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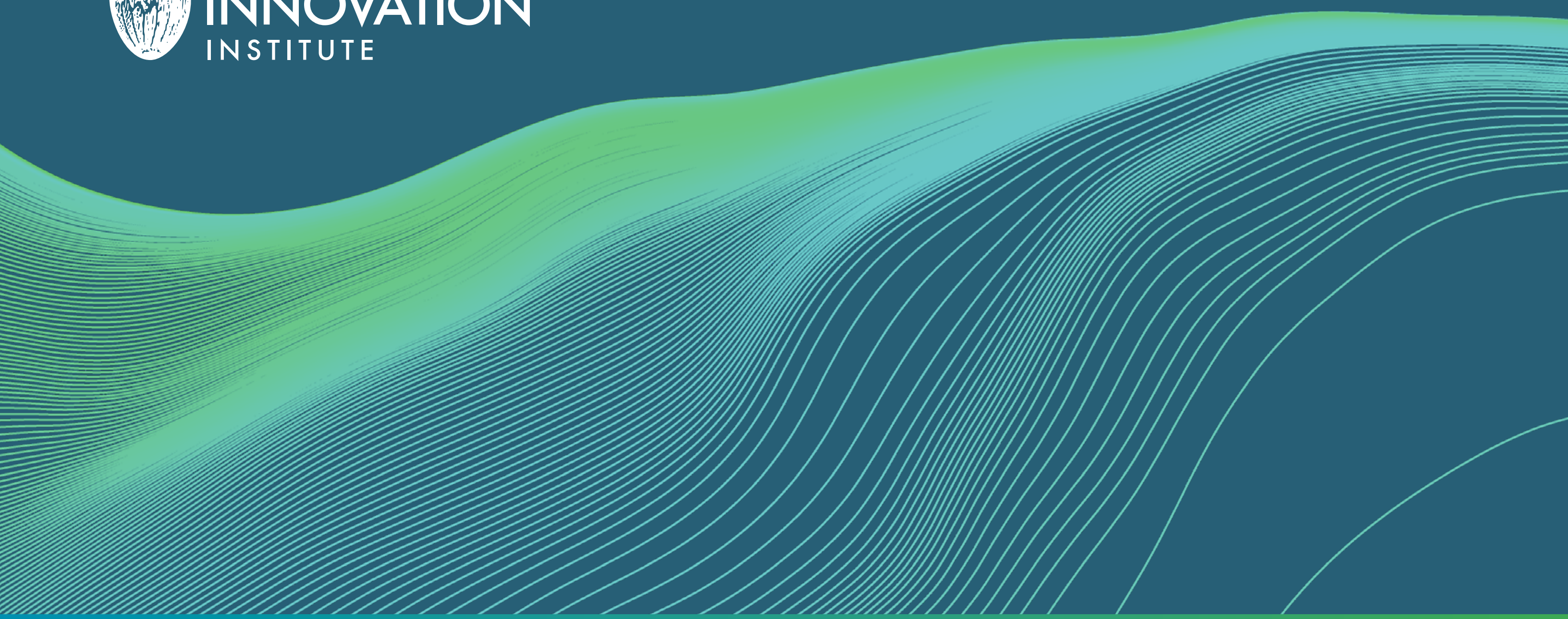

CEA Energy & Water Benchmarking Report:

Establishing Preliminary Benchmarks for Controlled Environment Agriculture (CEA) Operations

In Partnership with

ACEEE
American Council for an Energy-Efficient Economy

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Contents

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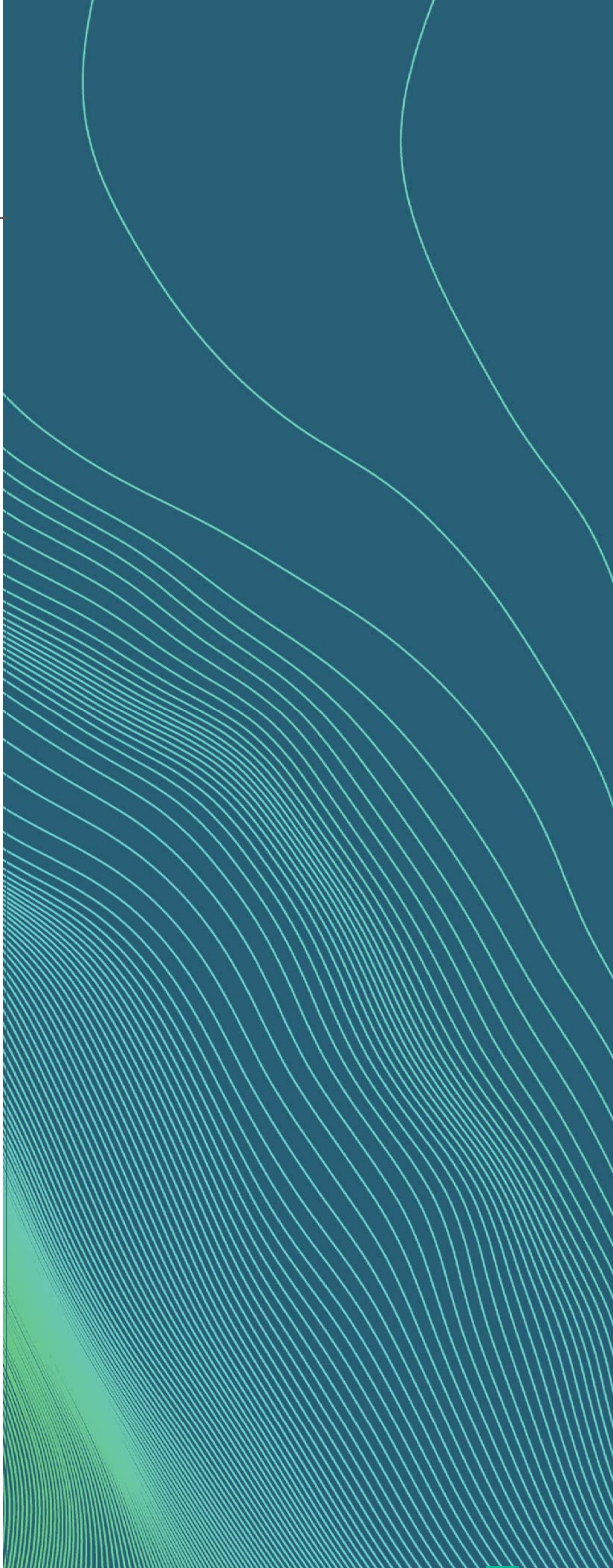

About

Resource Innovation Institute (RII)

Resource Innovation Institute (RII) is a not-for-profit, public-private partnership advancing climate resilience. RII provides resource efficiency education, training and data-driven efficiency verification, in collaboration with controlled environment agriculture producers, researchers, governments, utilities, and the design & construction sector.

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.

This report is part of a collection of resources developed by Resource Innovation Institute (RII) and the American Council for an Energy-Efficient Economy (ACEEE) in support of the Conservation Innovation Grant project titled Data-Driven Market Transformation for Efficient Controlled Environment Agriculture, funded by USDA Natural Resources Conservation Service.

Other Resources Available:

- Controlled Environment Agriculture Water Circularity Best Practices Guide
- Controlled Environment Agriculture (CEA) Policy Guide: Benchmarking, Rate Design, Water Efficiency, and Additional Policies
- Building Energy Codes and Industry Standards to Advance Controlled Environment Agriculture (CEA) Resource Efficiency
- Controlled Environment Agriculture Lighting Best Practices Guide
- Controlled Environment Agriculture HVAC Best Practices Guide
- Controlled Environment Agriculture Facility Design & Construction Best Practices Guide
- Controlled Environment Agriculture Utility & Efficiency Program Best Practices Guide
- Controlled Environment Agriculture Market Characterization Report: Supply Chains, Energy Sources and Uses, and Barriers to Efficiency
- Controlled Environment Agriculture Market Transformation Strategy & Implementation Plan

Executive Summary

Indoor and greenhouse farming, known as Controlled Environment Agriculture (CEA), is a growing sector of the agricultural industry. By operating year-round over multiple crop cycles in tightly controlled environments, CEA operators can increase their annual production. However, there is little public data available on the resource usage and efficiency opportunities of these facilities.

For this report, Resource Innovation Institute used its PowerScore platform to benchmark the annual resource consumption and productivity of 12 producers growing a variety of crops in greenhouse and indoor facilities across the United States. These aggregate, measured performance benchmarks are some of the first reported for the CEA sector.

Operations were analyzed on their productivity per area of foliar canopy, rather than floor area, to better define plant growing area across greenhouses and tiered vertical CEA facilities. Producer data is compared with relevant third-party benchmarks from academic and government sources.

Though facilities differed in their water use efficiency, the highest performing producers achieved greater than 90% water savings over field farming. PowerScore data on energy efficiency was consistent with published third-party benchmarks. Vertical farming can be energy intensive, though in some cases has an energy consumption similar to that of many greenhouses.

For this report, Resource Innovation Institute used its PowerScore platform to benchmark the annual resource consumption and productivity of 12 producers growing a variety of crops in greenhouse and indoor facilities across the United States.

Introduction & Context

Controlled Environment Agriculture (CEA) is the production of plants through the use of technologically controlled spaces, specifically mechanically regulated greenhouses, and indoor and vertical farming facilities. It addresses the need for a resilient food supply in a future characterized by increasing urban population, climate change events that damage crops, the aging-out of legacy farmers, reduced arable farmland, pandemics, and concerns for both food safety and food security.[1]

Within the context of a vast agricultural system dominated by field farm acreage, CEA has the advantage of year-round production in tightly controlled environments to increase annual yields. Vertical indoor farms further increase productivity per square foot of the building by several factors over greenhouses by utilizing multiple growing levels. While recirculating water systems show great promise in reducing water consumption in indoor farms compared to non-recirculating irrigation and field farm production, lighting and mechanical cooling used in these facilities may use a great amount of energy. Very few studies have taken a comprehensive look at energy and water use in CEA facilities.

Meanwhile, many US farms are expected to expand their energy use to improve production, and will likely continue to do so as electrification, decarbonization policies, and incentives influence their evolution.

With these dynamics, developing a data-driven understanding of resource use and efficiency opportunities will be important for agricultural decision-makers.

For this report, Resource Innovation Institute connected with producers growing a variety of crops in greenhouse and indoor facilities across the United States to benchmark the annual resource consumption and productivity of Controlled Environment Agriculture as it stands today. Published research from third parties in the US and abroad was used for comparison. To paint a rich picture of producers and facilities nationwide, both quantitative and qualitative information was gathered from June 2021 through February 2023.

Benchmarking data were standardized using Key Performance Indicators (KPIs) measuring resource consumption against two measures: pounds (kilograms) of production, and canopy area. The KPIs summarized in **Tables 1** and **2** (page seven) are the most relevant for the current data set. These KPIs originate within RII's PowerScore benchmarking platform, a confidential, not-for-profit tool used by hundreds of agricultural producers throughout North America to voluntarily assess their greenhouse and indoor operational performance.

Learn more about PowerScore KPIs, and the methodology underlying them, in the PowerScore glossary.

Purpose

The purpose of this report is to identify trends across CEA production methods. These facilities are located in many climate zones, growing many different types of crops. Importantly, this report does not rate CEA facilities or production methods against each other. A significantly larger data set would be necessary to support that type of analysis.

These aggregate, measured performance benchmarks are some of the first reported for the CEA sector. They are not intended to be the final word or negate existing third-party benchmarks. They offer a group of measured, annual, industry

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[1] Kozai, T. et al., (2021). Introduction: why plant factories with artificial lighting are necessary. In T. Kozai et al. (Ed.). Plant Factory: Basics, Applications and Advances. (pp.3-4). London, England: Academic Press.

benchmarks to help inform and reflect what can be expected in currently operating facilities.

This report highlights the importance of continued resource and production benchmarking, as well as the strengths and weaknesses of existing surveys and crop models. It also offers a group of current industry-informed KPIs to further an understanding of the CEA industry for those who serve in it.

About Benchmarking

Benchmarking is a tool that enables the comparison of data across entities. The metrics used for benchmarking depend on the type of entity and the type of input, process, or output being measured.[2] Data collection through benchmarking allows progress to be measured from an established baseline. As benchmarking is commonly used to evaluate performance over time, measured against a standard, their peers, or themselves.[3]

Benchmarking is performed by building owners and operators across many building segments. It is performed voluntarily and is also encouraged (and sometimes compelled) by governments. Benchmarking policies have a range of benefits to various stakeholder groups.[4,5] For example, for providing information on building energy performance, benchmarking policies incentivize energy efficiency actions by building owners, resulting in energy savings and reduced operational costs.[6]

Energy and water use are often benchmarked. Further, water conservation is a priority for many jurisdictions in drought-prone regions, and water benchmarking policies can incentivize conservation.

For policymakers, benchmarking policies provide detailed data on buildings in their jurisdictions, informing energy efficiency improvement policies.[6]

Benchmarking policies also equip utilities with data that can inform and improve energy efficiency programs to target key customers that stand to benefit from utility incentive programs.[6] As such, benchmarking policies provide a foundation for the development of other policies, like building performance standards, and voluntary programs such as utility energy efficiency incentive programs.

Data standardization is a critical element of a benchmarking system. Data platforms that calculate performance based on industry-accepted methodologies and address confidentiality and data security are key to driving data uptake from building owners and operators.

Benchmarking practices and resources, such as EPA's ENERGY STAR Portfolio Manager reporting tool for building owners, are well established for commercial and multifamily buildings as energy use in commercial and multifamily buildings is largely comparable across building types. However, industrial buildings historically have been more difficult to benchmark because industrial processes make the energy use profiles of these buildings specific to the production type.

Due to the CEA sector's rapid evolution, it is important to understand the benchmarking resources that currently exist for this sector. Greater data availability and understanding of energy use baselines can inform more accurate and appropriate benchmarking methods for CEA, in turn enabling stakeholders to increase resource efficiency in the sector.

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[2] DOE. (2012) "Energy Benchmarking, Rating, and Disclosure for Local Governments." *Department of Energy*, Retrieved 29 March 2023

[3] DOE. (2012)

[4] ACEEE. (2018). Commercial and Multifamily Building Energy Benchmarking, Transparency, and Labeling in US Cities. Retrieved 29 March 2023

[5] Hart, Zachary. (2015). "The Benefits of Benchmarking Building Performance." *IMT*. Retrieved 29 March 2023

[6] Hart. (2015)

Productivity & Efficiency KPIs

Optimizing input use to maximize output is generally the farmer's goal. Within agriculture, CEA facilities have unique energy use characteristics. Various greenhouse and indoor facility types and production methods lead to varying energy use profiles.

Table 1. Productivity Key Performance Indicators

Productivity KPIs	Units
Annual Crop Energy Productivity	kBtu / lb crop (kWh / kg crop)
Annual Crop Water Productivity	gal / lb crop (L / kg crop)

Table 2. Efficiency Key Performance Indicators

Efficiency KPIs	Units
Annual Facility Energy Efficiency	kBtu / ft^2 (kWh / m^2)
Annual Facility Water Efficiency	gal / ft^2 (L / m^2)

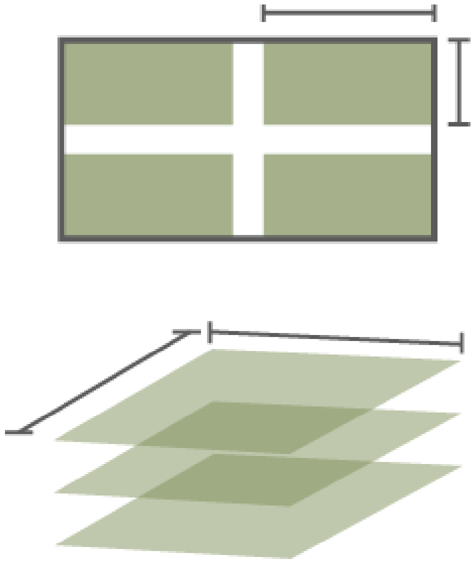
Why kBtu?

PowerScore KPIs use kBtu for energy. This is representative of all energy sources included in the KPI. In the US kWh is often viewed as electrical energy only. Energy sources can include electricity, natural gas, propane, diesel, and even wood.

To better define plant growing area across greenhouses and tiered vertical CEA facilities, canopy area, rather than floor area, should be used to measure CEA facilities' resource efficiency, as canopy area indicates space dedicated to the core product production.

Canopy area is measured as the area covered by the crop foliage. A vertical farm with six tiers of canopy will have a canopy area of one tier times the six stacks. A greenhouse canopy measurement excludes the area dedicated to aisles and walkways. The canopy area is the sum of the green areas in **Figure 1**.

Figure 1. Visualization of Canopy Area of a Greenhouse Farm (Top) and a Vertical Farm (Bottom)



While production metrics are most important for evaluating the value and impact of a CEA facility, area-based measures are still important to know and track. Buildings have been evaluated using metrics measuring energy use per square foot (Energy Use Intensity, EUI) across multiple disciplines, including utilities, energy efficiency, engineering, architecture, and HVAC. EUI is important information for understanding these buildings. It helps producers building new facilities or planning significant expansions to access rebates and incentives for efficient technology. It also compares facilities with multiple crops in the same building against single-crop facilities, for a larger reflection of the sector.

Figure 2. Left: Salad mix; Middle: Head of Butter Lettuce; Right: Cherry vs. Beefsteak tomato

Crop production is measured because it determines the benefit a facility provides to consumers. Production must be considered on a crop-specific basis as even within one crop category (e.g. leafy greens or tomatoes) there can be significant variations in the final product sold, as in the case of salad-ready baby greens versus a head of butter lettuce, or cherry tomatoes versus beefsteak varieties.

IMAGES: (LEFT) VERTICAL HARVEST; (MIDDLE) LOCAL BOUNTI

CEA Benchmarks To Date

Introduction

Benchmarks can be used to inform policies, develop and validate efficiency incentives, determine the sizing of facility construction or expansion, and enable the comparison of an operation's performance either historically or against other operations. Increasing the availability of consistent and reliable energy use data would benefit CEA operations, utility providers, and government agencies.[7]

Literature on resource benchmarking present within CEA from academia, industry, and government that reported on the efficiency and productivity of different facility types and crops was reviewed. **The purpose of this preliminary review is to give a general overview of the current landscape of available benchmarks globally and provide a comparison with the data set later in this report.** This review is not meant to criticize any one methodology or study, but to understand how these benchmarks are derived so that they are not taken out of context when referenced.

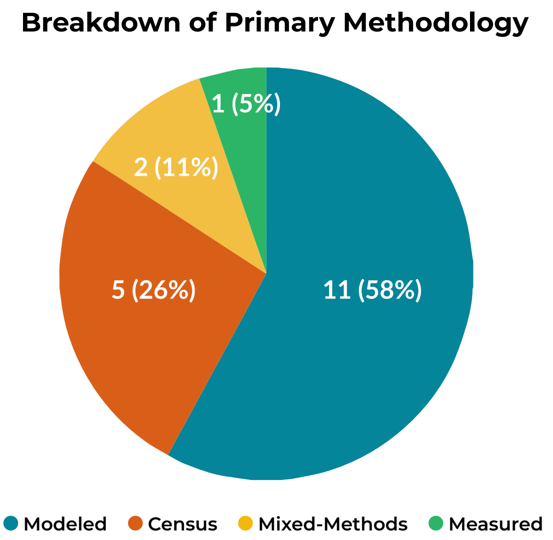
Current Landscape of CEA Benchmarks

A key finding of this literature review is methodologies used in CEA research vary greatly. There were four main categories reported; **Modeling** (Modeling, simulations, and theoretical values), **Self-Reported** (Census, survey, and interviews), **Measured** (Metered or sub-metered), and **Mixed-Methods** (Combination of methods).

Modeling

Making up more than half of the sources in this review, modeling was found to be the most popular methodology used within CEA research. This key finding also was present in Pacific Gas & Electric's *Literature Review of Energy and Water Use in Controlled Environment Horticulture and Potential Efficiency Opportunities*[8] Modeling refers to the use of energy modeling software, pre-existing sub-models, energy balancing calculations, or a combination thereof to simulate a facility's resource use and production. Popular in the building sector (i.e. schools, hospitals, etc.), modeling software like EnergyPlus are built from decades of available data to simulate the energy use intensity of buildings. Modeling has proved to be an important tool in CEA–it is already vital in planning the construction or expansion of facilities and equipment sizing. It can also provide some early predictions of harvest yield and resource consumption from the given inputs.[9] Crop models are vastly more cost-efficient and timely compared to real-world measurement and built around core principles of mechanical engineering, physics, and plant physiology.

Figure 3. Breakdown of Primary Methodology Used in the Third-Party Sources Researched



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Since there is no industry standard software currently available for CEA, modeling methodology

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[7] ETCC. (2022). Controlled Environment Horticulture Facility Assessment and Industry Survey Report. Retrieved 27 October 2022

[8] ETCC. (2022)

[9] GLASE. (2021). "Light and Energy Modeling in Controlled Environment Agriculture." YouTube video, 30:50. 16 November 2021

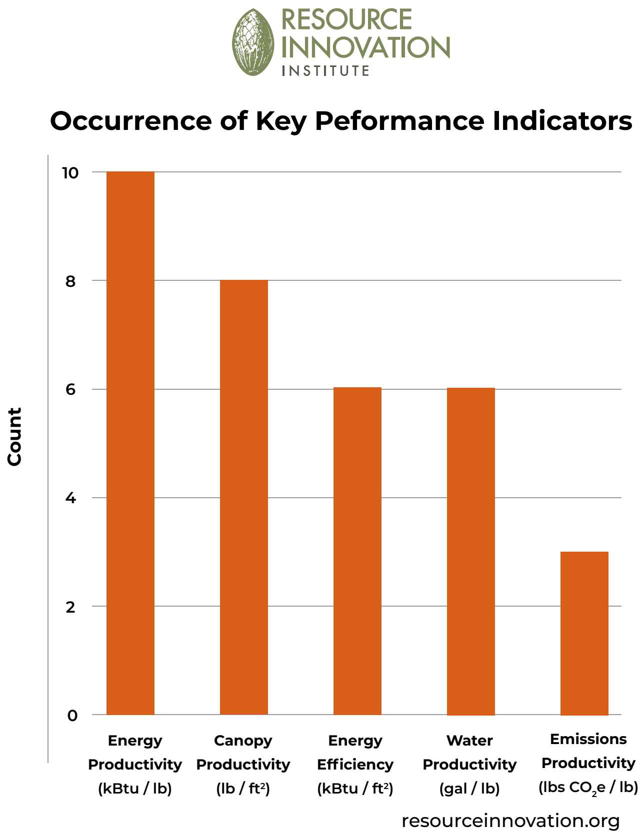
varies greatly between studies. For indoor farm energy use modeling, a building energy model (BEM) software designed for office or residential buildings such as EnergyPlus is a common substitute. Crop production values are determined outside of the software using assumptions or theoretical values from existing literature on production (weight of crop produced) or submodels. For greenhouse modeling, there are more available models such as Virtual Grower or KASPRO that can simulate energy use and crop growth, but they still share similar limitations as indoor models.

The models' quality is dependent on the data input quality. Currently, these models remain challenged by the difficulty of comparing modeling studies, as well as by the lack of understanding surrounding important inputs like evapotranspiration (ET) and production data outputs. The differences in scope and parameters, crop choice, and systems used within a facility (HVAC, lighting, controls, etc.) all affect resource use findings and vary greatly across models.[10]

Evapotranspiration is the sum of transpiration and the water that evaporates from the soil or substrate surface. Plants retain less than 5% of the water absorbed by roots for photosynthesis, cell expansion and plant growth. The remainder is lost to the atmosphere through transpiration to cool the plant.[11] A high ET rate can increase the overall energy demand, as HVAC systems need to remove large amounts of water from the air to maintain optimal growing conditions.

While many available models cover multiple crops, only two models have successfully estimated ET of specific key crops (lettuce and tomatoes) in high-technology CEA.[12] Further, most research studies on ET of crops are short-term and extrapolated for the full crop cycle. Filling research gaps by studying other crop types and extending study durations to the full crop cycle to capture variations in ET that occur in different stages of growth would benefit ET modeling in CEA.[19]

Figure 4. Occurrence of Key Performance Indicators in the Third-Party Sources Researched



Expanding the available data on CEA crop production values would also benefit modeling since resource use per lb (or kg) of crop is a valuable KPI for the industry. Energy productivity (e.g. kBtu / lb, or kWh / kg) values appeared in 10 of the studies included in this review. Of those, eight were from modeled studies. Productivity values in these studies are commonly derived from models, extrapolated calculations, or assumptions of crop spacing and weight from previous literature that may no longer be valid. This results in many highly productive values

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[10] Michael Eaton, Timothy Shelford, Melissa Cole, Neil Mattson, Modeling resource consumption and carbon emissions associated with lettuce production in plant factories, Journal of Cleaner Production,, Volume 384, 2023, 135569, ISSN 0959-6526

[11] McElrone, A. J., Choat, B., Gambetta, G. A. & Brodersen, C. R. (2013) Water Uptake and Transport in Vascular Plants. Nature Education Knowledge 4(5):6

[12] Liping Wang, Emmanuel Iddio, Brent Ewers, Introductory overview: Evapotranspiration (ET) models for controlled environment agriculture (CEA), Computers and Electronics in Agriculture, Volume 190, 2021, 106447, ISSN 0168-1699

that are not representative of a production CEA facility, as opposed to a research facility. It is also common for facilities less than five years in production to be in a constant state of research and development on crop choice, fine-tuning of lighting, and other aspects that can greatly impact crop productivity.

Self-Reported

Studies included in the self-reported category are those where the producer shares data through an interview or a survey. Seven of the 19 studies included in this review used self-reported data in their study (both mixed-method studies include a form of self-reported data). This is the most common methodology used to obtain a facility's operational data today. It allows researchers to capture larger data sets at different scales. This is how the USDA conducts their Census of Horticultural Specialties for CEA facilities in the US.[13] Other instances include local research done by utilities to better understand CEA in their region, like Southern California Edison's (SCE) Market Characterization of Indoor Agriculture (Non-Cannabis). Or the Global CEA Census Report carried out by Way Beyond and Agritecture.[14, 15]

Crop yield is an important benchmark CEA operations commonly track as it ties directly into sales and business success. It is less likely for facilities to measure and track their resource use as closely despite their impact on profitability and sustainability. Because of this, the resource use data reported by participants is almost always utility bill level (electric, heating, water, and waste). While utility readings can provide validated and measured data and are relatively easy for producers to provide, there are some gaps present in this level of data.

One limitation of utility bill level data: it is only as granular as the metering of the building. CEA facilities typically include their offices and/or post-production facilities on-site, and therefore on the same meter. Resources used for offices, bathrooms, refrigeration, and/or post-production produce washing are included with those used in the growing environment. While this may be useful in understanding all energy demands of the operation, sub-metering key end uses can help better identify sources of inefficiency and specific conservation strategies.

With self-reported research, response bias can occur. Response rates are generally low as CEA producers have concerns about the confidentiality of their private data. Those that do participate in these studies lean toward valuing sustainability to some degree, and their facilities typically reflect their values by using efficient technologies and practices. This results in the data not being completely representative of the CEA market as a whole, with a bias toward the more efficient side of CEA. Additionally, some censuses include in their research low energy-consuming greenhouses (e.g. those operating without supplemental lighting) and seasonal hoophouses, which can also skew findings toward less energy-intensive values.

Measured

Measured data is the rarest methodology in available CEA research. While there are measured studies that explore the efficacy of specific technologies used within CEA (including LED lighting, different hydroponic systems, and crop cultivars), there are no publicly available measured benchmarks of a CEA facility in production. The one measured study selected for inclusion in this review is from a master's thesis carried out at The University of Arizona's Controlled Environment Agriculture Center's (UA-CEAC) UAg vertical farm.[16] This thesis, while not focused on energy efficiency and productivity, included submetered energy and production data associated with one harvest

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[13] USDA NASS. (2019). 2019 Census of Horticultural Specialties, Volume 3, Special Studies, Part 3

[14] ETCC. (2021). Market Characterization of Indoor Agriculture (Non-Cannabis). Retrieved 27 October 2022

[15] WayBeyond Ltd and Agritecture LLC. (2021). 2021 Global CEA Census Report. Retrieved 1 January 2023

[16] Caplan, Brian Akira. Optimizing Carbon Dioxide Concentration and Daily Light Integral Combination in a Multi-Level Electrically Lighted Lettuce Pro duction System. University of Arizona,arizona-thes, 2018

period of lettuce (28 days) in a multi-tiered indoor farm (~485 square feet canopy area).

The CEA sector still lacks long-term studies. At least one full year of submetered data collection of an operational CEA facility would be the optimal form of measured data, as it would include seasonality impacts. The outdoor environment greatly impacts the energy and water required to maintain an optimal growing environment.

Conventional Field Farming: Third-Party Benchmarks Review

Being able to compare field farming to CEA could provide valuable metrics to the CEA sector, but there are still few benchmarks available to serve as comparisons. While six studies in this review include outdoor benchmarks, listed in Appendix I, it is important to focus on one of the most referenced studies in CEA today: *Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods.*[17]

The values produced in this study are used to substantiate the claims CEA uses ~90-95% less water. Though it is the product of sound, peer-reviewed science, the work highlights the challenges with industry relying on such comparison studies. The average industry professional might believe the study was an experiment with simultaneous cropping in three environments with all or most of the other variables controlled.

However, that is not the case. The outdoor KPIs were estimated by averaging yield and water usage from two other existing sources. Lettuce yield was found by averaging ten years of National Agricultural Statistics Service (NASS) data collected for the United States Department of Agriculture (USDA), which estimated an annual canopy productivity value of 3.9 kg/m^2 (0.8lb/ft^2). Two crop budgets produced by the University of Arizona Cooperative Extension for Yuma County were used to average water use per square meter per crop. This average was then coupled with the census yield data to find the annual water productivity: 250 L/kg (30 gal/lb).

As for the greenhouse values, hydroponic lettuce yield was determined by combining findings in the existing literature. Specifically, (1) an average of existing studies to determine a planting density of 24 plants per square meter, (2) an assumed 30-day growing period, and (3) an average weight per head of lettuce from a preexisting crop-budget model and a measured study of lettuce growth in Arizona in August. Resulting in an estimated annual canopy productivity value of 41 kg/m^2 (8.4 lb/ft^2). Water usage was determined by using existing calculations to estimate the average evapotranspiration per plant. This value was

Table 3. Summarized Benchmarks from Barbosa et. al

Title	Organization	Year	Crop	Climate Zone	KPI Classification	Facility type	KPI Value
Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods	School of Sustainable Engineering and the Built Environment Center for Environmental Security, The Biodesign Institute	2015	Lettuce	2B	Water Productivity	Greenhouse	**2.4 gal / lb (20 L / kg)**
						Outdoor	**30 gal / lb (250 L / kg)**

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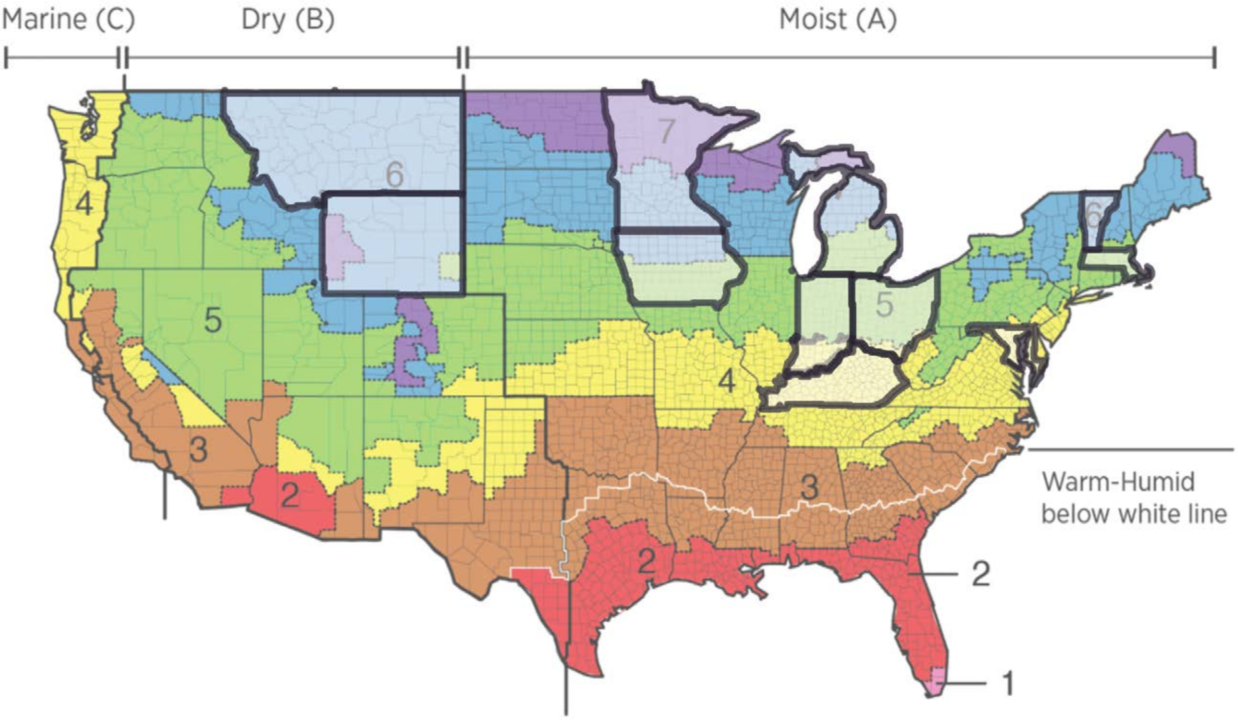
[17] Barbosa GL, Gadelha FD, Kublik N, Proctor A, Reichelm L, Weissinger E, Wohlleb GM, Halden RU. Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. Int J Environ Res Public Health. 2015 Jun 16;12(6):6879-91.

then increased by 10% to include the draining of nutrient solutions that occurs with hydroponic systems. This was then combined with the previously mentioned yield to arrive at an annual water productivity value 20 L/kg (2.4 gal/lb).

Summary of Current Landscape

There is a need in the CEA sector for collaboration between producers and stakeholders to advance market understanding of CEA's environmental impacts and resilience potential by establishing consistent and verifiable accounting and reporting standards. The current landscape shows high variability between study parameters and methodology, which creates difficulty when comparing study results and causes benchmark values to display wide ranges.

Overall, the CEA sector would benefit from more measured (metered and submetered) data to produce a large data set of operational data from which a CEA modeling software can be developed. With this report on utility bill level energy and water usage in operational facilities, the hope is to contribute to the publicly available data to build upon crop production and resource efficiency data.



[18]**Figure 5.** USA map highlighting states that participating facilities are located in, with an overlay of IECC climate zones (used in building energy modeling)

Participants

None of this could have been possible without the thought leadership and transparency of the producers who spent time speaking with us and sharing data. This is an emerging sector whose firms understandably need to protect their intellectual property. RII truly appreciates the producers who came together to bring this report to fruition.

Not all the data collected was included in this report, such as that from passively cooled hoop-houses or seasonal structures. Some producers did not yet have a full year of data. Others had issues with metering systems. Some ultimately chose not to participate due to data security concerns. As might be expected, the hardest thing for many producers to give was their time, it being so valuable to growing businesses. For those producers whose quantitative data was not included in this report, their qualitative knowledge remained invaluable.

Figure 5 shows the locations of greenhouse and vertical farm facilities whose quantitative data was included in this report. They tend to be in colder, lower solar insolation regions, including in frigid locales such as Jackson Hole, Wyoming, whose 365-day frost risk nets it an impressive zero days of outdoor growing season. The geography of study participants biases the data toward those who must consume more energy to operate through the colder, darker months. With their increased input use, these facilities tend to be more resource efficiency-minded. Producers who were able to prioritize spending time with us also may have biased the data toward those who are more sustainability-minded.

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[18] ICC. (2021). IECC, Chapter 3 [RE] General Requirements, Section R301 Climate Zones. Retrieved 14 June 2023
*note that these differ from plant hardiness zones used in outdoor plant production

Climate zones for the benchmarked facilities include 4A (Mixed-Humid,), 5A (Cold), 6A (Cold), 6B (Cold), and 7B (Very Cold).

While some producers shared multiple years of benchmarking data with us, only one year is included per facility to avoid skewing the data set. In those cases, the most representative year was selected, often meaning the year with the least significant changes to operations and/or the most KPIs within the range of other years. When facilities did share multiple years, often significant year-over-year improvements were observed across many KPIs , even without significant changes to the facility. This is measurable evidence that, with increased experience, producers can fine-tune their protocols and climate control strategies.

When interviewing producers, four groups were distinguishable who often had very different business styles, from company culture, funding sources, sales paths, and community engagement. While these business styles are a spectrum and not intended to be exclusive of one another, it can be helpful for those who serve the CEA sector to understand the differences often found between these groups. The next page describes these four types of CEA facilities.

IMAGE: FINN & ROOTS

Common CEA Facility Types

Large Greenhouses: These are legacy businesses, often family-owned. They typically are funded through traditional agribusiness means. They are using tried, true, and tested technology and are usually slower to adopt new technologies and methods due to slim profit margins. They specialize in a few reliable best-seller crops that may change seasonally. Consumers may not know their products are CEA-grown, even when it appears on the shelves of grocery stores off-season.

Large Vertical Farms: These are your all-in innovators. These operations often are start-up companies funded through venture capital money and occasionally niche grants. They are always trying out new technologies and methods, often making big process or technology changes. Often, they will specialize in producing specific varietals within a crop type. They are tech-savvy, high-energy, loud-and-proud champions for the sector, and often are identifiable on grocery store shelves as such.

Small Greenhouses: These are small local businesses, often growing both outdoor and greenhouse crops. They often are self-funded or use traditional small agriculture financing means. These operations are curious about new technology and are likely to dedicate some space to experimentation. That said, they are likely to stage changes over an extended time and are unlikely to make big changes quickly. They typically grow a variety of crops that change annually, keeping only a few core staples the same between years. Selling at farmers' markets, co-ops, and through Community Supported Agriculture (CSA).

Small Vertical Farms: These are typically urban, community-focused projects and often include container farms. Funding for these types of projects can come from everything from community action funds, a local business, or more formal investors. Often designed as multi-purpose educational growing spaces with an "anyone can learn" mentality, they typically are committed to a specific set of accessible technology. They also tend to be the most experimental with what they grow. Sales typically flow through a partnership with another business or feed people directly at an on-site business.

Vertical farms are a more attractive choice for locations with low light conditions and high heating needs. As regions become colder and darker, the benefits of glazing in a greenhouse are reduced and heating costs go up considerably. Greenhouse glazing's insulating factors are limited by the need to allow enough light transmission to benefit plants. Greenhouses in cold, dim climates need to be better sealed and equipped to function year-round, including with supplemental lighting, heating, and energy curtains, unless they are only used to extend growing seasons. The warmer and sunnier the location, the more efficient a greenhouse can be as it can take advantage of solar energy and be controlled with less technology.

Vertical farms are often strategically located to serve a dense population area with reduced shipping time. In the best-case scenario, their products can be consumed within 24 hours of being harvested. Small vertical farms are often located within an urban center, while larger vertical farms may be a short distance away and take advantage of efficient transportation infrastructure to serve that urban area.

Rooftop greenhouses are becoming more prevalent in urban areas, while massive high-tech greenhouse ranges are being built in rural areas near metropolitan hubs to take advantage of unobstructed skies, tax incentives, and affordable properties. In Europe, large greenhouses are often located around airports, where land is less valuable due to noise pollution.

Limitations of Data Collection

As was expected from the outset of the project, this is not a large enough data sample for statistical analysis. Nonetheless, this data is still valuable to the CEA sector, particularly when coupled with qualitative insights and third-party benchmarks from the literature review. Based on the current landscape, this appears to be the first of its kind public report on resource efficiency and production in the CEA sector. The reader is encouraged to consider these findings as important initial steps on a path to a better quantitative understanding of CEA facility resource utilization.

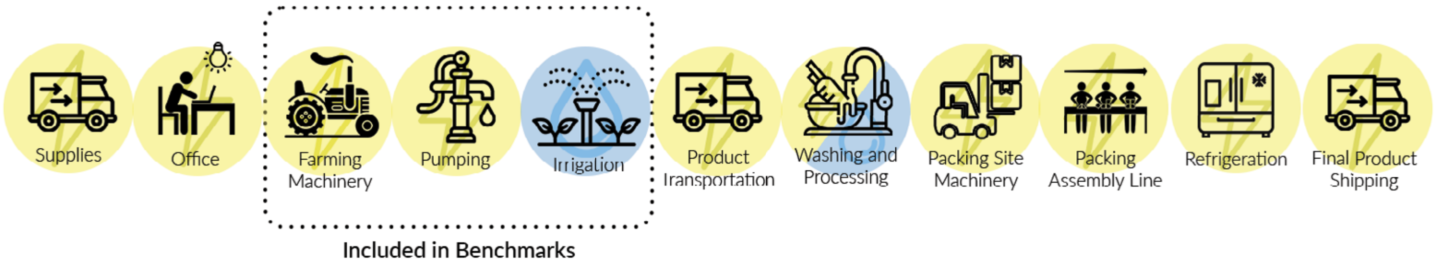
Annual energy and water consumption data were collected at the utility bill level, meaning consumption for the whole facility. All activities that take place on-site and consume energy or water are included in the benchmarks. It would be more precise to have submetered information that excludes activities like post-harvest sanitation, packaging, refrigeration, and office spaces. These metering decisions during facility design are a hurdle to obtaining more granular data.

The shared energy data also includes all energy sources without greater granularity between sources like electricity and natural gas. In future research with a larger data set, the segmentation of energy sources would be ideal.

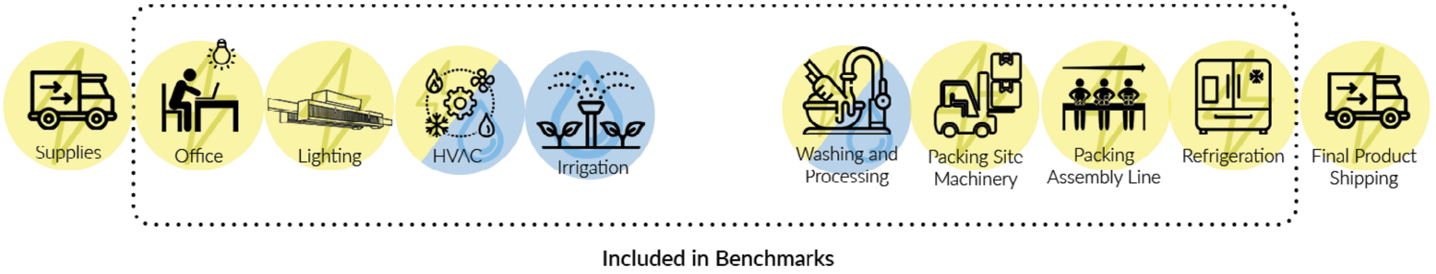
We also acknowledge that direct comparisons of field farming to CEA are often misleading, though they are benchmarks often sought by CEA producers. Field farming benchmarks generally encompass only activities that take place directly in the field, not the ancillary activities captured within a CEA facility. Many CEA facilities also include offices with related energy and water consumption. Field production is measured at harvest, with yield losses from post-harvest processing, quality checks, or packaging also not counted. It is important to keep in mind these key differences in scope when considering CEA and field farming benchmarks.

Figure 6. Visualization of field farming and CEA highlighting processes included in energy and water benchmarks

Field Farming



Controlled Environment Agriculture



Findings

Productivity

The reporting of PowerScore measurements of annual Energy Productivity and Water Productivity will focus on a single crop type: leafy greens. (This is to protect the identity of individual producers.) In addition, there is no data differentiation between greenhouse and vertical farms for these measures. The "leafy greens" crop category includes products like lettuces, petite greens, baby spinach, and live-root lettuce. It is important to keep in mind the significant weight differences between some of these types of final products.

Qualitatively, one of the key differences between leafy green producers in greenhouses and vertical farms is how lighting is used. For vertical farming, HID or LED fixtures are the sole source of energy for plants, while greenhouse fixtures might only be used to supplement solar energy or extend daylength. Supplemental lighting can also speed up greenhouse production of leafy greens, which allows greenhouse producers to time their lighting use to match their supply to the demand. Considering this accelerated growth, it's easy to see how CEA can result in considerably more harvests per year for leafy greens compared to field farming. This can allow CEA producers to maintain a predictable food supply and respond to demand.

Facility Energy Productivity

Figure 8 is a histogram of annual Facility Energy Productivity for the eight producers who shared this quantitative data on leafy greens. While it would improve granularity for this information to be from submetering, that is not the current industry standard. All PowerScore energy benchmarks are collected at the whole facility, utility bill level.

Some of these benchmarks come from facilities that only grow leafy greens, while others come from facilities that grow a variety of crops. For benchmarks from facilities that grow multiple crops, the energy consumption allocated to leafy greens was estimated by the percentage of the canopy area. If 80% of the canopy was dedicated to leafy greens, 80% of the total energy consumption of the building was allocated to leafy greens. (This is a limitation of this reporting.)

This KPI describes the energy required to grow a pound (kilogram) of harvested produce. It is measured as the total energy used in a facility, by all fuel sources, within 12 months (measured at the utility bill level). The production is of total pounds of sellable product produced at the facility over 12 months. As this chart is a histogram, the X axis shows ranges of kBtu per pound while the Y axis shows the number of facilities benchmarked within each range. (Note that 40 kBtu per pound is equivalent to 26 kWh per kilogram.)

The largest grouping of producers benchmarked had an energy productivity value ranging between 40-80 kBtu per pound of sellable product with three total facilities, followed by 0-40 kBtu per pound.

Figure 7. Visualization of Energy Productivity

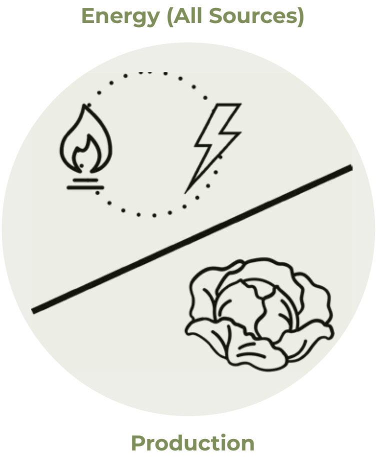
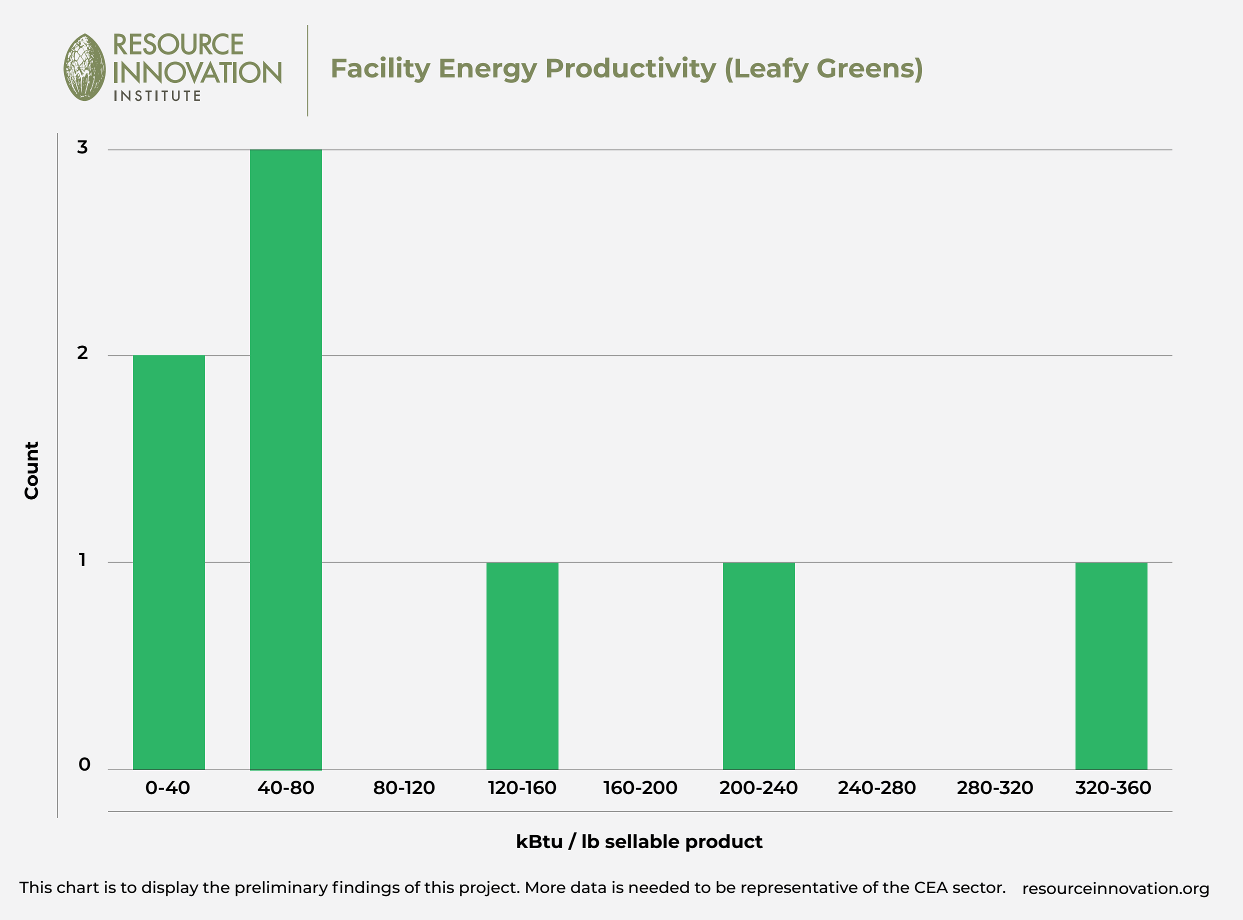


Figure 8. Annual Facility Energy Productivity of Leafy Greens

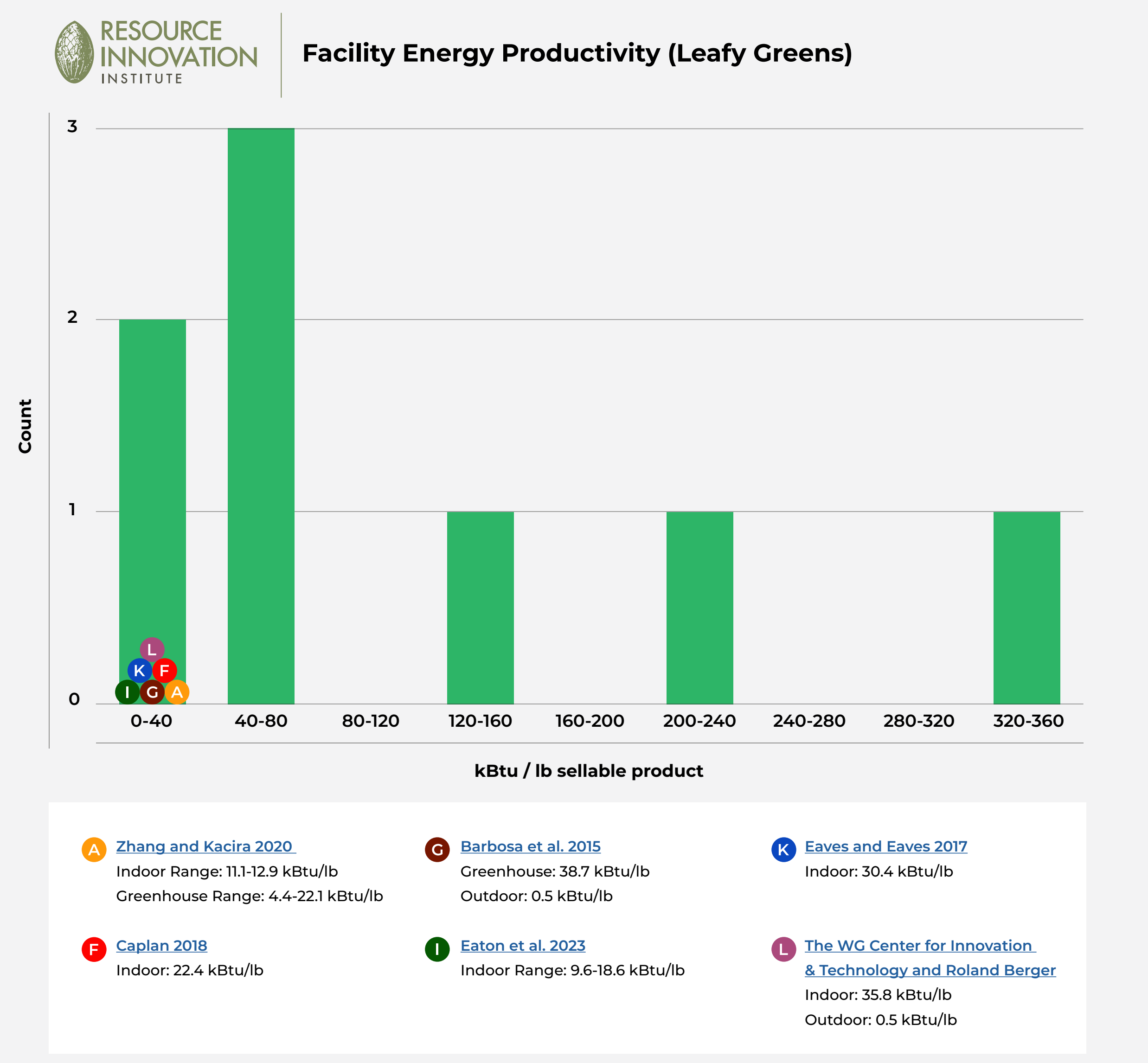


This chart is to display the preliminary findings of this project. More data is needed to be representative of the CEA sector.

From working closely with these producers, it was observed that those with lower energy usage had fine-tuned their operations over time. Since its founding in 2016, RII has consistently observed that when a producer grew a specific crop, they got better at growing that crop each year, resulting in increased canopy productivity and improvements in all productivity numbers (data not shown). It is anticipated that producers using more energy to produce the same volume will move toward a more efficient rate as they gain experience with their crop and facility as the more efficient producers continue improving with experience.

Due to the significant differences in the weight of product types coming from different facilities, while this energy productivity information is interesting, it contains significant pitfalls if its context is not carefully considered. This KPI is most useful for a producer to collect across time and facilities to understand their performance with their specific products.

Figure 9. Annual Facility Energy Productivity of Leafy Greens Including Third-Party Benchmarks



This chart is to display the preliminary findings of this project. More data is needed to be representative of the CEA sector. resourceinnovation.org

This second figure is the same as the first, except that third-party benchmarks have been layered over the histogram. The points' different colors and letters are references to the study from which they are sourced and the studies can be found in Appendix I. The figure key displays the third-party sources and their specific benchmark values.

Third-party energy productivity benchmarks display highly productive values compared to the PowerScore data set, ranging from 4.4-38.7kBtu/lb.[19,20] These reports were primarily of modeled data, which can explain the difference in productivity between the data set and third-party benchmarks. As discussed earlier, modeled studies can produce highly productive values due to factors such as nonrepresentative crop production (e.g. not including crop loss), equipment efficiency, and not including ancillary activities.

Note that all third-party sources assume a single crop, lettuce, while PowerScore producers often grew other low-weight leafy greens included in this metric. Additionally, modeled sources do not account for the ancillary activities measured in producers' energy consumption (e.g. office space, packaging, or refrigeration). The difference in parameters used between measured and modeled studies poses issues in making comparisons and conclusions about energy productivity in CEA.

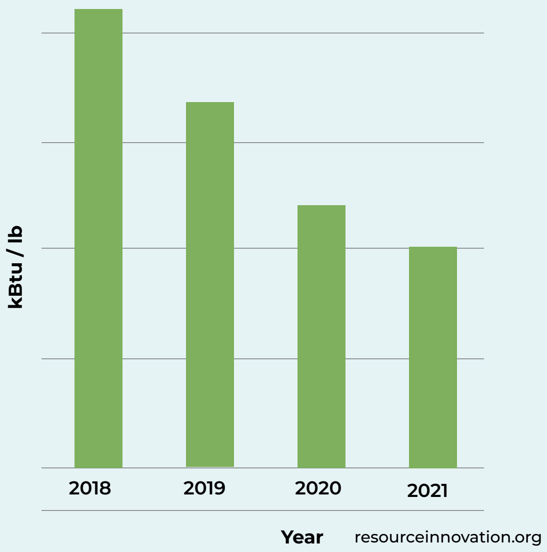
Facility Water Productivity

Figure 12 is a histogram of annual Facility Water Productivity for the six producers who shared this quantitative data about their leafy greens. While it would be ideal for this information to be from submetering for improved granularity, that is not the current CEA industry standard. All PowerScore water benchmarks are collected at the whole facility, utility bill level.

Some of these benchmarks come from facilities that only grow leafy greens, while others come from facilities that grow a variety of crops. For benchmarks from facilities that grow multiple crops, the water consumption allocated to leafy greens was estimated by the percentage of the canopy area. If 80% of the canopy was dedicated to leafy greens, 80% of the total water consumption of the building was allocated to leafy greens.

Figure 10. Improvement of Annual Facility Energy Productivity of an Anonymous Producer

This Facility Energy Productivity chart shows four years of a single producer's overall annual energy consumption per pound of product. From 2018 to 2021 this producer improved this KPI by 52%. The substantial improvement in this example illustrates the trend of producers achieving greater productivity and efficiency as they fine-tune their facilities and growing methods.



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[19] Ying Zhang and Kacira, M. (2020). Comparison of energy use efficiency of greenhouse and indoor plant factory system. Eur.J.Hortic.Sci. 85(5), 310-320.

[20] WayBeyond Ltd and Agritecture LLC. (2021)

Facility Water Productivity describes. the water required to grow a pound (kilogram) of harvested produce. It is measured as the total water used in a facility, for all processes, within 12 months, measured at the utility bill level. The production is of total pounds of sellable product produced onsite over 12 months. As this chart is a histogram, the X axis shows a range of gallons per pound while the Y axis shows the number of facilities benchmarked within each range. (Note that 3 gallons per pound is equivalent to 25 liters per kilogram.)

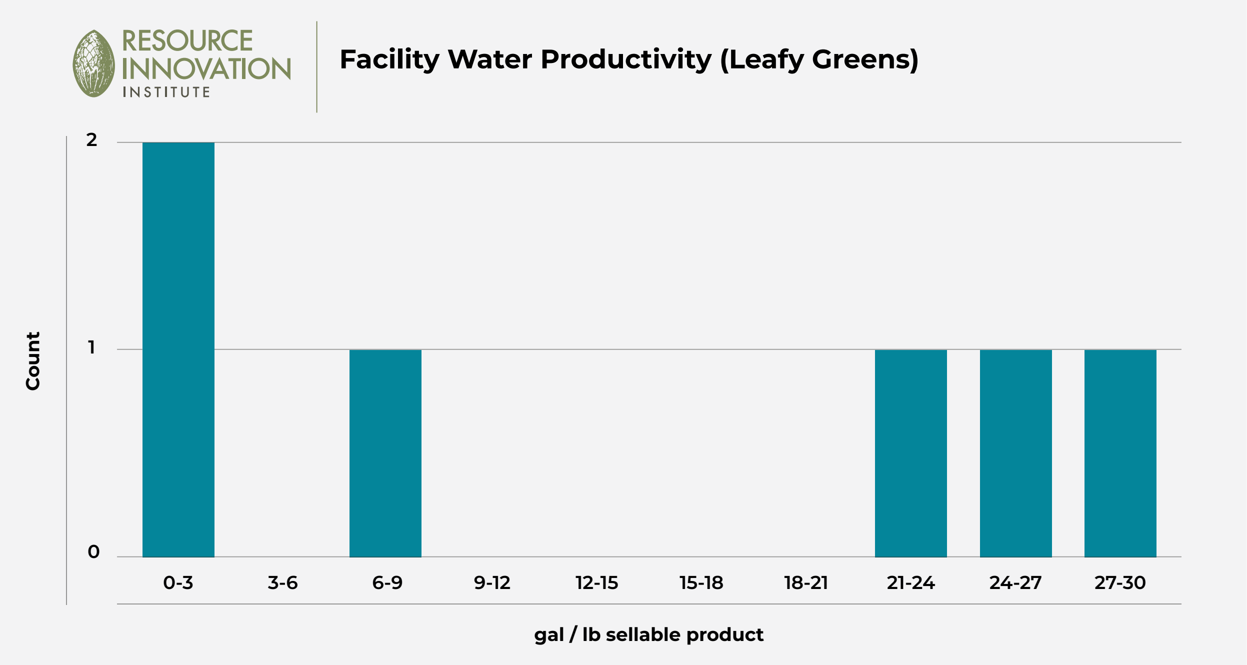
Figure 11. Visualization of Water Productivity

There is a significant spread in annual water productivity. Two producers used between 0-3 gallons per pound of sellable product for their leafy greens, one used between 6 and 9 gallons per pound while three others were between 21 and 30 gallons per pound.

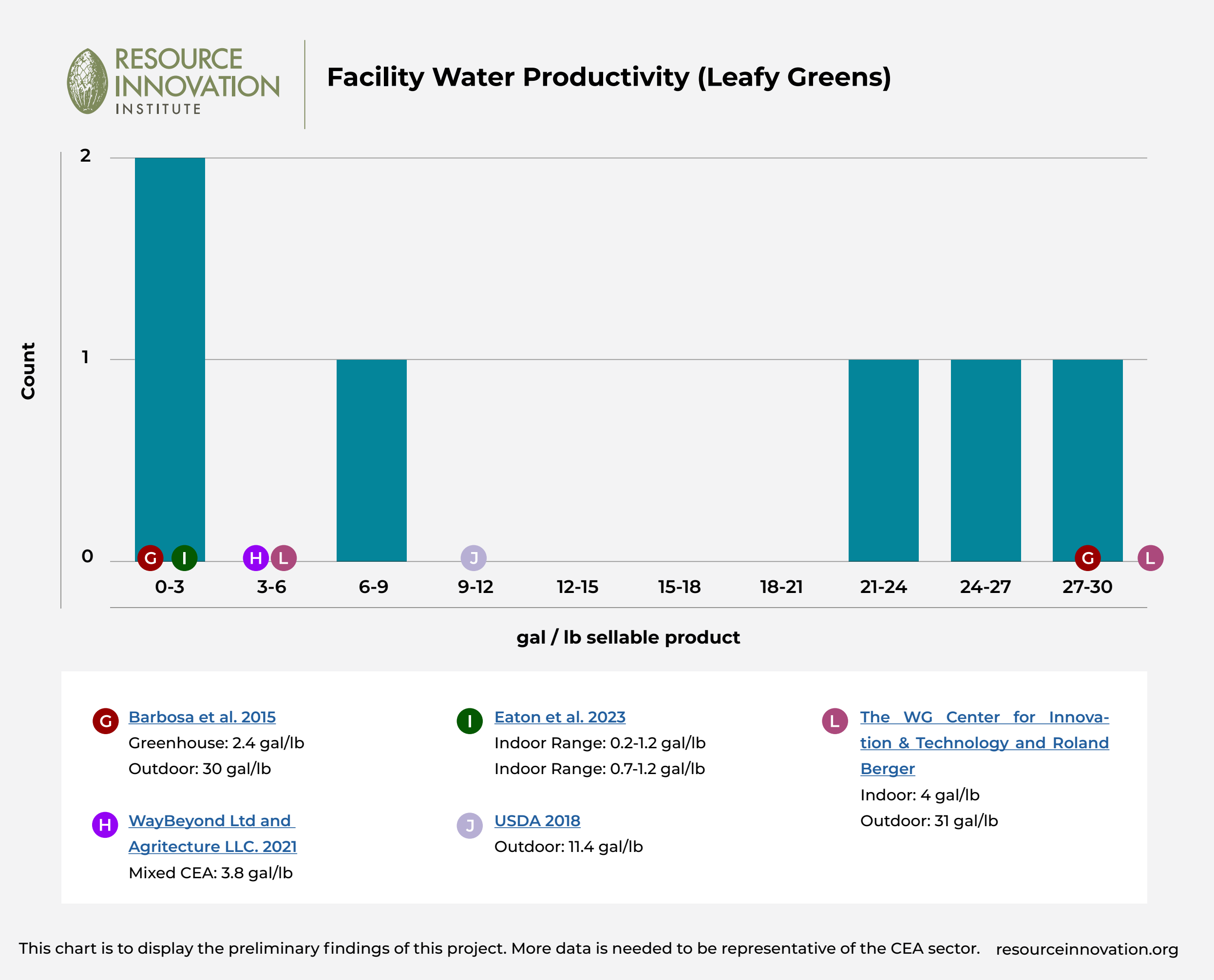
Qualitatively, some producers prioritize their water consumption and by doing so achieve low gallons per pound rates. Others have poor water productivity numbers that resemble field benchmarks. The PowerScore producers' geographic distribution may explain this, as many are concentrated in areas where water availability is not a high concern.

Water is clearly an area where CEA can easily excel over field farming, but not without the prioritization of and investment into water efficiency and circularity. Unlike with energy, there are very few financial incentives available to producers for water remediation and reuse equipment despite how return on investment (ROI) timelines can be close to the lifetime of the equipment. As has been shown with LED lighting, an increase in financial incentives from the energy sector would significantly increase the adoption of circular watering systems in CEA.

Figure 12. Annual Facility Water Productivity of Leafy Greens



This chart is to display the preliminary findings of this project. More data is needed to be representative of the CEA sector. resourceinnovation.org



G Barbosa et al. 2015
Greenhouse: 2.4 gal/lb
Outdoor: 30 gal/lb

H WayBeyond Ltd and Agritecture LLC. 2021
Mixed CEA: 3.8 gal/lb

I Eaton et al. 2023
Indoor Range: 0.2-1.2 gal/lb
Indoor Range: 0.7-1.2 gal/lb

J USDA 2018
Outdoor: 11.4 gal/lb

L The WG Center for Innovation & Technology and Roland Berger
Indoor: 4 gal/lb
Outdoor: 31 gal/lb

This chart is to display the preliminary findings of this project. More data is needed to be representative of the CEA sector. resourceinnovation.org

Figure 13. Annual Facility Water Productivity of Leafy Greens Including Third-Party Benchmarks

Again, this second figure is the same as the first, except that third-party benchmarks have been layered over the histogram for comparison. The studies can be found in Appendix I. The figure key displays the third party sources and their specific benchmark values.

When comparing water use savings between conventional field farming and CEA, it is the water productivity value (gal/lb) that is used, **not** the water efficiency (gal/ ft^2). Important to note, the maroon point labeled G in the 27-30 gal/lb is a conventional field farming benchmark at 30 gal/ lb of lettuce. The highest performing producers in the 0-3 gal/lb range have shown it is possible to achieve annual >90% water savings compared to conventional field farming. Specifically, the most efficient producer achieved 94% water savings compared to field farming, even though producers' water usage included uses beyond irrigation. Similarly, the *2021 Global CEA Census report* found that two-thirds of their respondents achieved >90% water savings when compared to the same field farming benchmark.[21] The census also reported an average annual water productivity of 3.8 gal/lb for leafy greens grown in greenhouses and indoor facilities, displayed as the dark purple point labeled H.

The widely referenced 30 gal/lb outdoor benchmark was derived from two crop budgets for Yuma County, Arizona. For context, this county is located in climate zone 2B (hot-dry) which likely results in above-average water

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[21] WayBeyond Ltd and Agritecture LLC. (2021)

usage compared to most other regions in the US due to high irrigation needs. The second outdoor benchmark, displayed as light purple point labeled J was pulled from the USDA's *2018 Irrigation and Water Management Survey*. This survey found the national average annual water productivity value associated with outdoor lettuce production was 11.4 gal/ lb.[22] This benchmark can serve as a more representative value as it incorporates different outdoor irrigation methods and, more importantly, the varying climate zones in the US which can heavily impact field farming water usage.

Again, note that all of the third-party sources assume a single crop, lettuce, while PowerScore producers grew other low-weight leafy greens. Additionally, the data set includes other onsite activities of CEA facilities that contribute to water consumption, such as produce-washing, sanitation, and office water usage. Consider that field water benchmarks only include irrigation water. For additional context, the water productivity associated with growing field-farmed almonds is 12,000 gal/lb.[23]

Waste

While not enough quantitative information was collected in this report to present data related to waste, there emerged a significant focus on waste by the producers during qualitative interviews. A focus on food waste is especially important as it has been reported to account for about 8% of global greenhouse gas emissions.[24]

Producers are constantly looking into ways to reduce food waste and improve packaging waste. They think about food waste not just within their facility, but also on store shelves and even customer refrigerators. A producer's goal is for their product to make it into people's mouths, not just sales out the door.

Similar to the producers in this data set, those surveyed in the 2021 Global CEA Census Report share a focus on reducing food waste. The census of CEA facilities reported an average of 88.2% of produce grown reaches consumers and 5% is donated, resulting in only 6.8% wasted.[25]

Food miles, or how far food travels before consumption, is another constant consideration of producers in the CEA space. Many producers partnered with other local businesses to improve the circularity of their operation, sending products that don't meet human consumption standards to animal farms.

Facility Energy Efficiency

Figure 15 shows a histogram of the annual Facility Energy Efficiency for each of the 12 producers who participated (seven greenhouse and five vertical farms). These facilities encompass the full spectrum of facility size, crop types, growing methods, lighting, and HVAC systems.

The largest facility had a growing area of approximately 2,600,000 square feet (241,548 m^2) with the smallest at 2,707 square feet (251 m^2). Crops grown include (in rough order of frequency): leafy greens, tomatoes, herbs, microgreens, cucumbers, and strawberries. Lighting included all LED, mixed LED and HPS, and all HPS systems. HVAC systems were most often a mixture of electric and natural gas but included all electric systems and even a wood-heated unit. All energy sources were converted into kBtu for this KPI.

Figure 15 is a distribution of the facilities by their annual energy use. The X-axis shows energy ranges of kBtu per square foot, while the Y-axis shows the number of facilities within each range. Purple highlights the vertical farming facilities benchmarked, while yellow highlights

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[22] USDA NASS. (2018). Census of Agriculture 2018 Irrigation and Water Management Survey. Retrieved 1 May 2023

[23] Julian Fulton, Michael Norton, Fraser Shilling, Water-indexed benefits and impacts of California almonds, Ecological Indicators, Volume 96, Part 1, 2019, Pages 711-717, ISSN 1470-160X

[24] Project Drawdown. (n.d.) Reduced Food Waste. Retrieved 15 May2023

[25] WayBeyond Ltd and Agritecture LLC. (2021)

the greenhouses benchmarked. This KPI is measured as the total energy used in a facility, by all fuel sources, within a 12-month period, measured at the utility bill level. The square footage is of the average area dedicated to growing canopy over the 12-month period. (For reference, 200 kBtu per square foot is equivalent to 631 kWh per square meter.)

It is important to remember these facilities are in multiple climate zones and grow many different types of crops. The intention of this report is not to measure them against each other. Focusing on greenhousess, four of the seven greenhouses benchmarked fall within the 200 - 400 kBtu per square foot range, with half as many in the 400 - 600 range, and one in the 0 - 200 range.

This shows a relatively tight group benchmark for greenhouses.

Turning to vertical farms, one facility reported efficiency rates in the 200 - 400 kBtu per square foot range, one facility was in the 400 - 600

Figure 14. Visualization of Energy Efficiency

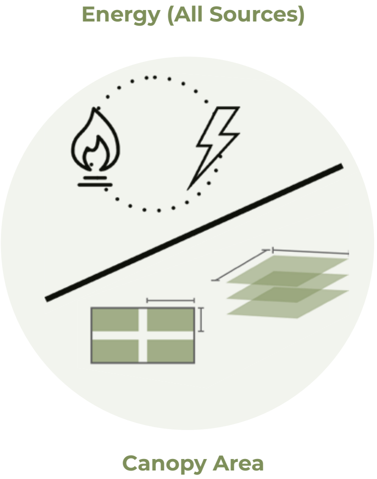
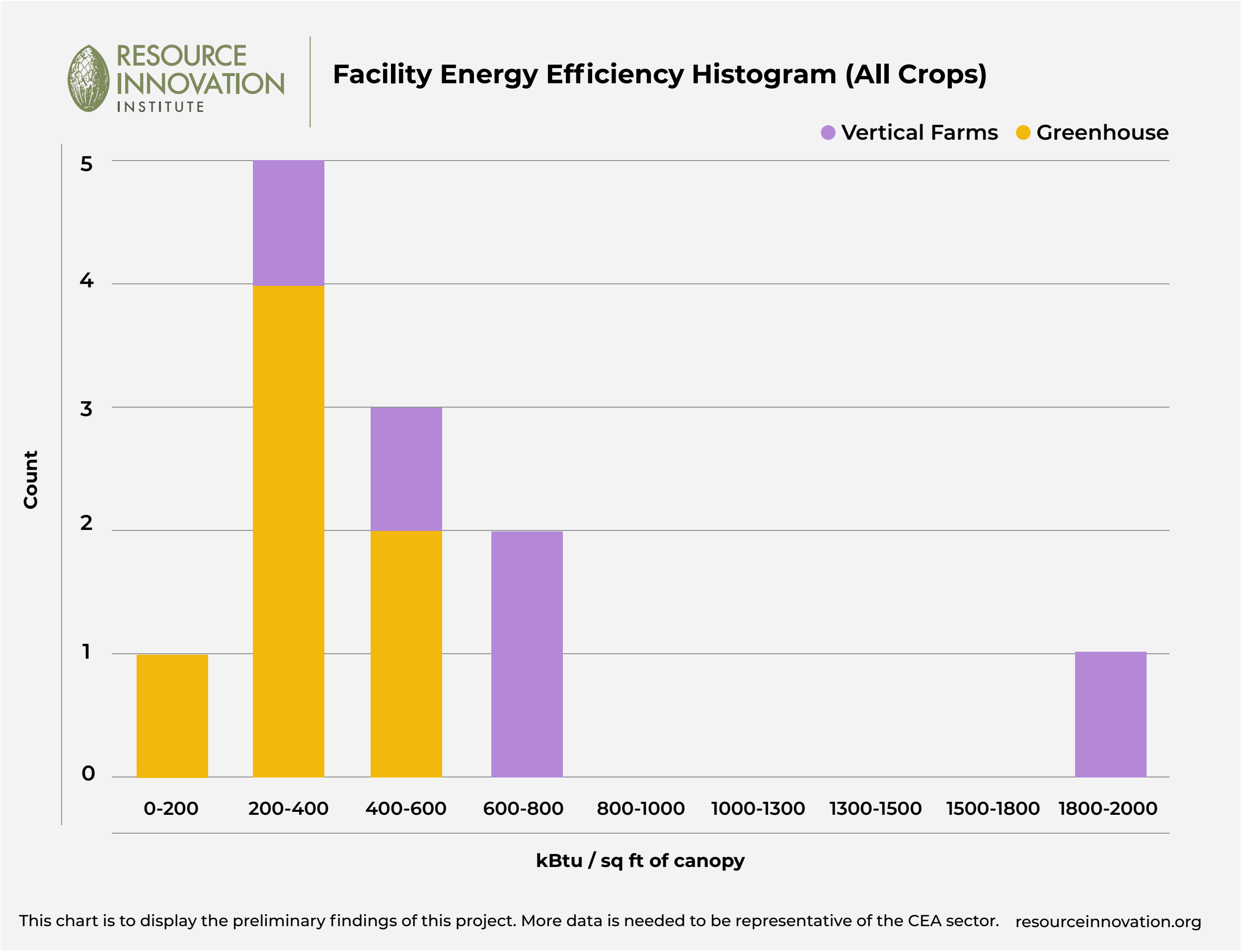


Figure 15. Annual Facility Energy Efficiency of Mixed Crops



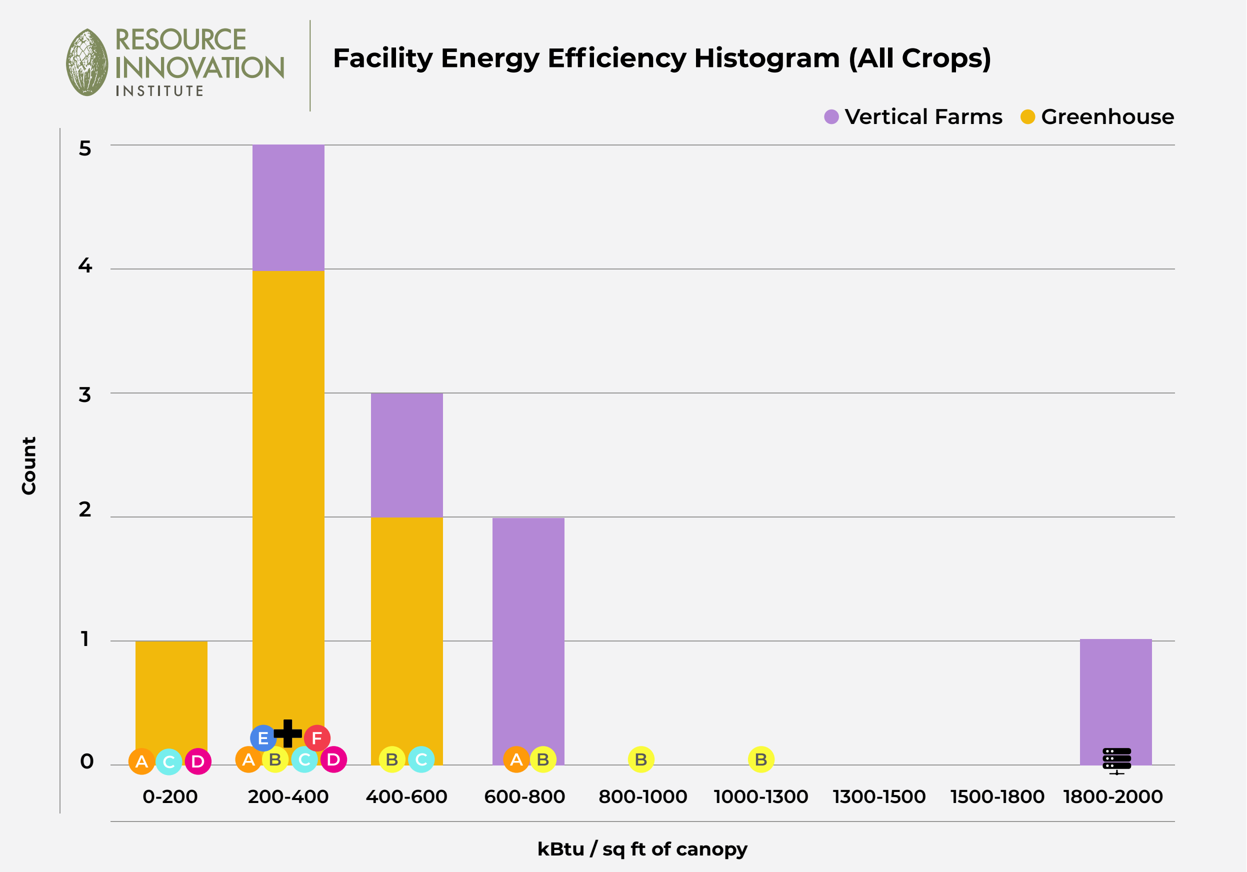
This chart is to display the preliminary findings of this project. More data is needed to be representative of the CEA sector. resourceinnovation.org

range, two were 600-800 range, and one outlier reported falling into the 1,800 - 2,000 range.

Combining this data with the qualitative information from working directly with these producers, it is clear that the vertical farming sector is in a period of fast-paced innovation and is not yet standardized. With the significant spread of data, averaging the vertical benchmarks would not be a valuable representation. The data shows on a per square foot of canopy basis, vertical farming **can** have an energy consumption similar to that of many greenhouses. At the same time, vertical farming **can** be relatively energy intensive. Overall this KPI is best used to understand the changes in the performance of a specific facility and can be misleading when comparing between different facilities.

When reviewing the annual Facility Energy Efficiency, remember that CEA, while energy-intensive relative to field farming, is able to

Figure 16. Annual Facility Energy Efficiency of Mixed Crops Including Third-Party Benchmarks



A [Zhang and Kacira 2020](#)
Indoor Range: 127-159 kBtu/sq ft
Indoor (multi-tier): 793 kBtu/sq ft
Greenhouse Range: 63-349 kBtu/sq ft

B [Graamans et al. 2018](#)
Indoor: 616 kBtu/sq ft
Greenhouse Range: 396-1145 kBtu/sq ft

C [Southern California Edison](#)
Indoor Range: 137-512 kBtu/sq ft

D [Posterity Group 2019](#)
Greenhouse Range: 139-249 kBtu/sq ft

E [Harbick and Albright 2016](#)
Indoor: 322 kBtu/sq ft

F [Caplan 2018](#)
Indoor: 401 kBtu/sq ft

✚ [Energy Star](#)
Hospitals: 234 kBtu/sq ft

☰ [Energy Star](#)
Data Centers: 2,000 kBtu/sq ft

This chart is to display the preliminary findings of this project. More data is needed to be representative of the CEA sector. resourceinnovation.org

achieve greater annual canopy productivity per square foot.

The second figure is the same as the first, except that third-party benchmarks have been layered over the histogram for comparison. The different colors and letters of the points refer to the study from which they are sourced. The studies can be found in Appendix I. The figure key displays the third-party sources and their specific benchmark values.

The other points included are energy use intensities of other building types to serve as context outside of the world of CEA.[26, 27] Note that third-party energy efficiency benchmarks are relatively consistent with the producers' data. All sources that researched CEA facilities' energy efficiency produced at least one benchmark value within the range 200-600 kBtu where eight of the facilities fall.

Beyond Productivity & Efficiency: Energy Sources, Renewables & Carbon Emissions

While this report emphasizes energy productivity and efficiency, it is worth noting that energy sources are a key factor in CEA facilities' carbon emissions profiles. Some producers source their power from renewable sources–one producer showed a greater than 60% reduction in total carbon emissions from all energy sources combined when compared to sourcing their electricity from the state grid. Producers have a significant opportunity to reduce carbon emissions by sourcing their electricity from renewable sources, where possible. While some states have made significant strides in reducing the carbon intensity of their grid, others lag.

PowerScore offers producers KPIs that calculate carbon emissions related to the actual source of energy used. Through PowerScore analysis, it was found the carbon emissions profile of a facility is most strongly related to the carbon emissions profile of the electricity grid from which it sources its power.

Next Steps in Data Standardization: CEA Footprint Project

In early 2023, an international coalition of leading CEA producers and stakeholders committed to working together to agree upon methodologies to account for energy, water, and emissions benchmarking and KPI development. The industry-led initiative, called the CEA Footprint Project, is a natural extension of this USDA Conservation Innovation Grant-funded report.

CEA Footprint Project Goals:

1. Develop an international environmental accounting framework through consensus to enable complete, consistent, ongoing evaluation of modern farming methods
2. Provide tools to enable CEA producers and stakeholders to adopt standardized measurement as put forth by the CEA Footprint Project
3. Advance a broader understanding of the environmental benefits and impacts of CEA

Participating companies include:

- 80 Acres
- Bowery Farming
- GrowUp Farms
- Jones Food Company
- Little Leaf Farms
- Local Bounti
- Ljusgårda
- Revol Greens
- Vertical Harvest

Steering Committee members include:

- CEA Alliance
- FarmTech Society
- International Fresh Produce Association
- IVL Swedish Environmental Research Institute
- Resource Innovation Institute
- US Departmentof Energy
- World Wildlife Fund

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[26] Energy Star. (n.d.). What is Energy Use Intensity (EUI)? Retrieved 16 June 2023

[27] Energy Star. (2018). Data Center Estimates in the United States and Canada. Retrieved 16 June 2023

Conclusions

Data collection through benchmarking allows progress to be measured from an established baseline. Data platforms, such as RII's PowerScore, that calculate performance based on industry-accepted methodologies and address confidentiality and data security are key to driving data uptake from building owners and operators.

Though excellent crop modeling tools have been developed and self-reporting surveys have been useful, measured data is the rarest methodology in available CEA research. The current landscape of third-party benchmarks shows high variability between study parameters and methodology, which creates difficulty when comparing results and causes benchmark values to display wide ranges.

In this report, the annual resource consumption and productivity of twelve producers growing a variety of crops in greenhouse and indoor facilities were benchmarked. Energy and water consumption data were collected at the utility bill level, meaning consumption for the whole facility. These aggregate, measured performance benchmarks are some of the first reported for the CEA sector.

Operations were analyzed on their productivity per area of the foliar canopy, rather than floor area, to better define plant growing areas across greenhouses and tiered vertical CEA facilities. Producer data is compared with relevant third-party benchmarks from academic and government sources.

Resource productivity is the most effective way to assess the efficiency of a CEA operation. CEA operations are similar to industrial processes, so comparing resource use to production output is key.

When producers submitted multiple years of operational data, significant increases in efficiency and productivity were observed. Suggesting that as producers become experienced they learn to optimize their facility.

Though facilities differed in their water use efficiency, the highest performing producers achieved greater than 90% water savings over common field farming benchmarks. This performance level is consistent with academic models relied upon by the CEA sector. As this dataset grows, these claims could be verified. Water circularity strategies in closed environments appear effective at driving significant levels of water efficiency relative to open-field farming. This is clearly an area for future study, particularly in drought-prone areas such as the western United States.

PowerScore data on annual facility energy efficiency was consistent with published third-party benchmarks. Vertical farming can be energy intensive, but in some cases has an energy consumption similar to that of many greenhouses. There is a wide spread of performance in this area especially amongst vertical farming.

Calls for Additional Study

Future studies could be greatly beneficial by dialing into specific types of facilities. Large greenhouses offer a great opportunity to do so with more established practices and many years under their belt. Utilities in regions with many greenhouses should work to engage with greenhouse growers and benchmark facilities to understand the needs and performance of greenhouses in their region and climate zones. By offering incentive projects that can directly benefit producers, they are more likely to be comfortable sharing information and able to prioritize the project. Topics for study could focus on specific technologies ie. radical lighting developments, advanced greenhouse glazing, heat pumps, and cogeneration.

This study is somewhat limited in crop variety. For example, mushrooms are completely excluded from this report but make up a significant portion of the CEA market. Floriculture is also a significant market that is not included in this report. Crop-specific studies can allow for more productivity compared to square footage-related findings.

This report does not adequately represent the South and West of the nation. These areas have significantly different climates than many of those benchmarked in this report. Better representation from operations located in more drought-prone areas as well as hotter areas is needed to paint a more complete picture of the state of the CEA sector.

While short-term studies can be helpful, four-season data in a variety of climate zones is vital for understanding the CEA space. Measured data, and eventually submetered data, can make a significant difference.

Continued collaboration and sharing remain key to benchmarking success. The producers who chose to share data for this report are thought leaders. It is hoped that others will follow in their footsteps and will collaborate on future projects.

Modeling has significant opportunities to continue to grow in CEA. Improved evapotranspiration models, equipment efficiency understanding, and incorporating product losses are major modeling considerations that can get models closer to results found in operational CEA facilities.

Improved data collection and reporting standards can significantly help those within the CEA space communicate with each other.

Multi-year benchmarking, studying how producers improve year-over-year, as well as studying how ramp-up periods and large facility retrofits impact production can better define the learning curve of CEA facilities.

Scope 3 carbon emissions become more defined and calculable, this area is one of great interest to many. With Scope 3 diving into areas like fertilizer consumption, packaging, soil and substrate, CEA and field farming can start to be evaluated on the same playing field. In addition to carbon emissions, overall waste streams and circularity opportunities should be explored as well.

Appendix 1: Summary of Third Party Benchmarks

Source Name	Organization	Year	Primary Methods	Climate Zone	Facility Type	Crop	KPI Value	KPI Units	KPI Classification	Key for Visuals
2018 Irrigation and Water Management Survey	USDA	2018	Census	-	Outdoor	Lettuces	11.4	gal / lb	Water Productivity	J
2019 USDA Census of Horticultural Specialties	USDA	2019	Census	-	Protection	Tomatoes	9	lb / sq ft	Canopy Productivity	-
						Lettuces	11	lb / sq ft		
						Fresh Herbs	3	lb / sq ft		
						Strawberries	2	lb / sq ft		
2021 Global CEA Census Report	WayBeyond/ Agritecture	2021	Census	-	Mixed	Leafy Greens	3.8	gal / lb	Water Productivity	H
						Vining Crops	5	gal / lb		
						Berries	10.1	gal / lb		
				-	Greenhouse	-	6.2	gal / lb	Water Productivity	
							8.6	kBtu / lb	Energy Productivity	
				-	Indoor	-	2.4	gal / lb	Water Productivity	
							62	kBtu / lb	Energy Productivity	
2022 Specialty Crop Automation Report	The WG Center for Innovation & Technology	2022	Modeled	3C	Outdoor	Leafy Greens (Lettuce)	0.3	lb / sq ft	Canopy Productivity	L
							31	gal / lb	Water Productivity	
							0.5	kBtu / lb	Energy Productivity	
				-	Indoor (8-tiers)	Leafy Greens (Lettuce)	9.8	lb / sq ft	Canopy Productivity	
							4	gal / lb	Water Productivity	
							35.8	kBtu / lb	Energy Productivity	
Comparing the Profitability of a Greenhouse to a Vertical Farm in Quebec	Canadian Journal of Agricultural Economics	2017	Modeled	Cold	Indoor	Lettuces	30.4	kBtu / lb	Energy Productivity	K
Comparison of energy consumption: greenhouses and plant factories	Biological and Environmental Engineering, Cornell University	2016	Modeled	-	Indoor	Lettuces	321.5	kBtu / sq ft	Energy Efficiency	E

Appendix 1: Summary of Third Party Benchmarks

Source Name	Organization	Year	Primary Methods	Climate Zone	Facility Type	Crop	KPI Value	KPI Units	KPI Classification	Key for Visuals
Comparison of Energy Use Efficiency of Greenhouse and Indoor Plant Factory System	Department of Biosystems Engineering, The University of Arizona	2020	Modeled	Cold	Greenhouse	Lettuces	222	kBtu / sq ft	Energy Efficiency	A
							349	kBtu / sq ft		
				Hot	Greenhouse	Lettuces	63	kBtu / sq ft		
							127	kBtu / sq ft		
				Cold	Indoor	Lettuces	127	kBtu / sq ft	Energy Efficiency	
							159	kBtu / sq ft		
				Hot	Indoor	Lettuces	127	kBtu / sq ft		
							159	kBtu / sq ft		
				Cold	Indoor (Multi Tiers)	Lettuces	793	kBtu / sq ft	Energy Efficiency	
				Hot	Indoor (Multi Tiers)	Lettuces				
				Cold	Greenhouse	Lettuces	14.1	kBtu / lb	Energy Productivity	
							22.1	kBtu / lb		
				Hot	Greenhouse	Lettuces	4.4	kBtu / lb		
							8.2	kBtu / lb		
				Cold	Indoor	Lettuces	11.05	kBtu / lb	Energy Productivity	
							11.12	kBtu / lb		
				Hot	Indoor	Lettuces	11.05	kBtu / lb		
							12.9	kBtu / lb		

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Source Name	Organization	Year	Primary Methods	Climate Zone	Facility Type	Crop	KPI Value	KPI Units	KPI Classification	Key for Visuals
Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods	School of Sustainable Engineering and the Built Environment Center for Environmental Security, The Biodesign Institute	2015	Modeled	2B	Greenhouse	Lettuces	8.4	lb / sq ft	Canopy Productivity	G
							2.4	gal / lb	Water Productivity	
							38.7	kBtu / lb	Energy Productivity	
				2B	Outdoor	Lettuces	0.8	lb / sq ft	Canopy Productivity	
							30	gal / lb	Water Productivity	
							0.5	kBtu / lb	Energy Productivity	
Energy optimisation of plant factories and greenhouses for different climatic conditions	University of Oxford, Department of Engineering Sciences, Michigan State University, Dept. of Community Sustainability	2021	Modeled	5A	Indoor	Multi	25.2	kBtu / lb	Energy Productivity	-
				5A	Greenhouse (Closed)	Multi	8.7	kBtu / lb	Energy Productivity	
					Greenhouse (Open)	Multi	6	kBtu / lb		

Source Name	Organization	Year	Primary Methods	Climate Zone	Facility Type	Crop	KPI Value	KPI Units	KPI Classification	Key for Visuals
Evaluating tomato production in open-field and high-tech greenhouse systems	Department of Biological Systems Engineering, Washington State University, Pullman, WA, United States	2022	Modeled	5B	Outdoor	Tomatoes	2.2	lb / sq ft	Canopy Productivity	-
							5.6	gal / lb	Water Productivity	
							0.02	kBtu / lb	Energy Productivity	
							0.05	lbs CO2e / lb	Emissions Productivity	
				4C	Greenhouse	Tomatoes	14.6	lb / sq ft	Canopy Productivity	
							3.8	gal / lb	Water Productivity	
							5.4	kBtu / lb	Energy Productivity	
							0.88	lbs CO2e / lb	Emissions Productivity	
				5B	Greenhouse	Tomatoes	12.3	lb / sq ft	Canopy Productivity	
							4.1	gal / lb	Water Productivity	
							4.7	kBtu / lb	Energy Productivity	
							0.86	lbs CO2e / lb	Emissions Productivity	
				5B	Greenhouse	Tomatoes	14.7	lb / sq ft	Canopy Productivity	
							4.5	gal / lb	Water Productivity	
							4.8	kBtu / lb	Energy Productivity	
							0.96	lbs CO2e / lb	Emissions Productivity	
Greenhouse Energy Profile Study	Posterity Group, Independent Electricity System Operator (IESO), Enbridge Gas Inc. (Enbridge), Ontario Greenhouse Vegetable Growers (OGVG)	2019	Mixed-Methods	Cold	Greenhouse	Vegetables	249	kBtu / sq ft	Energy Efficiency	D
							154	kBtu / sq ft		
						Ornamentals	204	kBtu / sq ft		
							139	kBtu / sq ft		

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Market Characterization of Indoor Agriculture (Non-Cannabis)	Emerging Products, Customer Service, Southern California Edison	2021	Mixed-Methods	-	Indoor	-	137-512	kBtu / sq ft	Energy Efficiency	C
Modeling resource consumption and carbon emissions associated with lettuce production in plant factories	School of Integrated Plant Sciences, Cornell University, College of Engineering, Systems Engineering, Cornell University	2023	Modeled	4A	Indoor	Lettuces	9.6-18.6	kBtu / lb	Energy Productivity	I
							0.2-1.2	gal / lb	Water Productivity	
							0.7-1.2	gal / lb	Water Productivity	
							0.6-3.9	lbs CO2e / lb	Emissions Productivity	
Optimizing Carbon Dioxide Concentration and Daily Light Integral Combination in a Multi-Level Electrically Lighted Lettuce Production System	University of Arizona	2018	Measured	2B	Indoor	Lettuces	22.4	kBtu / lb	Energy Productivity	F
							401.4	kBtu / sq ft	Energy Efficiency	
Plant factories versus greenhouses: Comparison of resource use efficiency	Delft University of Technology, Faculty of Architecture and the Built Environment Wageningen University & Research, Unit Greenhouse Horticulture	2018	Modeled	Cool	Indoor	Lettuces	616	kBtu / sq ft	Energy Efficiency	B
				Hot	Indoor	Lettuces	616	kBtu / sq ft	Energy Efficiency	
				Cool	Greenhouse	Lettuces	396	kBtu / sq ft	Energy Efficiency	
							418	kBtu / sq ft		
				Hot	Greenhouse	Lettuces	1145	kBtu / sq ft	Energy Efficiency	
				Cool	Indoor	Lettuces	602	kBtu / lb	Energy Productivity	
				Hot	Indoor	Lettuces	602	kBtu / lb	Energy Productivity	
				Cool	Greenhouse	Lettuces	967	kBtu / lb	Energy Productivity	
							903	kBtu / lb		
				Hot	Greenhouse	Lettuces	1397	kBtu / lb	Energy Productivity	

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Source Name	Organization	Year	Primary Methods	Climate Zone	Facility Type	Crop	KPI Value	KPI Units	KPI Classification	Key for Visuals
Plant factory: An indoor vertical farming system for efficient quality food production	Japan Plant Factory Association (NPO)	2020	Modeled	3A	Indoor	Leafy Greens	18.7	lb / sq ft	Canopy Productivity	-
							47	lb / sq ft		
Quantitative Information on Dutch Greenhouse Horticulture 2019	Wageningen University & Research, Wageningen Economic Research	2019	Census	-	Protection	Lettuces	0.6	lb / sq ft	Canopy Productivity	-
The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands	Delft University of Technology, Department of Architectural Engineering and Technology University of Florence, Department of Architecture	2022	Modeled	Cool	Indoor	Lettuces	8.2	lbs CO2e / lb	Emissions Productivity	-
							20.7	lb / sq ft	Canopy Productivity	
				Cool	Greenhouse (Soil)	Lettuces	1.2	lbs CO2e / lb	Emissions Productivity	
							5.9	lb / sq ft	Canopy Productivity	
				Cool	Greenhouse (Hydroponic)	Lettuces	1.5	lbs CO2e / lb	Emissions Productivity	
							10.9	lb / sq ft	Canopy Productivity	
				Cool	Outdoor	Lettuces	0.5	lbs CO2e / lb	Emissions Productivity	
							1.8	lb / sq ft	Canopy Productivity	
USDA NASS	USDA	Mixed	Census	-	Outdoor	Tomatoes	2.2	lb / sq ft	Canopy Productivity	-
USDA NASS						Lettuces	0.73	lb / sq ft		
USDA NASS						Herbs	0.11	lb / sq ft		

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