures, Equipment, and Technology (pp. 102–123) (Independent Publishers Group)
- ANSI/ASABE/ASHRAE EP653: Heating, Ventilating, and Air Conditioning (HVAC) for Indoor Plant Environments Without Sunlight (ANSI Webstore)
- Cultivation HVACD System Comparison Study (Anderson Porter Design)
- Heat pumps integrated with greenhouses literature review (Appropedia)
- Greenhouse heating by energy transfer between greenhouses: System design and implementation (*Applied Energy*)
- Geothermal Source Heat Pump Performance for a Greenhouse Heating System: An Experimental Study (*Journal of Agricultural Engineering*)
- Two types of temperature & humidity control (*Greenhouse Management*)
- Water use for pad and fan evaporative cooling of a greenhouse in a semi-arid climate
- Controlled Environment Agriculture HVAC Best Practices Guide (RII)