Controlled Environment Agriculture Market Characterization Report

Supply Chains, Energy Sources and Uses, and Barriers to Efficiency

Gretchen Schimelpfenig, PE and Derek Smith

September 2021

Controlled Environment Agriculture Market Characterization Report

Supply Chains, Energy Sources and Uses,
and Barriers to Efficiency

Prepared in partnership with:

The American Council for an Energy-Efficient Economy In support of the USDA Natural Resource Conservation Service Conservation Innovation Grant funded project, Data-Driven Market Transformation for Controlled Environment Agriculture

American Council for an Energy-Efficient Economy

About Resource Innovation Institute (RII)

Resource Innovation Institute (RII) is an objective, data-driven non-profit organization whose mission is to measure, verify and celebrate the world's most efficient agricultural ideas. We cultivate a better future for all of humanity with our vision of resilient harvests for the next hundred years. Our consortium of members brings perspectives from across the field—uniting architects and engineers, growers and operators, researchers and analysts. Founded in 2016 to advise governments, utilities and industry leaders on the resource impacts of cannabis cultivation, an under-studied and resource-intensive market, we have since extended our research to other sectors in partnership with the US Department of Agriculture. To take on the challenges of our changing world, we believe that food, medicine and other vital crops demand data-driven insights, securely shared with integrity. By nurturing the human connections in our complex and dynamic industry, we can build deeply restorative systems for people and the planet.

About the American Council for an Energy-Efficient Economy (ACEEE)

The American Council for an Energy-Efficient Economy (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

About the Authors

Gretchen Schimelpfenig conducts research and analysis on benchmarking controlled environment agriculture facilities for energy, water, and emissions impacts. Her areas of research include the energy efficiency opportunities of emerging technologies and key performance indicators for comparing greenhouses and indoor farms. She also serves as a member of the Energy Committee of the town of Huntington, Vermont. Prior to joining RII, Gretchen worked at the Burlington Electric Department and Cx Associates. She earned a bachelor's degree in architectural engineering from the University of Wyoming and a master's degree in civil engineering from Stanford University.

Derek Smith conducts research on government efforts to adopt and implement equitable policies to increase resource efficiency of controlled environment agriculture operations. His areas of research include inclusive, incentive-based policies, energy codes and standards, and energy and water reporting compliance. Prior to founding RII, Derek led Clean Energy Works, a non-profit organization funded by the US Dept. of Energy and the State of Oregon. He earned a bachelor's degree in mass communications from San Jose State University and a master's degree in business administration from University of Oregon.

Acknowledgements

This report was made possible through the generous support of the United States Department of Agriculture. Internal contributors include Carmen Azzaretti and Hamza Bahri. The authors would like to thank Jen Amann of ACEEE for her strategic contributions. We also appreciate Ben

Somberg of ACEEE for his help launching this report. We gratefully acknowledge external reviewers, internal reviewers, colleagues, and sponsors who supported this report. External review and support do not imply affiliation or endorsement. External reviewers and consulted sources are listed in the References appendix of this report.

Suggested Citation

Schimelpfenig, G., Smith, D. 2021. Controlled Environment Agriculture Market Characterization Report: Supply Chains, Energy Sources and Uses, and Barriers to Efficiency. Portland, OR: Resource Innovation Institute. RII link.

Executive Summary

The US Department of Agriculture Natural Resources Conservation Service engaged the American Council for an Energy-Efficient Economy (ACEEE) and Resource Innovation Institute (RII) in April 2021 to initiate the three-year Conservation Innovation Grant project entitled ***Data-driven market transformation for efficient, sustainable controlled environment agriculture***[1] (CEA). The first objective in the project is to characterize the market to inform the development of a strategy to transform the market toward efficient cultivation practices and thus enhance the competitiveness of farmers while advancing energy savings, carbon emissions reductions and more resilient communities.

The beneficial environmental impacts of the project will be achieved by working directly with 5- 10 producers to improve the energy efficiency of their CEA operations, with estimated benefits:

- **Energy Savings:** 12.9 to 25.8 million kBtu
- **Greenhouse Gas Emissions Reductions:** 952,000 to 1,904,200 kg CO_2eq

This estimate assumes a 4:1 mix of greenhouse to indoor vertical farms participating in our project. Savings are based on facility energy use estimates reported in ACEEE 2018 and an assumed 20% savings for implementation of efficiency upgrades.

The team will use the results of this market characterization report to update savings estimates to be specific to the energy-saving technologies that can effectively serve CEA facilities, some of which may achieve greater energy benefits from energy efficiency projects than initially anticipated. Table 8 from the report shows how several energy savings measures for greenhouses and indoor farms can reduce energy use by up to 50%.

Table 8: Energy Savings Potential by Measure

Energy Savings Measure	*Energy Savings Potential*
Greenhouse Envelope Systems[2]	5 - 50%
LED Horticultural Lighting[3]	30 - 40%
High Performance HVAC Systems[4]	20 - 30%
Integrated Controls Systems[5]	15 - 30%

[1] "Controlled environment agriculture" is used synonymously in this proposal to mean non-livestock industrial facilities that can incorporate indoor horticultural cultivation as well as post-cultivation processing activities such as drying, extraction, and product manufacturing. All Federal and non-Federal funds associated with this project will be used to support activities related to non-cannabis crops.
[2] (R-082), (R-098)
[3] (R-019), (R-058)
[4] (R-057)
[5] (R-055)

Research Objectives

The research objectives for this market characterization report were the following:

1. Describe the supply chain, key market actors, barriers to energy efficiency, and the best leverage points for market interventions;
2. Describe the energy used by producers (including on-site renewable energy, microgrids, and back-up generation);
3. Describe the energy and non-energy benefits realized through implementation of efficiency projects;
4. Identify key market baselines to be used in evaluating the impact of the market transformation initiative over time.

Key Findings

Major findings contained in this report:

1. ***Supply Chains***
   The CEA cultivation supply chain can be grouped into three major segments: CEA producers, technology vendors, and design & construction professionals. Producers are generally grouped into two categories: greenhouse and indoor. The technology vendor segment includes several types of vendors: technology manufacturers, manufacturer sales representatives, distributors, and retail businesses. Design & construction professionals include architects, mechanical and electrical engineers, lighting designers, commissioning agents, energy consultants, construction management professionals, systems integrators, and construction contractors like HVAC, lighting, and controls contractors.

   Actors from other supply chains connect to cultivation supply chain actors in the post-harvest supply chain, which includes processing, packaging, transportation, distribution, and retail.

2. ***Key Market Actors***
   Alongside producers and their supply chain of vendors and design & construction professionals, consumers, energy suppliers, efficiency programs, investors and financial institutions, industry organizations, and governments play key roles in the CEA landscape. These actors use tools like purchasing decisions, utility rate structures, technical assistance, efficiency incentives, financing mechanisms, third party certification programs and standards for equipment and facility design, and regulations to coax the market toward resilient best practices.

3. ***Barriers to Energy Efficiency***
   Barriers to widespread adoption of energy efficiency practices persist despite CEA producers understanding and increasingly valuing the benefits. Upfront costs are

considered the primary barrier, with access to capital and financing, a lack of knowledge of efficient technologies, and skepticism and lack of trust in product performance as secondary barriers. Barriers specific to emerging technologies are also prevalent and affect new construction and retrofit projects differently, may require challenging production shut-downs, can suffer from low producer awareness and trust, and may receive less energy efficiency program support.

4. ***Market Interventions***
   The best leverage points for advancing efficiency practices include increasing knowledge and understanding of technologies and their benefits, demonstrating peer success through benchmarking and case studies, engaging financial institutions on the value of efficiency-related lending, providing marketing opportunities for growers to showcase their sustainability commitment, targeting producers in regions with high power costs, and emphasizing certain efficiency benefits toward ranges of producers based on size and method of cultivation.

5. ***Energy Sources for CEA Facilities***
   CEA facilities use diverse sources of energy depending on the facility type and the location. In addition to electrical energy, various fuels (such as natural gas and propane) are used. Electric rate structures often dictate fuel choice for CEA producers. CEA producers also install distributed energy resources (DERs) on-site to improve operational resilience, offset grid energy consumption, and lower operating expenses from utility bills. Typical DERs on CEA sites include on-site renewable energy sources like solar, cogeneration microgrids served by natural gas, and back-up generators using a variety of fuels.

6. ***Energy and Non-Energy Benefits of Efficiency***
   CEA producers engage in energy efficiency projects of varying sizes and implement them for diverse reasons, including energy benefits and non-energy benefits. Energy benefits include lower electricity and fuel bills. Common non-energy benefits include lower costs for operational expenses, labor, and maintenance. CEA facilities can realize additional non-energy benefits when implementing energy efficient technologies and approaches.

7. ***Key Market Baselines***
   Baselines of energy usage will be measured to evaluate the impact of our market transformation initiative over time. Industry-standard Key Performance Indicators (KPIs) on resource efficiency and productivity will be quantified via the PowerScore resource benchmarking platform. Quantitative and qualitative analysis will be performed.

Conclusions

- The CEA sector can be grouped into two categories: greenhouses and indoor farms.
- The equipment used to sustain optimal environments for plant growth dictates the energy intensity of CEA facilities.

- The two sectors produce different and diverse crops. Greens are the primary food crop produced by both greenhouses and indoor farms.
- Greenhouses produce food and floriculture crops and grow both nursery stock and finished plants. Major greenhouse food crops are cucumbers, tomatoes, peppers, leafy greens, herbs, and strawberries. Mushrooms and microgreens are major crops for indoor farms.
- The range of canopy area of U.S. CEA facilities is wide and varies by market segment and facility infrastructure.
- Key market actors can be leveraged as partners and collaborators to reach CEA producers and influence their operations with best practices guidance.
- The energy sources used by producers are diverse and several key market actors can benefit from influencing resource consumption in CEA facilities.
- The energy and non-energy benefits of efficiency projects can be substantial and both are valued by CEA producers.
- Financial challenges of efficiency projects and technology-specific barriers remain for both segments of CEA producers.

Recommendations

To overcome barriers to efficiency, market intervention strategies should be developed to:

1. **Benchmark a range of production environments to enable development of energy use baselines.**
2. **Promote the benefits of energy efficiency in ways that are compelling to producers.**
3. **Target producers effectively based on cultivation approach, geography, power supply costs and size/scale of operation.**
4. **Leverage key market actors to develop coordinated producer support systems.**

Introduction

Research Objectives

To accomplish the four research objectives of the market characterization report, ACEEE and RII conducted two activities to gather data to meet the project's market characterization objective: a review of secondary sources and interviews with market actors.

- **Review of secondary sources:** This research compiled quantitative information, such as the size of the CEA market, size of CEA facilities, cultivation methods, crop types, and market baselines.

- **Interviews with various market actors:** This research collected information about energy sources used by producers, barriers to energy efficiency, energy and non-energy benefits of efficiency projects, and best leverage points for interventions.

ACEEE and RII used data collected to develop a description of the CEA market in the quantitative and qualitative areas identified above to define the target market for our market transformation initiative.

Methodology

To achieve the research objectives, the project team conducted both secondary and primary research.

Primary Research

The research team assembled a Project Advisory Group for the market transformation project called the Controlled Environment Agriculture Leadership Committee (CEA LC), which serves under RII's Technical Advisory Council. The CEA LC is composed of leaders in the CEA space, including designers, operators, program implementers, and representatives from industry organizations, including national and regional energy efficiency organizations (REEOs), third-party certification organizations, and standards organizations[6].

Meetings and Surveys

In April 2021, two benchmarking input sessions with several greenhouse and vertical indoor producers were held to inform this report and other project objectives; some responded to a survey[7]. Four committed pilot producer partners attended a meeting in June 2021 to review the project objectives and prepare to gather facility information for their personal benchmarking sessions in August 2021.

---

[6] The list of members of the CEA LC is provided in this report's References section.
[7] Survey questions and the list of participating producers are provided in this References section of this report. Primary sources submitted survey responses; questions asked in surveys can be reviewed in the Survey Appendix.

The CEA LC participated in two meetings in May 2021 to inform and validate the findings of this report. The CEA LC also responded to two surveys[8]. A primary survey was conducted of CEA LC members informed by secondary research understanding. The results of a primary survey were discussed with Leadership Committee members in order to refine a secondary survey sent out to CEA LC members and a larger audience of key CEA stakeholders. Members of the CEA LC provided an initial review of this report in mid-June 2021.

Interviews

In-depth interviews were also conducted with those with subject matter expertise relevant to answering the research questions for this report in July 2021. These individuals include CEA LC members, Technical Advisory Council Working Group members, and pilot producer partners.

Secondary Research

The research team leveraged existing datasets, academic literature, utility reports, and trade group publications to address the research objectives. These resources are listed in the Resource Database linked in this report's References section.

Research Questions

These seven research questions were used to inform the team's strategy for achieving the four research objectives of this report:

1. Which supply chains serve CEA operations?
2. Who are the key market actors influencing the CEA market?
3. What are the major barriers to energy efficiency for CEA producers?
4. Which are the most effective leverage points for CEA market interventions?
5. What sources of energy are being used by CEA producers (including on-site renewable energy, microgrids, and backup generation)?
6. Describe the energy and non-energy benefits realized through the implementation of efficiency projects.
7. What market baselines should be used in evaluating the impact of this CEA market transformation initiative?

Findings

The key findings for CEA market characterization are described in more detail below in the following sections:

- Supply Chain

[8] Survey questions and the list of participating producers are provided in this References section of this report. Primary sources submitted survey responses; questions asked in surveys can be reviewed in the Survey Appendix.

- Key Market Actors
- Energy Sources for and Energy Consumption of CEA Facilities
- Distributed Energy Resources
  - Back-Up Generation
  - Microgrids
  - On-Site Renewable Energy
- Energy Benefits of Energy Efficiency Projects
- Non-Energy Benefits of Energy Efficiency Projects
- Barriers to Energy Efficiency
- Best Leverage Points for Market Interventions
- Key Market Baselines

It is worth noting some data are not yet available to support this report; this information should be encouraged to be researched and shared by key market actors to enhance the impact of future CEA market transformation initiatives. The missing data are summarized in the References section of this report.

Supply Chain: Producers

The worldwide CEA industry has seen rapid growth over the past decade. Drivers such as extreme weather conditions, droughts, and fires have created an expansive and thriving market. Growers cited concerns around pests and pesticides, as well as overall product quality as their primary reasons for growing indoors. Secondary concerns (according to all stakeholders) included proximity to markets, space and water efficiency, crop resiliency, and general environmental control (R-015).

The CEA cultivation supply chain can be grouped into three major segments: CEA producers, technology vendors, and design & construction professionals. Actors from other supply chains connect to cultivation supply chain actors in the post-harvest supply chain, which includes processing, packaging, transportation, distribution, and retail. Consumers are also a critical terminal of the overall CEA value chain and are discussed in the Key Market Actors section of this report.

The project team will transform the CEA market by connecting key actors throughout the supply chain to build comprehensive, equitable, and diverse ways to overcome barriers to energy efficiency and implement the best leverage points for market interventions. The project will focus primarily on the CEA cultivation supply chain to implement market interventions and will account for how post-harvest supply chain actors and consumers can affect change to accomplish project goals.

Market Identities

Within the CEA market, there are two distinct segments: protected agriculture approaches like greenhouse cultivation, and indoor growing strategies including vertical farms. In contrast with traditional outdoor farming in most regions, CEA facilities allow for year-round production with multiple harvests and can be located closer to the customers (R-015). CEA facilities are located across the United States, with many operations clustered around metropolitan areas.

Greenhouse cultivation facilities may operate seasonally or year-round and can produce seeds, young plants, finished plants, or a combination. Wholesale greenhouses may sell plants to distributors that have relationships with retail buyers like garden centers and grocery stores. Retail greenhouse vendors sell finished plants to consumers.

Indoor CEA operations usually grow for perpetual harvest and focus predominantly on finished plants, with the exception of the microgreens market.

Market Value

The size of the CEA market has been estimated by several market studies. While Europe's CEA market is notably innovative and efficient (R-117), North America accounts for the largest indoor farming and greenhouse market share, with the United States followed by Canada and Mexico. The CEA market in the Asia-Pacific region is also growing rapidly.

The CEA industry in the United States is predominantly dominated by greenhouse crop production (R-025). In 2018, the estimated trajectory for growth (compound annual growth rate, CAGR) of the United States CEA market[9] between 2018 and 2023 was 3.4% (R-023).

Greenhouse

The 2017 USDA Census of Specialty Crops valued the United States nursery, greenhouse, and floriculture market at $20 billion. Speciality crops are defined as "fruits and vegetables, tree nuts, dried fruits, and horticulture and nursery crops (including floriculture) cultivated or managed and used by people for food, medicinal purposes, and/or aesthetic gratification". The Specialty Crops census includes traditional agricultural producers (field farmers) as well as those growing crops under protection (under glass or other coverings).

To show the CEA landscape inside the specialty crops market, Table 1 below describes specialty crop products in the "Nursery, greenhouse, floriculture, and sod" category, a market served by 48,643 operations. This category was split into subcategories in Table 1 to cover only crops grown under protection.

> ***Term: Canopy Area***
> Canopy area is used to describe a farm's plant area under production. In a vertical growing environment, the canopy area includes the area of all tiers used for growing. Canopy area does not equal gross floor area; gross floor area describes a greenhouse or vertical farm's total built footprint, including aisles, walkways, processing areas, and other non-production areas.

[9] Including both 'smart greenhouse' and vertical farming markets.

Table 1: Market Value of U.S. Operations Producing Specialty Crops[10], 2017

Crop	Operations Under Protection	Canopy Area Under Protection (square feet)	Market Value of Specialty Crop Products Under Protection[11]
Floriculture & bedding crops	17,051	869,496,529	-
Nursery stock crops	4,302	308,879,616	-
Greenhouse vegetables and fresh cut herbs	10,849	112,564,105	$748,301,654
Mushrooms	1,261	36,281,409	$1,331,571,459
Greenhouse fruits and berries	846	11,708,439	$25,051,238
Seeds: Vegetables	599	8,972,753	-
Seeds: Flowers	294	495,223	-

Table 2 below describes food crops grown in protected environments. 2,994 operations grew fruits, vegetables, and herbs valued at $1.4 billion in the 2019 USDA Census of Horticultural Specialties.

Table 2: Market Value of U.S. Operations Producing Food Under Protection[12], 2019

Crop	Operations[13]	Wholesale Sales	Retail Sales
Cucumbers	1,003	$512,758,000	$190,711,000
Tomatoes	2,205	$253,332,000	$91,693,000
Other Food Crops Grown Under Protection	1,005	$122,919,000	$44,038,000
Peppers	745	$49,008,000	$22,122,000
Greens	1,042	$40,996,000	$24,157,000
Fresh Herbs	700	$40,192,000	$5,499,000
Strawberries	161	$6,055,000	$2,521,000

Term: Protected Agriculture

Protected agriculture describes the modification of an environment to achieve improved conditions

[10] (R-049), Table 1. (R-081), Table 39.
[11] Market value only provided for Specialty Crop categories for crops grown solely under protection.
[12] (R-048), Table 15.
[13] Number of operations exceeds 2,994 as many operations grow more than one crop.

for plant growth. Techniques vary in complexity from the use of row covers to sophisticated controlled environment plant systems. Systems may manage air and root temperature, light intensity and quality, water and plant nutrition, growth substrates, temperature and relative humidity, and protection from harm from pests and pathogens (R-111).

Term: Advanced Greenhouse
More farms are cultivating crops in 'advanced greenhouses' which involve enhanced structural configuration, environmental control, crop production, material handling, labor utilization, resource allocation, and return on investment (R-116). Advanced greenhouse facilities may use higher-tech infrastructure like sealed and automated building envelopes, HVAC systems, LED horticultural lighting systems, irrigation systems (including hydroponics), and controls hardware and software to more precisely manage environmental conditions. Advanced greenhouses may also demonstrate operational optimization of labor and materials without the use of sophisticated infrastructure. The results of the 2018 Autonomous Greenhouse Challenge found that artificial intelligence (AI) and automated control can serve indoor farming needs. When growing cucumbers, the winner was one of the four teams of robots controlled by AI, achieving 6% higher yields and 17% higher net profits. The second-place team of experienced human growers still performed well and achieved high yields, but was outperformed by robots controlled by an AI team with little experience growing the crop (R-101).

A 2018 analysis found that within the protected agriculture market, the value of the North American advanced greenhouse market was approximately $567 million (R-023).

Indoor

The vertical farming market was valued in 2018 at $740 million, with some expecting it to grow with a CAGR of 10.5% to be worth $3 billion by 2024 (R-023). Producers note that there is a lot of opportunity for the CEA space in the US due to the amount of investment in the industry allowing companies to "operate for multiple years without really generating a profitable business model" (R-031). Producers in the space have raised hundreds of millions of private capital and pioneers have gone public to fund expansion of their operations (R-044, R-045, R-046).

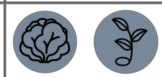
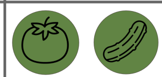
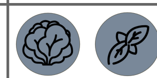
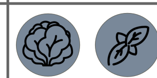
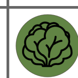
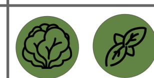
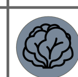
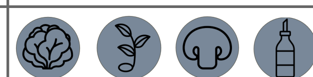
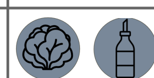
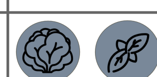
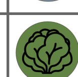
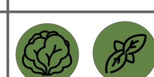
Productivity of indoor horticulture is higher per square foot than traditional agriculture due to several factors. Growing indoors allows producers to optimize environmental conditions, more precisely control systems that affect plant growth and development, cultivate vertically, and perpetually harvest. Facilities producing greens, microgreens, herbs, and vine crops indoors can be over 4,000 times more productive on a revenue basis than conventional outdoor commodity farming. Revenue is proportional to production; greens and tomatoes grown indoors can produce nearly $2.2 million dollars per acre compared to outdoor lettuce at less than $13,000 per acre. Smaller producers can achieve higher revenue per square foot, with larger greens producers getting over $65 per canopy square foot (csf) while smaller producers with less than 1,500 square feet of canopy can get $72/csf; this is also reflected in microgreens and vine crops (R-024).

CEA Producer Landscape

Figure 1 and Table 3 on the following pages represent a subset of CEA producers active in the United States in 2021, their locations, their cultivation approach, and their major crop types. This map of the CEA producer landscape skews more urban and represents companies with larger, more high-tech facilities that serve metropolitan demands for fresh produce. These facilities represent the members of the CEA Food Safety Coalition, include committed pilot partners for this project, and reflect operations focused on being thought leaders in the CEA industry.

Figure 1: Locations and Types of U.S. CEA Facilities (Indoor and Greenhouse), 2021

Table 3: United States CEA Producer Landscape, 2021

Producer	Locations	Producer Type
80 Acres Farms	AR, NC, OH	
Aerofarms	NJ	
AppHarvest	KY	
Bowery Farms	MD, NJ	
Brightfarms	IL, NC, OH, PA	
Clear Water Farms	NY	
DeGoede Farms	WA	
Element Farms	NJ	
Elevate	NJ	
Farm.One	NY	
Fifth Season	PA	
Go Green Agriculture	CA	
Gotham Greens	CA, CO, IL, NY, RI	
Green Life Farms	FL	
Houweling’s	CA, UT	
Infarm	NY, WA	
Little Leaf Farms	MA	
Local Bounti	MT	
Mastronardi Produce	ME, MI, NY, OH	

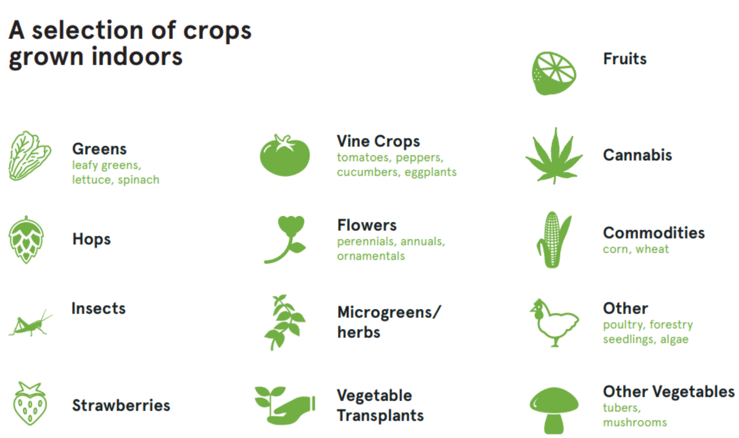
Oishii	NJ	
OnePointOne	AZ, CA	
Planted Detroit	MI	
Plenty	CA, WY	
Pure Green Farms	IN	
Revol Greens	MN	
Sensei Ag	HI	
Square Roots	MI, NY	
Superior Fresh	WI	
Vertical Harvest	IL, ME, PA, WY	
- Leafy Greens	- Tomatoes	- Berries
- Microgreens	- Peppers	- Mushrooms
- Herbs	- Cucumbers	- Fish
- Value Add Products (salad bowls, meal kits etc.)	- Greenhouse	- Indoor
Note: This map of producers is slanted towards well-funded, larger operators due to the availability of information. Further project work will ensure a range of producers is engaged in informing market transformation strategies.		

Primary Crop Types

Greenhouse

In protected agriculture, greenhouse producers grow nursery crops, ornamental plants and floriculture, transplants for commercial production, propagative materials, and fruits and vegetables (R-048). Greens (see Figure 1) are the primary greenhouse crop; other popular crops include peppers, vine crops like cucumbers and tomatoes, strawberries, and herbs. In a 2016 study of 98 greenhouse facilities, 39 grew greens, 23 grew microgreens and herbs, 24 grew vine crops, and 10 grew flowers (R-024). The vegetable segment is expected to grow the fastest (R-047). Emerging crops in greenhouses include specialty greens like edible crop covers such as chickweed and sorel, and herbs usually imported, like saffron.

Figure 2: Crops Grown in CEA Facilities (Indoor and Greenhouse), 2016



Indoor

Figure 2 shows a selection of crops grown indoors. In vertical farming, fruits and vegetables (a category that includes greens like lettuce and spinach) have a 47% share of the overall market, followed by herbs and microgreens with 35% in 2019 (R-027). These crops are in demand year-round, and they tend to command higher prices and have shorter shelf lives than other horticultural products (R-009). In a 2016 study of 78 vertical farming facilities, 31 grew microgreens and herbs, and 32 grew greens (R-024). Emerging crops in vertical farming include vine crops, rare varieties of greens and shoots, strawberries, and mushrooms of culinary value. Mushrooms have been cultivated indoors for hundreds of years; in the U.S., the market value in 2017 was $1.3B, with the largest industry in Pennsylvania (R-050).

Indoor berries is a blooming global market, with lots of R&D being done to bring berries into CEA and master automation of delicate fruit-picking. There are over 1,200 acres of indoor berries in The Netherlands (R-025), and Japanese plant factories are being designed to create the perfect-tasting strawberry.

> *"Strawberry is the holy grail of vertical farming. And the reason being it's the hardest crop to grow in a vertical plant environment....whoever unlocks strawberries will be closest to unlocking all of the other flowering crops, which is everything beyond leafy greens...we're not talking about five or ten years out, but we are talking about a much nearer future where this will be in the single digits [dollars] at which point anyone can buy these strawberries at their local supermarket," said Oishii founder and CEO Hiroki Koga (R-031).*

Facility Size & Production

Greenhouse

In 2019, data describing operations growing food crops produced under glass or other protection, displayed in Table 4 below, showed that around 3,000 operations produce nearly 880 million pounds (7.8 million hundredweight (cwt)) of cucumbers, herbs, leafy greens, peppers, strawberries, and tomatoes. 53% of produced crops are grown from hydroponic systems (R-048).

Table 4: Area and Production of U.S. Operations Producing Food Under Protection[14], 2019

Crop	*Annual Production (pounds)*	*Canopy Area (square feet)*	*Annual Production Per Unit Area (pound per canopy square foot)*
Tomatoes	466,551,120	52,576,000	8.9
Other Food Crops Grown Under Protection	244,194,720	10,674,000	22.9
Greens	61,792,192	5,531,000	11.2
Cucumbers	57,153,600	6,337,000	9.0
Fresh Herbs	36,546,608	10,685,000	3.4
Peppers	12,402,768	2,481,000	5.0
Strawberries	1,320,704	659,000	2.0

Indoor

CEA production facilities range in size by cultivation approach. Roughly 61% of the indoor vertical farms in the country are estimated to be of small scale, generally defined as 5,000 square feet or less (R-027). Table 5 describes the range of canopy area of greenhouse and indoor CEA producers represented by the sample of producers selected for Figure 1 and Table 3.

Table 5: Canopy Area of U.S. CEA Facilities

Facility Type	*Minimum Canopy Area (square feet)*	*Median Canopy Area (square feet)*	*Maximum Canopy Area (square feet)*
Greenhouse	13,500	348,000	5,000,000
Indoor	500 (research chamber) 5,000 (production)	60,000	280,000

[14] (R-048), Table 15.

Supply Chain: Technology Vendors

Producers trust several key actors in the technology community. Producers work with different supply chain actors to obtain technology to serve their operations. The technology vendor supply chain includes several types of vendors: technology manufacturers, manufacturer sales representatives, distributors, and retail businesses.

Technologies serving the CEA supply chain can be broken into these five major[15] categories:

1. Greenhouse building envelope systems
2. Horticultural lighting
3. HVAC and dehumidification equipment
4. Water management systems
5. Controls for lighting, HVAC, and water systems

Figure 3: Projected Growth of CEA Technologies

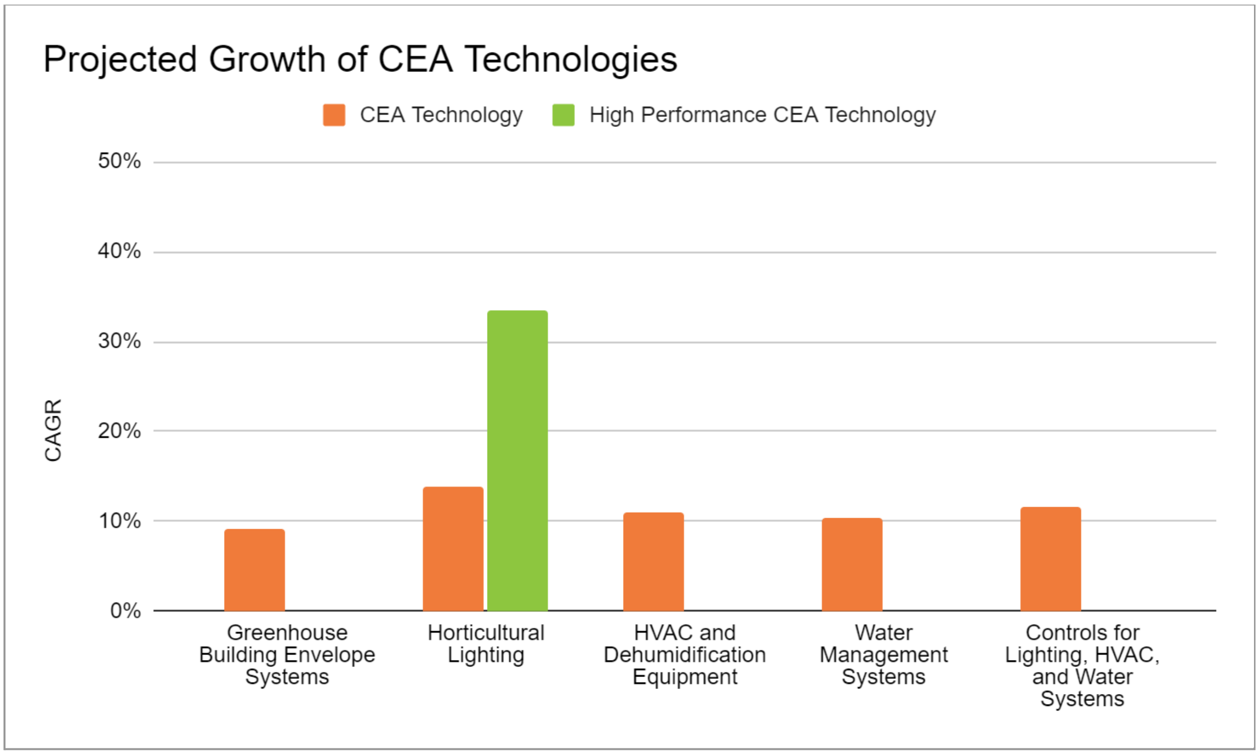


Figure 3 is a visual depiction of the projected growth of CEA detailed in the following paragraphs. Note that high-performance horticultural lighting systems (LED) are growing much faster than the horticultural lighting market at large.

[15] Several minor technology categories to characterize as they become more defined in the market: turnkey vertical farming systems, camera and drone technology for crop monitoring, software for crop data management and analysis, waste prevention solutions, robotics for harvesting and shipping, logistics solutions for distribution, and software solutions like Application Programming Interface (APIs) to allow for connectivity between facility systems.

Table 6 below shows how greenhouses and indoor vertical farms use horticultural lighting based on the requirements for optimal production of crops being grown. Horticultural lighting is one of the greatest contributors to energy use in CEA facilities, and the intensity to which the technology is used to satisfy crop needs can be an indicator of the overall energy intensity of the CEA facility.

Table 6: Intensity of Horticultural Lighting System Applications by Crop Type

Crop Type	*Horticultural Lighting*[16]
Cucumbers	Medium-High
Tomatoes	High
Peppers	High
Greens	Medium
Fresh Herbs	Low-Medium
Strawberries	Medium-High
Mushrooms	Low
Nursery & Floriculture	Low-Medium

In 2018, the North American market for smart greenhouse technologies was valued at $567 million (R-023). The compound annual growth rate, or CAGR, for equipment like building envelopes, HVAC systems, irrigation systems, and controls hardware and software for greenhouses is estimated to be 9.2% between 2020 and 2025 (R-029).

Worldwide shipments of horticulture lighting devices are expected to increase at a CAGR of 13.9% between 2021 and 2030. Worldwide horticultural LED shipments are expected to grow at a higher rate of 33.4% in the same period (R-013). Lighting purchasing was found most to be influenced by facility staff and technology manufacturers, manufacturer sales representatives, and distributors (R-033).

The global ventilation and air conditioning market for indoor agriculture is estimated to grow at a CAGR of 11% between 2021 and 2025 (R-012).

Between 2020 and 2025, the global greenhouse irrigation systems market is projected to register a CAGR of 10.4% (R-052).

[16] (R-005),(R-114),(R-115), (R-118), (R-119), (R-120), (R-121), (R-122)

According to the recent research report, the global agricultural sensors[17] market in 2020 was valued at $1.36 billion dollars. The market is expected to grow at a CAGR of 11.56% and is anticipated to surpass $2.63 Billion by 2026 (R-051).

Equipment purchasing for CEA facilities was surveyed to be influenced by several influencer types (R-033). Table 7 below describes the influencers most able to affect purchasing decisions of lighting, HVAC, water, and controls equipment for CEA facilities.

Table 7: Influencers Affecting CEA Technology Purchasing Decisions

Technology Type	*Influencer: CEA Facility Staff*	*Influencer: Technology Manufacturers*	*Influencer: Manufacturer Sales Representatives*	*Influencer: Technology Distributors*
Horticultural Lighting		X	X	X
HVAC	X	X		
Water Management		X		X
Controls & Automation		X	X	X

Supply Chain: Design & Construction Professionals

Design and construction (D&C) professionals with experience serving commercial facility projects are interested in serving the CEA industry and some leaders are nimbly expanding their businesses to carve out an expertise in indoor plant factories and greenhouses. Actors in the D&C sector include architects, mechanical and electrical engineers, lighting designers, commissioning agents, energy consultants, construction management professionals, systems integrators, and construction contractors like HVAC, lighting, and controls contractors.

To be a CEA specialist, professionals working in the CEA space seek to distinguish themselves as knowledgeable in best practices. Credentialing for CEA facilities and continuing education are necessary for this constantly evolving field with diverse emerging technologies. Members of RII's Technical Advisory Council who are thought leaders in the design and construction community seek to educate the market and establish the value of their services to producers and owners.

D&C professionals influence purchasing decisions like technology vendor influencers. Design professionals can indirectly influence technology manufacturer sales representatives and distributors by specifying equipment and requesting technology be sourced for their projects. Construction contractors can influence purchasing decisions by value-engineering equipment choices based on first cost and have close contact with distributors. Electric infrastructure

[17] Agricultural sensors include humidity sensors, electrochemical sensors, mechanical sensors, optical sensors, pressure sensors, water sensors, and soil sensors for lighting, climate, soil, and water management processes.

purchasing was surveyed to be most influenced by design professionals for both new and retrofit projects. For new construction, HVAC equipment and controls purchases can be more swayed by designers and contractors. In retrofit projects, contractors can have the most influence on equipment purchasing decisions, particularly for lighting systems.

Key Market Actors

In addition to producers, technology vendors and design & construction professionals, several market actors play significant roles in shaping the development of the CEA market, including:

- Consumers
- Energy suppliers
- Efficiency programs
- Investors and financial institutions
- Industry organizations
- State governments
- Educational institutions

In many cases, these actors are operating with goals other than market growth, such as protecting regional energy infrastructure or reducing emissions. These actors have tools at their disposal to coax the market toward efficient and renewable practices. The CEA market has the potential to leverage all these market actors and their various interests to increase consumer demand, buy down the cost of efficient technologies, improve competitive positions, and lower environmental footprints. The trick is to engage and coordinate effectively.

Consumers

Consumer demands for high-quality[18] and continuously-available produce have further accelerated the advancement of indoor agriculture (R-015). CEA production is the only viable method for reliable, high quality, year round local produce (R-091).

Between 2006 and 2015 the national market demand for local food expanded from $1B to $7B dollars. The CEA industry's current and future growth is also credited to the local food movement driven by consumers, with "we're far from peak on local food, value-added sales will continue to increase, and a merging with the culinary field will happen" (R-024). CEA facilities offer fresher, local food for consumers. Some grocery retailers are installing vertical farm modules in stores so produce can be picked on-site (R-083) and incorporated into menu items at (R-084). International brands are seeing clear sustainability benefits in growing their own greens (R-099).

Food brands that are able to showcase their sustainability efforts and local production will continue to succeed with consumers. Research has revealed that around 40% of North American consumers are 'frontrunners', deeply committed to sustainability and aware of their own impact. They often seek to influence manufacturers, brands and public authorities to meet their

[18] 'High-quality' can be defined in diverse ways by consumers using terms like fresh, tasty, nutritious, safe. MI State University Consumer Leafy Greens Survey (R-078)

sustainability needs. Additionally around 30% are 'followers', willing to make sustainable food and beverage choices but looking to companies and public institutions to take the lead. These more motivated groups tend to be younger as well and thus will continue to affect the purchasing landscape for years to come. (R-085).

Energy Suppliers

Energy suppliers offer a variety of fuels to drive production; primary fuels used by CEA producers are electricity and natural gas. Electricity is mission-critical to run horticultural lighting and HVAC equipment for greenhouses and indoor farms alike. Natural gas and propane are common fuels for space heating. Diesel, gasoline, and natural gas are used to serve back-up generation infrastructure. Back-up generation is described in more detail in the Energy Sources for and Energy Use of CEA Facilities section of this report.

Table 8: Average Commercial and Industrial Energy Prices[19], 2021

Fuel	Sector	National Average	Lowest (State)	Highest (State)*
Electricity ($/kWh)	Commercial	$0.11	$0.734 (NV)	$0.1708 (CA)
	Industrial	$0.0715	$0.490 (NV)	$0.1634 (RI)
Natural gas ($/ccf)	Commercial	$7.81	$5.58 (ND)	$12.18 (RI)
	Industrial	$5.07	$3.00 (WV)	$10.29 (MA)
Propane ($/gallon)	Wholesale	$0.894 to $1.474	NA	NA

Fuel and electricity costs and cost structures can differ greatly from region to region and utility to utility. Table 8 above displays a snapshot of commercial and industrial energy prices for early 2021, capturing the variations in electricity and natural gas costs nationwide. These local price differences impact the energy source choices of producers. Urban, suburban, and exurban customers are most likely to get their electricity from regulated investor-owned utilities (IOUs) that establish rates in accordance with state public service commission regulations. Rural electric cooperatives (co-ops) provide electricity to the majority of customers in rural areas, including roughly 85% of farms in the U.S. (R-102). Many small towns and 26 larger cities are served by publicly-owned power companies such as municipal utilities ('munis'). While all IOUs are subject to regulatory oversight by state public service commissions, only some co-ops and, more rarely, munis fall under public service commission authority.

Utilities typically apply industrial or commercial tariffs to horticultural producers. The specific tariff may depend on location, facility electricity consumption, or peak demand. Some may offer an

[19] (R-103), Q1 2021 Propane Prices; (R-104), May 2021 YTD Natural Gas Prices ;(R-105), Q1 2021 Electricity Prices. High prices are for the continental U.S. Alaska and Hawaii are outliers with much higher rates associated with their unique geographic locations.

agricultural tariff for irrigation pumping separate from other end uses. Table X summarizes national average energy prices for electricity, natural gas, and propane for commercial and industrial customers.

Utilities are represented by several national associations and utility-sponsored research organizations. These groups are active in identifying opportunities and challenges facing their member utilities in customer service, regulatory compliance, and incorporating emerging supply- and demand-side technologies.

- Edison Electric Institute (EEI)
- Electric Power Research Institute (EPRI)
- National Rural Electric Cooperative Association (NRECA)
- American Public Power Association (APPA)
- American Gas Association (AGA)

Utilities in some regions encourage customers to install distributed energy resources and prioritize them in areas with supply constraints. Alternative fuel systems used by CEA facilities are addressed further in the Distributed Energy Sources section of this report.

Efficiency Programs

Energy efficiency programs are sometimes housed within an energy supplier as part of the utility or, in other cases, are administered by third parties called 'implementers.' Programs funded by investor-owned utilities are typically regulated by state public utility commissions to ensure ratepayer money is spent effectively to improve resilience and affordability of energy supply and efficiency, and to align with state policy goals (e.g., greenhouse gas emissions reductions). Investor-owned utilities serve more than 70% of US electricity customers including most large metropolitan areas. A few large cities are served by municipal utilities (munis) and the majority of rural customers are served by rural electric cooperatives (co-ops) or munis that do not fall under the regulatory authority of utility commissions. In the absence of regulatory requirements, many munis and co-ops report challenges in securing the funding needed to staff and support energy efficiency programs for their customers (R-067).

Efficiency programs seek to deliver cost-effective energy savings while relieving energy supply constraints and achieving government goals for energy use and emissions reductions. IOUs are required to conduct independent evaluations of their efficiency programs and report results of program impacts and cost-effectiveness in accordance with screening tests specified by the state public service commission. As the electric grid is increasingly powered by renewable energy sources, energy efficiency programs are evolving to include building electrification and flexible demand management technologies and services for a more comprehensive approach to decarbonization. Program offerings include technical assistance and financial incentives for energy efficiency projects. Technical assistance can include energy education, design guidance, energy modeling, and review of equipment choices. Financial incentives on efficient technologies are determined based on energy savings potential, informed by research on industry standard practice. Incentive programs for CEA facilities are often limited by the availability of data from construction projects in service territories implementing emerging technologies in diverse applications. Incentives can vary dramatically from one market to the next, and drastically affect payback periods of efficiency projects.

To date, programs targeting the CEA sector have focused on gas efficiency measures in greenhouses, but programs have expanded in recent years to include lighting and HVAC measures in indoor facilities(R-106). CEA program offerings are expanding by learning from tools used in emerging markets for specialty crops. New construction programs in CEA hotspots are evolving to work with developers as they design facilities to capture the greatest energy savings. In some states, efficiency programs may also target education, training, technical assistance, and financial incentives to contractors, distributors, retailers, and other supply chain actors as well as their end-use customers.

Investors and Financial Institutions

Producers can raise hundreds of millions of dollars of private investment in the CEA industry to allow companies to research and develop before becoming profitable. This funding creates deep partnerships between producers and their investors and financial institutions, who often drive technology choices based on investment return expectations. Efficient technologies frequently increase capital expenditures and may result in longer returns on investment, making them less attractive to investors with shorter-term horizons. This is particularly true in cases where utility incentives are not as available. Bundling efficiency upgrades so their total package meets ROI targets is one example of how to overcome these hurdles.

Industry Organizations

Industry organizations include national and regional energy efficiency organizations (REEOs), industry associations, third-party certification organizations, and standards organizations. Standards organizations serve markets by bringing together a wide range of market actors to establish test methods and standards of practices that quantify and routinize operational practices, and enable defensible verification of savings methodologies. Third-party certification organizations verify performance and approve lists of qualified products so REEOs can support efficiency programs with designing and implementing offerings for CEA businesses for efficient technologies.

REEOs supporting CEA efficiency programs include:

- Consortium for Energy Efficiency (CEE)
- Midwest Energy Efficiency Alliance (MEEA)
- Northeast Energy Efficiency Partnerships (NEEP)
- Northwest Energy Efficiency Alliance (NEEA)
- South Central Partnership for Energy Efficiency as a Resource (SPEER)
- Southeast Energy Efficiency Alliance (SEEA)
- Southwest Energy Efficiency Project (SWEEP)

Active industry associations in the CEA space include:

- Controlled Environment Agriculture Design Standards (CEADS)
- CEA Food Safety Coalition (CEAFSC)
- FarmTech Society (FTS)
- Greenhouse Lighting and Systems Engineering (GLASE)
- Optimizing Indoor Agriculture (OptimIA)
- Resource Innovation Institute (RII)

Third-party certification organizations creating certification programs for CEA technology include:

- DesignLights Consortium (DLC)
- Air-Conditioning, Heating, and Refrigeration Institute (AHRI[20])

Active standards organizations in the CEA space include:

- American Society of Agricultural and Biological Engineers (ASABE)
- American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE)
- ASTM International (ASTM)
- Illuminating Engineering Society (IES)
- Underwriters Laboratories (UL)

State Governments

Governments establish policies, codes and standards, often informed by other market actors, generally with goals of energy savings, carbon emissions reductions and economic development. While several states have established energy requirements directed toward certain forms of indoor cultivation, California, with its Title 24, Part 6, standards, has recently become a bellwether for broader energy codes that will apply to all forms of CEA[21].

State energy offices, economic development agencies, and departments of agriculture may offer efficiency programs that complement those offered by energy suppliers or efficiency program implementers. These agencies are often able to leverage state, federal, and private funding to support program implementation, particularly to rural communities or others that may be underserved by utility programs. Several national associations represent the interests of these state agencies by facilitating peer learning, sharing resources, and offering opportunities for collaboration. Leading organizations include:

- National Association of State Energy Officials (NASEO)
- National Development Council (NDC)
- National Association of Development Organizations (NADO)
- Federation of Southern Cooperatives/Land Assistance Fund (FSC/LAF)
- National Association of Regulatory Utility Commissioners (NARUC)

[20] AHRI also publishes standards as a standards organization.
[21] In California, CEA is described as Controlled Environment Horticulture (CEH).

Research & Educational Institutions

USDA supports research programs in the Land-Grant University (LGU) system and other partner organizations through cooperative research and extension services. The National Institute of Food and Agriculture (NIFA) is the federal partner connecting the nation's more than 100 LGUs to provide extension services to address public needs. USDA extension scientists, educators, and staff provide education and training to farmers and communities, bringing knowledge gained through research and bringing it directly to the people to create positive changes. Extension experts focus on several subjects related to this project, including food safety and quality, sustainable agriculture, and waste management. For example, the University of Vermont Extension's Agricultural Engineering Program focuses on helping food entrepreneurs in a rapidly changing and highly competitive industry.

The USDA provides funding for programs that advance agriculture-related sciences and ensure the long-term viability of agriculture to reach the people who can put them into practice. The National Resource Conservation Service (NRCS) is a federal agency funding grants to develop science-based tools and standards to assist farmers, private landowners, and ranchers with implementing conservation practices. The Agricultural Research Service (ARS) is the research arm of the US Department of Agriculture focusing on scientific tools and solutions for American farmers, producers, industry, and communities. Under the Rural Development USDA program, the Rural Energy for America Programs offer financial assistance for energy audits, renewable energy development and energy efficiency improvements. NIFA, NRCS, ARS, and REDA are key actors disbursing funding to researchers to deliver the mission of the USDA[22].

Some USDA initiatives and programs relevant to this project include: the Farm Energy Initiative with projects focused on renewable energy policy, waste management, and healthy soils issues; the NRCS Environmental Quality Initiatives Program (EQIP) with grant programs supporting 'climate-smart agriculture', installation of protected agriculture infrastructure, and adoption of conservation practices; and the NIFA Specialty Crop Research Initiative (SCRI) grant programs focusing on topics including production efficiency and new innovations and technology.

Several key academic research institutions[23] with influential CEA research include:

- Michigan State University Controlled Environment Lighting Laboratory
- University of Arizona Controlled Environment Agriculture Center
- Utah State University Crop Physiology Laboratory
- Ohio State University Controlled Environment Plant Physiology & Technology Lab
- Cornell University and Rensselaer Polytechnic Institute Greenhouse Lighting & Systems Engineering (GLASE) Controlled Environment Agriculture Open Data Initiative
- North Carolina State University Controlled Environments Horticulture Team

---

[22] (R-086), (R-087), (R-108), (R-123)

[23] U.S. researchers collaborate and learn from international researchers such as those at the Department of Agricultural and Food Sciences and Technologies (DISTAL) at the University of Bologna and Frontiers of Energy Econometrics (FEEM) in Italy, McGill University in Canada, and Wageningen University in the Netherlands.

- University of California Davis Controlled Environment Agriculture

Energy Sources for and Energy Use of CEA Facilities

CEA facilities use diverse sources of energy depending on the facility type and the location. In addition to electrical energy, various fuels (such as natural gas and propane) are used as an energy supply and sometimes as a CO_2 source (R-015). In areas with greener grids, producers are encouraged to electrify their operations, but electric rate structures often dictate fuel choice for CEA producers.

CEA facilities have varying electric energy intensity, ranging from 40 kWh to 150 kWh per square foot based on the size, crop, and configuration of the building. Southern California analysis found that horticultural lighting accounts for 38% of electricity use, with HVAC accounting for 56% of the electricity use (30% ventilation, 21% air conditioning, and 5% heating). Water handling, CO_2 injection, and drying of harvested plant material were found to account for less than 3%, 2%, and 1% respectively. Other factors that influence energy usage are lighting schedules, environmental control, lighting system type, lighting power density, and other plant-specific requirements (R-015). Indoor facilities use more electricity than fuel due to their dependence on sole source horticultural lighting and refrigerant-based cooling systems (R-053).

Other energy sources are used to supplement or replace electricity for both indoor and greenhouse facilities. Indoor facilities are more often located within natural gas supplier territories and incorporate cogeneration systems served by natural gas. Greenhouse facilities can have higher heating loads than indoor facilities and use more fuel; their locations and availability of energy suppliers make it more likely for them to incorporate delivered fuels like propane in their fuel mix. Greenhouses also often rely on passive or low-energy ventilation and cooling systems and can have lower electricity usage than indoor operations, especially if they don't use supplemental lighting (R-053).

Distributed Energy Resources

CEA producers install distributed energy resources (DERs) on-site to improve operational resilience, offset grid energy consumption, and lower operating expenses from utility bills.

Backup Generation

Backup energy sources afford producers resiliency during power outages. This infrastructure is critical for these operations as even a couple hours of no power can have catastrophic effects on a CEA operation. Generators for CEA facilities often use natural gas, and in more rural areas, use diesel and gasoline. Generators are more commonly used by greenhouses, which may be located in areas where outages happen more often.

Microgrids

Energy independence is important for CEA producers, especially in areas where electric grids have insufficient capacity to serve their loads. Microgrids have emerged as a form of DER well-suited to serve CEA facilities in some regions of the United States, in particular areas with high electricity rates. Microgrids in the CEA sector are commonly fueled by natural gas.

As overall interest in microgrids has grown across the US, CEA facilities have become a good candidate for these projects due to their desire for uninterrupted operation and high energy use. Microgrids employing natural gas cogeneration systems offer resilience, predictable energy costs, and can utilize 'energy as a service' models to avoid capital expenses of infrastructure.

Renewable energy sources are often used in tandem with microgrids to further reduce dependence on the grid, especially by producers with sustainability and environmental leadership goals. CEA production facilities serving metropolitan areas are incorporating rooftop PV, combined heat and power (CHP), and battery storage to create independent energy networks for their mission-critical operations.

Energy represents a major line item for indoor agriculture, accounting for 30 to 50 percent of the operational expenses at a plant factory. Energy-as-a-service models, some of which predict the future cost of energy, are making it easier to create business plans and attract investors (R-021).

> *A well established indoor vertical producer partnered with an energy as a service supplier to establish a microgrid for their new converted urban warehouse facility in New Jersey, where electricity rates are 10% higher than the national average (R-056). This microgrid is interconnected with the local grid but able to operate independently. The facility's microgrid is predominantly powered by solar PV, producing peak power when there is high grid demand in the area. A natural gas generator and on-site lithium-ion battery storage system are utilized to further lower grid demand from the facility. Software optimization provides real-time tariff management, frequency regulation, peak shaving and storm hardening (R-059)(R-054).*

Other fuels are emerging to serve CEA producers in some markets. As natural gas grids experience constraints, fuel cells are emerging in some regions as a mechanism for 'islanding' some indoor CEA facility load (R-059). While other solutions require connection to the grid, fuel cell solutions offer an opportunity to be grid independent.

Some producers seek alternatives to microgrids utilizing fossil fuels. Technology converting food waste into biofuel for CEA has been experimented with in an academic laboratory with community educational component (R-064). While this technology has not been put into practice on a large scale in the US, there is interest from the CEA market (R-063).

On-Site Renewable Energy

Solar photovoltaic (PV) is the most common DER chosen to serve CEA facilities as in many regions, solar is reaching grid parity in some regions with higher power costs and projects are well supported by government and utility programs[24]. Some energy suppliers help customers PV is chosen to supplement power supply in many ways, including large arrays as part of a more complex microgrid system, partnering with local utilities to utilize power from PV sources and simple arrays both large and small. The increasing affordability of solar has allowed even small facilities to access this resource[25].

Energy Benefits of Energy Efficiency Projects

CEA producers engage in energy efficiency projects of varying sizes and implement them for diverse reasons, including energy benefits. Operators seek to reduce energy use to lower electricity and fuel bills while achieving other non-energy benefits.

Utilities and energy efficiency programs across North America have engaged CEA producers in efficiency projects to reduce energy use and demand via efficient technology measures and strategic energy management programs. As the CEA market has grown and more producers come online, program implementers are finding the energy-saving technologies described earlier in this report offer a range of energy savings, as described below in Table 9 below. Benchmarking activities can narrow the range of potential energy savings of efficient technology by crop, cultivation approach, and location.

Table 9: Energy Savings Potential by Measure

Energy Savings Measure	*Energy Savings Potential*
Greenhouse Envelope Systems[26]	5 - 50%
LED Horticultural Lighting[27]	30 - 40%
High Performance HVAC Systems[28]	20 - 30%
Integrated Controls Systems[29]	15 - 30%

Non-Energy Benefits of Energy Efficiency Projects

Energy efficiency projects for any facility can result in non-energy benefits. Common non-energy benefits include lower costs for operational expenses, labor, and maintenance. CEA facilities can

[24] Some programs include initiatives like the federal Investment Tax Credit (ITC) for solar, tradable Renewable Energy Credits or Certificates (RECs) as part of some state-sponsored Renewable Portfolio Standards (RPS) programs, and other state and utility offerings like job credits, research and development incentives, technical assistance, and sales and use and/or property tax exemptions for renewable property. (R-109)
[25] (R-060)(R-061)(R-062)
[26] (R-082), (R-098).
[27] (R-019), (R-058)
[28] (R-057)
[29] (R-055)

realize additional non-energy benefits when implementing energy efficient technologies and approaches (R-019). For vertical farming environments, efficiency is more than a perk, and seen as paramount to the farm's success (R-084).

The primary energy efficiency measure evaluated in the CEA market is LED horticultural lighting systems. LED grow lights lower operating costs by 30 - 40%. LEDs also offer reduced capital expenses for HVAC systems due to reduced lighting heat loads. A 20%-30% reduction in HVAC system size is possible compared to systems sized to handle rooms lit with high pressure sodium lighting technology. Labor hours and maintenance costs from room cleaning are reduced and relamping are eliminated. LED products offer greater longevity and durability, reducing risks and improving safety for operators (R-019).

There are unique non-energy benefits of LED horticultural lighting for cultivation environments that are relevant only to plant production facilities. These photomorphogenic effects include biomass yield and diverse quality expressions. Biomass yield is most affected by light intensity, and LED light fixtures can put out more photons than legacy lighting technologies, affording plants more energy to use to generate roots, stalks, leaves, and flowers. Light recipes only possible with LED lighting solutions can create phytochemical responses that influence plant structure, appearance, color, taste, aroma; the traits desired vary by crop grown. Pigmentation influences nutritional content of food, and hardier structures allow for longer shelf lives (R-019).

Indoor facilities see greater impact of lighting on plant expression, as the impacts of spectrum on plant growth and development are much greater in sole-source lighting than in greenhouse supplemental lighting where electric lighting makes up only a small portion of the plant lighting diet (R-003).

Biomass yield can be increased with LED light treatments. Tomato production in greenhouse environments has been shown to increase by an average of 3% to 11% when grown with full-spectrum LED light treatments versus high pressure sodium treatments (R-001).

Desirable quality expressions can be influenced by changing ratios of red to blue and red to far red photons light fixtures provide to plants. Indoor-grown basil has the greatest biomass production when grown with LED lighting as compared to using fluorescent lamps. LED treatments can achieve optimal growing conditions for CEA crops, foster improved growth and resource use efficiency (R-036).

LED horticultural lighting opens up unique operational and control methodologies for CEA producers including adjusted environmental setpoints, lighting controls, and vertical racking approaches. Operational expenses can be further reduced for indoor operations using LED lighting. To maintain leaf temperature and VPD, growers increase temperature setpoints by 7–8°F to make up for the lack of infrared radiation. If growers increase temperature by 5°F, lower relative humidity by 5% and keep watering rate equal, HVAC loads can be reduced by 50%. With lighting control strategies like dimming and spectral tuning, growers can steer plants throughout stages of growth to optimize specific quality expressions. With lower heat output, LED horticultural lighting allows producers to mount fixtures closer to plants and grow vertically to stack canopy in racks three to ten tiers high (R-019).

Barriers to Energy Efficiency

Efficiency Measures

Four major types of energy efficiency projects include one or more typically installed energy conservation measures. Producers face several hurdles as they contemplate integrating these technologies into their operations.

1. High-performance greenhouse building envelope systems:
    a. Insulated structures
    b. Energy screens
    c. Shade curtains
2. Horticultural lighting
    a. LED light fixtures
    b. Lighting controls
3. HVAC and dehumidification equipment
    a. High-performance systems
4. Controls for lighting and HVAC systems
    a. Integrated systems

Barriers Specific to Technology

High performance greenhouse envelope systems are easier to incorporate into new facilities, as highly insulated envelopes cannot be easily retrofitted onto existing greenhouse structures. Interior systems like energy screens and shade curtains are more manageable for existing operations to implement, but still require production shutdowns that are undesirable for producers. Materials with lower insulation and higher infiltration rates are used by many smaller producers. The capital expense installing new high performance building envelope technologies may be too large of a barrier for smaller greenhouse producers to overcome.

Despite an increasingly positive reputation among cultivators, LED lighting still suffers from awareness and perception challenges. For example, LED market share estimates for CEA facilities within the USA vary between 25% to 40% depending on the study (R-022), with one report[30] showing as little as 2% penetration in greenhouses[31]. Despite regional utility incentives offered, segments of commercial CEA producers have not participated in programs, with 38% indicating they were not aware of incentives for LED horticultural lighting. (R-014).

---

[30] (R-065)
[31] This low adoption of LED systems can be partially attributed to the supplemental nature of electric light serving greenhouses; lights are not a necessity as they are for indoor growing. Lighting systems are used to grow in periods of low light so annual lighting system hours of use are low. Also, some greenhouse growers see benefit from the heat gain from HPS lights, depending on location.

High-performance HVAC systems for CEA facilities are challenged by a diversity of lower first cost alternatives well-trusted by producers in the market. Producers often choose cheaper, standalone systems than working with engineers to design systems that take care of ventilation, cooling, heating, and humidity management. Greenhouse producers opt for fossil fuels to heat their spaces, and may use older equipment past its useful life.

Controls for lighting and HVAC systems can range from simple to sophisticated, and smaller, lower-tech facilities have staff manually operating many systems in their facilities. Lighting controls for dimming in both indoor and greenhouse environments have energy and non-energy benefits. DLI controls for greenhouses are an emerging technology demonstrating energy savings. Environmental controls to optimize conditions for plant growth and development can make facilities more productive. Greenhouse energy screens, horticultural lighting, and environmental control systems can be monitored and controlled in concert with each other, but integrated controls infrastructure requires considerable capital outlay, which is prohibitive for producers with less access to capital. There is less energy efficiency program support for controls equipment as industry standard practice is not comprehensively documented, baselines are yet to be established, and incentive programs are nascent if non-existent.

General Barriers to Efficiency

Barriers to energy efficiency projects include upfront costs, access to capital and financing, and a lack of knowledge of efficient technologies. Lack of understanding may be exacerbated by a lack of connections to vendors and guides who can help reduce the cost of capital, increase access to education, and offer technical and financial assistance, particularly for producers from historically marginalized communities. Based on a recent survey of CEA market leaders, Table 10 below describes the primary barriers to energy efficiency and rates them from 1 to 15, with 15 describing the largest barrier (R-033).

Table 10: Rating of Barriers to Energy Efficiency

Barrier	Rating
Upfront costs	14
Access to capital and financing	9
General lack of knowledge of efficient technologies	8
Skepticism and lack of trust in product performance	8
Lack of executive support for trying something new	4
Not enough cultivator training on how to effectively use technologies	3

For existing CEA facilities, the primary barrier to EE implementation is financial. “Brand new projects are more heavily influenced by utilities or programs available, or working with a designer who brings a full solution with those rebate and incentive factors already considered” (R-035).

Average CEA facility profit margins can be too thin to invest any capital. Because of this, financial incentives for EE technologies can have a significant impact on technology adoption if they can reduce payback periods to meet grower requirements (R-015). Producers and efficiency programs can look at projects holistically to take into account life cycle analysis including first costs and operations and maintenance savings.

As governments establish energy codes, new baselines for industry standard practice are established for other key market actors like efficiency programs. As code baselines rise, programs supporting CEA producers are unable to claim as much energy savings and over time must reduce technical assistance and financial incentives for projects involving some efficient technologies. An example of this is LED horticultural lighting; when minimum efficacy rises in regulated regions, incentives may decrease, increasing upfront costs for producers to engage in efficiency projects (R-106).

Some producers lack knowledge of efficient technologies while others hold skepticism about their efficacy. Training providers find that CEA audiences may not have enough time to spare to attend training sessions or live educational events, as the demands of continuous production limit their availability and attention to other topics (R-035).

RII's survey of the CEA LC[32] found facility sizes and types influence barriers to energy efficiency. Smaller facilities are less likely to be open to efficiency investments while large, high-tech facilities realize economies of scale through efficiency investments. The facility types most open to energy efficiency projects appear to be large indoor vertical farms and large greenhouses (>50 acres of canopy area). Indoor vertical farm operators appear more attuned to energy savings than greenhouses due to the year-round nature of indoor crop production.

Greenhouse efficiency projects may generate smaller returns than indoor projects given that some equipment runs less often (such as supplemental lighting) or draws a lower power demand than systems used for indoor cultivation. Greenhouse growers can see more benefit from heating system efficiency projects as they have higher heating loads than indoor farms.

Small greenhouses, especially to grow vegetables seasonally, are generally older facilities, and growers do not see as much value investing in efficiency. Larger greenhouse facilities are more likely to invest in environmental control systems to maintain lighting schedules and space temperature setpoints and explore building envelope solutions like energy screens and shade curtains along with lighting and HVAC projects. "The benefit to energy efficiency is exponential. The bigger you go, the more benefit there is to be had" (R-035).

Some crops are less energy-intensive to grow and therefore do not result in the same degree of savings as more energy-intensive crops. For example, floriculture producers generally do not focus on efficiency unless building a new facility. The crop types most open to efficiency projects are vine crops and leafy greens as they have the lowest sale price and so making a profit depends on keeping cost of production as low as possible. Delicate crops like microgreens require more

[32] (R-033)

precisely controlled environments, which usually leads to producers using better performing equipment.

In addition to barriers to adoption of efficient technologies, a study of the California market[33] noted several barriers to verification of savings from efficiency projects:

- Environmental and energy use requirements differ by crop type and and by stage of crop type
- Lack of data on standard baseline practices and sharing of best management practices among growers
- Widely accepted performance metrics for CEA operations are not fully developed or accepted by industry
- Lack of CEA HVAC standards

Best Leverage Points for Market Interventions

Operational challenges for CEA producers[34] were individually ranked by CEA survey respondents on a scale of 1 to 5, indicating messaging opportunities for efficiency advocates in Table 11 below. Reducing operating costs was the only leverage point ranked 1 out of 5 (most challenging), while several other leverage points are seen as much easier challenges to overcome.

Table 11: Operational Challenge Rankings for CEA Producers

Challenge	Rank
Keeping operating costs down	1
Predictability/stability of operating costs	3
Sales	4
Predictability of plant performance	4
Managing farm labor	4
Food safety or regulatory compliance	5

Meetings with the CEA LC[35] identified six specific opportunities for market intervention:

1. **Knowledge and understanding:** If producers do not understand a technology, they do not want to pay the upfront costs because they cannot see the gains. With knowledge and understanding, it is easier to demonstrate that there's energy efficiency to be had and there's money to be made or saved. "Financing becomes no problem so upfront costs become irrelevant."

[33] (R-008), Table 8
[34] (R-027)
[35] (R-035)

2. **Visibility:** Peer influence is significant; growers want to see how a technology works in their own backyard. They are unlikely to trust, and thus invest, in something that they have not seen work locally. "Benchmarking, 'show and tell' how it works, what works, and what works better."

3. **Financial influence:** Many facilities are built with either a significant amount of debt or some type of private equity. "Financial institutions in general have a huge say over what that life cycle looks like for the facility."

4. **Marketing:** Across the CEA market, there are both growers who are doing their own marketing of their products to consumers and growers who are selling to an intermediary. "Sustainability, and the messaging of sustainability by having energy efficient projects, is also something that they can heavily use with their customer base. That's a big driver for opening up to efficient ideas."

5. **Power costs:** Market actors agreed on the influence of power supply costs in investment and interest in efficiency projects. "Size [of facility] matters less than regional power costs. Cost of regional power is vital".

6. **Greenhouses:** Large and small operations have different leverage points. "Very large greenhouses have a tech staff onboard to make the various systems work, and need educated people. That's more of a technology hurdle to overcome when operations are smaller because the amount of staff needed to keep systems working is different."

Key Market Baselines

Baselines of energy usage will be measured by the project team to evaluate the impact of our market transformation initiative over time. System-level performance for the most energy-consuming systems like lighting and HVAC will support facility-level baselines and account for interactive effects between energy efficiency measures.

Industry-standard Key Performance Indicators (KPIs) on resource efficiency and productivity will be quantified via the PowerScore resource benchmarking platform and will guide the development of benchmarks on energy, water and emissions, to be featured in a *Report on Energy and Water KPIs, Baselines and High-Performance Strategies*. Qualitative impacts will also be assessed. Several impact measurements may be used to track the project's impact:

- Quantitative impact of our initiative
    - PowerScore KPIs on efficiency and productivity, such as:
        - Energy use per unit of canopy area
        - Production per unit of energy
    - KPIs of key market actors
        - Adoption of best practice policies and programs

        - Number of key supply chain actors manufacturing, distributing, and selling efficient products
- Qualitative impact of our initiative
    - Events held
    - Key market actors reached
    - Case studies with producers
    - Attitudes toward high performance technologies like LED
    - Trainings completed per CEA professional
    - Utilities engaged
- Actions of the players we bring in
    - Adoption of different technologies
    - Facility-level efficiency metrics
    - Number of dedicated CEA utility programs

Conclusions & Recommendations

The CEA market is dynamic and growing, fueled by significant investment. Despite the nascent stage of market development, several general conclusions can be drawn. Recommendations below offer the best leverage points for market interventions to advance this project's Market Transformation Strategy.

Conclusions

While the supply chain of CEA producers represents a variety of crops grown across a range of cultivation methods, the sector can be grouped into two categories: greenhouses and indoor farms. Both categories can be broken down into segments by facility infrastructure. Greenhouse segments include traditional protected agriculture and smart, high-performance greenhouses. Indoor farm segments include vertical operations of varying sophistication. The equipment used to sustain optimal environments for plant growth dictates the energy intensity of CEA facilities.

The two sectors produce different and diverse crops. Greens are the primary food crop produced by both greenhouses and indoor farms. Greenhouses produce food and floriculture crops and grow both nursery stock and finished plants. Major greenhouse food crops are cucumbers, tomatoes, peppers, leafy greens, herbs, and strawberries. Greenhouses also grow nursery crops, ornamental plants and floriculture, transplants for commercial production, propagative materials, and fruits and vegetables including vine crops. Mushrooms and microgreens are major crops for indoor farms. Indoor farms also grow other vegetables and fruits including berries.

The range of canopy area of U.S. CEA facilities is wide and varies by market segment and facility infrastructure. To create representative benchmarks of the CEA market segments, the typical canopy areas of target facilities should range between:

- Greenhouse 700,000 sq ft - 2,600,000 sq ft
- Indoor 60,000 sq ft - 70,000 sq ft

Key market actors will be engaged as partners and collaborators to reach CEA producers and influence their operations with best practices guidance. The supply chain supporting producers (technology vendors and design & construction professionals) can influence producers to install high-performance equipment and engage in efficiency projects, especially when supported by active engagement from key market actors like efficiency programs. Energy suppliers affect producer energy supply choices with rate structures and programs supporting electrification and distributed energy resources. Investors and financial institutions are crucial partners to reduce the cost of capital and first cost of efficiency projects for producers. Industry organizations guide producers and create standards and third-party certification programs which are in turn referenced by efficiency programs in their incentive offerings and governments in their energy codes. Academic institutions share knowledge gained by their researchers with producers through extension services and initiatives.

The energy sources used by producers are diverse and several key market actors can benefit from influencing resource consumption in CEA facilities. Greenhouse and vertical farm electric energy intensities are on an industrial scale, offering considerable energy savings opportunities for producers and other key market actors like efficiency programs. Energy suppliers seek to influence fuel consumption; utilities want to serve more customers and more systems in their facilities and the resulting energy choices of customers impacts the environmental impact of energy use in CEA operations. Distributed energy resources are being increasingly deployed by producers to increase resilience, and can also be an opportunity for energy suppliers, industry organizations, and governments to demonstrate and quantify the emissions reductions possible with alternative energy in the CEA industry.

The energy and non-energy benefits of efficiency projects can be substantial and both are valued by CEA producers. However, the financial challenges of efficiency projects (first cost, access to financing, cost of capital) remain barriers for both segments of CEA producers. Leveraging key market actors like investors and financial institutions is critical to reducing the hurdles facing producers so they may realize the diverse advantages of resource efficiency. Sharing producer stories through best practices guidance can be an effective way to increase awareness, counter technology-specific skepticism, and build trust.

Evaluating the impact of the market transformation initiative over time will use quantitative and qualitative metrics like key performance indicators of producers and key market actors. Metrics will be calculated via benchmarking tools and market surveys.

Recommendations

A host of market intervention strategies should be developed to overcome barriers to efficiency.

1. **Benchmark a range of production environments to enable development of energy use baselines.** Data on energy performance of CEA facilities is limited and often based on models from a small number of producers or crop type. Benchmarking will enable more accurate and useful data. Operational benefits and assurance of data security should be emphasized to compel market leaders to benchmark. Benchmarking analysis should incorporate contributing factors such as geography, facility construction, cultivation practices, a technology used and more. Ultimately, a statistically significant data set that can validate technologies and practices can be leveraged to inform best practices, codes, standards, third party certification programs, utility load forecasts, and efficiency program savings estimates.

2. **Promote the benefits of energy efficiency in ways that are compelling to producers.** Producers would value thought leadership opportunities such as case studies spotlighting efficiency features of their facilities. Producer concerns about the impact of efficiency upgrades on crop production should be addressed via peer-to-peer knowledge-sharing. Curriculum and training on best practices should be supported in the market. Efficiency programs should emphasize both energy and non-energy benefits of efficient technologies in their outreach to producers.

3. **Target producers effectively based on cultivation approach, geography, power supply costs and size/scale of operation.** Given that climate zones and operating expense structures impact the cost-effectiveness of efficiency actions in producer facilities, certain jurisdictions and utility service territories will provide greater savings returns and help ensure that taxpayers and ratepayers are equitably served. Services, programs, codes and standards can be tailored toward target producers.

4. **Leverage key market actors to develop coordinated producer support systems.** Working together in a facilitated manner, critical stakeholders such as agriculture extension offices, vendors and financial institutions, can drive adoption of efficient technologies and practices. Standards can be developed with the input of multiple stakeholders. Hurdles such as upfront costs can be overcome via financing and incentive programs. Developing a workforce system that supports credentialed professionals performing efficiency project work can result in persistent, cost-effective energy savings for producers and utility programs.

References

The references used as background information for this report and cited within are described in the following sections.

Primary Sources

Primary sources for this report include:

- Members of the RII Strategic Advisory Council
- Members of the RII CEA Leadership Committee
- Participants in the April 2021 greenhouse producer benchmarking input session
- Participants in the April 2021 vertical producer benchmarking input session
- Participants in the June 2021 Producer meeting

Primary sources submitted survey responses; questions asked in surveys can be reviewed in the Survey Appendix.

RII Strategic Advisory Council			
Organization	**Market Segment**	**Representative**	**Role**
Equilibrium Capital	Greenhouse real estate	Marco De Bruin and Kimberley Player	Principal in Controlled Environment Foods and Director of Research
Fifth Season	Producer - indoor vertical leafy greens	Grant Vandenbussche	Chief Category Officer
Fluence by OSRAM	Supply chain - lighting manufacturer	Steve Graves	Vice President of Business Development
Grodan	Supply chain - grow media	Don Courtemanche	Commercial Sales Director for North America
Hort Americas	Supply chain - distribution	Chris Higgins	President and General Manager
McGill University	Research institution	Dr. Mark Lefsrud	Associate Professor
Schneider Electric	Supply chain - power management systems manufacturer	Travis Graham	Global Business Development
World Business Council for Sustainable Development	Agriculture	David Bennell	North American lead for the Food and Nature Program
World Wildlife Fund	NGO	Julia Kurnik	Director of Innovation Start-Ups

RII CEA Leadership Committee			
Organization	**Market Segment**	**Representative**	**Role**
ASABE	Standards organization - agriculture	Darrin Drollinger	Executive Director
ASHRAE (Board Member)	Standards organization - HVAC	Jeff Clarke, EnviroAir Industries	CEO
CEA Consultancy	Supply chain - controls design & operation	Rob Eddy	Owner
Ceres Greenhouses	Supply chain - greenhouse facility design & construction	Josh Holleb	Solutions Architect
Energy Solutions	Supply chain - energy-efficient building energy codes & standards	Kyle Booth	Senior Engineer
Fluence	Supply chain - lighting manufacturer	Corinne Wilder	VP Global Commercial Operations
Grodan	Supply chain - substrate	Phil Johnson	Business Support Manager
MEEA	Regional energy efficiency organization	Molly Graham	Programs Director
Oregon Association of Nurseries	Producer - greenhouse floriculture	Jeff Stone	Executive Director/CEO
Priva	Supply chain - water management & controls	Jan Westra	Strategic Business Developer
Resource Innovations	Supply chain - energy efficiency program delivery & evaluation	Damien Markiewicz	Program Manager
Schneider Electric	Supply chain - power management & data	Lisa Causarano	International Account Manager
AB Ludvig Svensson	Supply chain - greenhouse technology	Mauricio Manotas	President - Americas
Signify	Supply chain - lighting manufacturer	Blake Lange	Business Development Manager
UVM Extension Services	University Extension	Chris Callahan	Extension Associate Professor
Zartarian Engineering	Supply chain - design engineering	Mike Zartarian	Owner, Electrical / Horticultural Design Engineer

Additional Peer Reviewers			
Organization	**Market Segment**	**Representative**	**Role**
DesignLights Consortium	Third-party Certification Organization- Lighting	Stuart Berjansky	Technical Director
EnSave	Supply Chain - Energy Consulting	Kyle Clark	Vice President, Business Development
Symphony RetailAI	Supply Chain - Retail	Dianarose Fraum	Supply Chain Management Solutions Consultant
US Department of Agriculture	Government	Kip Pheil	Energy Co-Leader, Energy & Environmental Markets Technology Development Team, Natural Resources Conservation Service

Participants in Benchmarking Input Sessions			
Organization	**Market Segment**	**Representative**	**Role**
AppHarvest	Producer - greenhouse tomatoes	Nickie Cashdollar	Sustainability Lead
Elevate Farms	Producer - indoor vertical leafy greens	Matthew Mickens	Chief Science Officer
Fifth Season	Producer - indoor vertical leafy greens	Grant Vandenbussche	Chief Category Officer
Houweling Nurseries	Producer - greenhouse tomatoes	Casey Houweling	Proprietor
Ontario Plants	Propagator - greenhouse	Steve Vanderkooy	CEO
Revol Greens	Producer - greenhouse leafy greens	Nic Helderman	General Manager, TX
Signify	Supply chain - lighting manufacturer	Colin Brice	Plant Specialist

Secondary Sources

Secondary sources used as resources for this report are listed in the Resource Database.

Data not yet available to support this report:

- Publications describing more traditional protected ag producers in more rural areas that are phasing in CEA (adding indoor or greenhouse cultivation areas)
- Data describing the market share of CEA compared to traditional agricultural approaches
- Public national repository of indoor and greenhouse operations

Resource Innovation Institute
https://resourceinnovation.org/