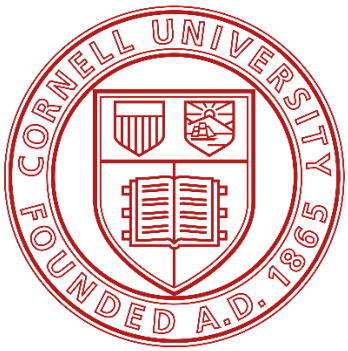
Controlled Environment Agriculture (CEA): A Strategic Industry Analysis



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Executive summary

Multiple food crises over the past two decades have exposed the vulnerability of food supplies to the vagaries of global forces including extreme weather events, conflicts, and pandemics.[1]

In just 2022 alone, inclement weather, higher than normal temperatures, drought, hurricanes, and heavy pest pressures severely disrupted fresh produce production in key agricultural regions including Florida, California, and Mexico, resulting in fresh produce prices increasing by 33%.[2]

With projections of increasingly frequent climatic shocks and the unpredictability of other major disruptive events, concerted efforts have been made to develop solutions to future-proof food supplies.[3][4][5]

To date, one of the most promising solutions is controlled environment agriculture (CEA), a form of agriculture where crops are grown in an indoors setting. CEA is not only able to address the vulnerability of conventional farming to climate change and other disrupting factors, but also allows for more localized crop production, providing a robust supply of fresh produce to feed local populations, especially in urban areas where densities are high.

However, given CEA's demonstrated commercial potential yet recent industry challenges, its viability as a long-term solution to food insecurity remains unclear. There is a need for

[1] IMF. (2022). Tackling the Global Food Crisis. https://www.imf.org/en/Publications/IMF-Notes/Issues/2022/09/27/Tackling-the-Global-Food-Crisis-Impact-Policy-Response-and-the-Role-of-the-IMF-523919.
[2] Davis, W. V. (2022). Vegetables and Pulses Outlook: December 2022. https://www.ers.usda.gov/webdocs/outlooks/105511/vgs-369.pdf?v=2679.

[3] De Winne, J., & Peersman, G. (2021). The adverse consequences of global harvest and weather disruptions on economic activity. Nature Climate Change, 11(8), Article 8. https://doi.org/10.1038/s41558-021-01102-w
[4] IPCC. (2012). Chapter 5: Food Security — Special Report on Climate Change and Land. https://www.ipcc.ch/srccl/chapter/chapter-5/.
[5] Konduri, V. S., Vandal, T. J., Ganguly, S., & Ganguly, A. R. (2020). Data Science for Weather Impacts on Crop Yield. Frontiers in Sustainable Food Systems, 4. https://www.frontiersin.org/articles/10.3389/fsufs.2020.00052.

clarification on the long-term viability of CEA before further decisions on investments into the sector can be made.

In this report, a strategic industry analysis of CEA was carried out by 1) Reviewing recent industry developments, 2) Considering the associated opportunities, and 3) Considering the associated risks and trade-offs.

Current data and trends regarding market size and growth, regional and domestic competition, demand, and public funding indicate high potential for growth in the CEA industry. However, being a relatively nascent industry, risks related to business complexity, long breakeven horizon, and sustainability are also high. Given these risks, entering the sector at its current stage does not seem particularly attractive. However, continued investments by public funding and higher-risk financing may help to reduce costs and improve sectoral expertise and profitability, and future opportunities for investment may emerge. In order for the financial attractiveness of CEA to improve, key factors to monitor would be potential reduction in initial infrastructure, energy, and labour costs.

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1. Industry Overview

1.1. CEA vs Conventional Farming

CEA addresses many of the potential problems faced by conventional farming such as vulnerability to extreme weather events and other food supply chain disruptions. However, there are also major disadvantages including high upfront costs of infrastructure and high energy usage and costs. The main advantages and disadvantages of CEA in comparison to conventional farming (CF) are discussed below and summarised in *Table 1*.

Advantages of CEA

Lower vulnerability to adverse environmental conditions: CEA has lower reliance and vulnerability to environmental conditions due to the indoor setting whereas in CF, crops are exposed and highly vulnerable to variable weather conditions.

Resource-use efficiency: The controlled environment of CEA allows for optimization of nutrients, water, and pesticides, improving resource-use efficiency and reducing costs – CEA is able to reduce water-use by up to 90% of what is usually used in CF. In addition, CF has higher exposure to pests and diseases, requiring greater use of pesticides. Nutrients and water loss to the open environment leads to less efficient resource-use and higher costs.[6]

Higher yields: CEA has higher yield per unit area due to smaller space and greater growing density – certain crops in CEA systems (especially vertical farming) may produce up to 100x the yield of CF for the same area. In addition, the optimization of conditions in CEA also

[6] Cowan, N., Ferrier, L., Spears, B., Drewer, J., Reay, D., & Skiba, U. (2022). CEA Systems: The Means to Achieve Future Food Security and Environmental Sustainability? Frontiers in Sustainable Food Systems, 6. https://www.frontiersin.org/articles/10.3389/fsufs.2022.891256.

facilitates higher yields. For CF, exposure to open environment also increases chances of crop damage.[7]

Year-round production: Being indoors and in a controlled environment, CEA is not subject to growing seasons. Year-round production not only increases yield, but also allows for strategic production to improve competitiveness and value of produce – crops can be grown during specific times of demand, even when not feasible for CF.[8]

Location flexibility: CEA facilities can be located in or near urban areas as they do not need cheap, arable land, allowing for less time between harvest and consumption, and therefore fresher produce and longer shelf-life. CEA also allows for domestic production, shortening supply chains and reducing vulnerability to external supply chain disruptions.[9]

Disadvantages of CEA

High initial setup costs: CEA requires significant infrastructure, technology, and R&D investments.[10]

Highly energy intensive: CEA is highly energy-intensive due to need for artificial lighting and temperature control.[11] However, energy efficiency can be significantly improved with scale.[12]

Table 1. Summary of comparison between CEA and Conventional Farming, advantages and disadvantages.

Factor	CEA	CF
Vulnerability to adverse environmental conditions	Low	High
Resource-use efficiency	High	Low

[7] Ibid.
[8] Ibid.
[9] Ibid.
[10] Ibid.
[11] Ibid.
[12] Agritecture LLC, & Way Beyond Ltd. (2021). 2021 Global CEA Census Report. https://engage.farmroad.io/hubfs/2021%20Global%20CEA%20Census%20Report.pdf.

Yields	High	Medium
Year-round production	Yes	No
Location flexibility	Yes	No
Costs	High	Low
Energy usage	High	Low

Overall, CEA has the potential to improve resource-use efficiency and yields, resilience against supply chain disruptions, and be situated closer to consumers, thereby providing fresher produce with longer shelf-life compared to conventional farming. However, high CapEx and OpEx, especially for high-tech vertical farming, are currently major roadblocks to financial feasibility.

1.2. Greenhouse vs Vertical Farming

The two most prevalent forms of CEA are greenhouses (GH) and vertical farming (VF). GH require more land and make use of natural sunlight with supplemental lighting, whereas VF are situated completely indoors, requiring artificial lighting for crop growing. Key differences between GH and VF are discussed below and outlined in *Table 2*.

Yield: VF has multi-layer production and therefore higher growing density, with c.6x the yield of GH.

Cost: GH has both lower CapEx and OpEx due to lower technology use and use of free, natural sunlight (with supplemental artificial lighting). VF has c.8.5x higher CapEx per sqft than GH due to use of automation and technology. Since VF is carried out in a completely enclosed space, complete artificial lighting has to be used all the time, leading to much higher OpEx than GH.

Location: GH requires c.4x more land space than VF and is usually located further out from urban areas where land cost is cheaper. While VF is able to be located in urban areas, land costs will be significantly higher as well.

Water use: GH have higher average water use of c.51 l/kg of produce, about 2x that of VF (20.4 l/kg of produce).

Energy use: GH have significant lower average energy use of c.5.4 kW/kg of produce, about 7x less than that of VF (38.8 kW/kg of produce).

Environmental control: GH have semi-controlled environments, which may not be suitable for areas of extreme climate or for highly sensitive crop types. VF is carried out in fully controlled and enclosed environment, which is suitable for areas with extreme climates and highly sensitive crop types. However, this comes with higher costs.

Table 2. Summary of comparison between greenhouses and vertical farming, advantages and disadvantages.

Factor	GH	VF
Yield	Lower	Higher
Costs	Lower	Higher
Location	Further out from urban areas	Closer to urban areas
Resource-use	Higher water use	Lower water use
	Lower energy use	Higher energy use
Environmental control	Semi-controlled environment	Fully controlled environment

In general, greenhouses are better suited for areas with more available, plentiful sunlight, and high-cost electricity, whereas vertical farms are more ideal for space-constrained areas with

limited access to freshwater, low-cost energy, and within proximity of higher-income populations which may have higher demand for fresh, locally grown produce.[13]

1.3. CEA by Location

These characterizations align with current CEA operations in the US. The top ten states for CEA by area under protection (sqft), number of operations, as well as production by weight, can be seen in *Table 3.* States including Pennsylvania, Ohio, New York, and California, rank consistently within the top ten for all categories, which may suggest more favourable conditions for CEA, and also aligns well with the expected value propositions of respective CEA options.

Indeed, while California is the nation's largest agriculture producing state, water scarcity is a huge problem, with agriculture irrigation taking up 80% of all water used for businesses and homes.[14] Given land availability and favourable climate, greenhouses are a good option to help reduce water use while leveraging upon the plentiful, natural sunlight.

For Pennsylvania, New York, and Ohio (and other Midwestern/Northeastern states where applicable), CEA addresses the problems of limited arable land, unfavourable weather, and short growing season, as well as increased demand for premium and local food from potentially higher-income populations.[15]

Table 3. Top ten states for CEA by area under protection, no. of operations, and production by weight

Rank	Area under protection (sqft)	No. of operations	Production by weight
1	California	Pennsylvania	California
2	Texas	Michigan	Texas
3	Michigan	Ohio	Tennessee
4	New York	Missouri	Ohio
5	Ohio	Florida	Pennsylvania

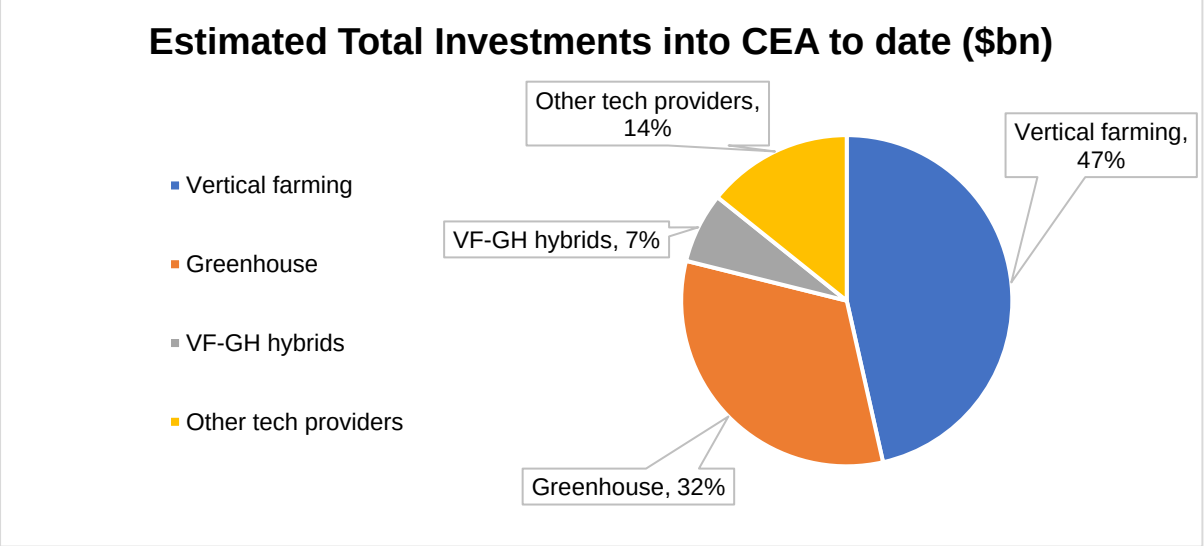
[13] iFarm. (2021a). Vertical Farms vs Greenhouses – The First Consideration: Location. https://ifarm.fi/blog/2021/02/vertical-farms-vs-greenhouses.
[14] PPIC. (2023). Water Use in California. Public Policy Institute of California. https://www.ppic.org/publication/water-use-in-california/.
[15] iFarm. (2021a).

6	Florida	Indiana	Colorado
7	Pennsylvania	New York	New York
8	Utah	North Carolina	Virginia
9	Colorado	Wisconsin	Kentucky
10	Minnesota	California	Arizona

1.4. Investments in CEA

Greenhouses have existed for decades and have been proven to be commercially viable, typically utilizing lower-tech and taking advantage of free, natural sunlight. Meanwhile, the interest in and development of vertical farm technologies has only been a relatively recent phenomenon, with many startups entering the scene offering high-tech, innovative solutions to improve efficiency and increase yields in a fully controlled environment.[16] Indeed, the CEA space has attracted huge amounts of investments in recent years, with an estimated $7.1bn in funds raised to date. 86% ($6.1bn) of that has gone to farm operators, of which 55% ($3.3bn) has gone to vertical farm operators, 37% ($2.3bn) to greenhouse operators, and 8% ($488m) to hybrid vertical farm-greenhouse operators (*Figure 1*).[17]

Figure 1. Breakdown of Total Investments into CEA by CEA type.



[16] Agritecture LLC. (2019). Growing More With Less: The Past, Present, and Future of Greenhouses (Part 2). Agritecture. https://www.agritecture.com/blog/2019/5/13/growing-more-with-less-part-2.
[17] Stephens, R. (2022). The Influx of CEA Investment: Where Has the Money Gone? Agritecture. https://www.agritecture.com/blog/2022/12/5/the-influx-of-cea-investment-where-has-the-money-gone.

Of the $7.1bn, 75% ($5.3bn) has gone towards just a handful of companies, including Plenty, Bowery Farming, AppHarvest, InFarm, Soli Organics, Gotham Greens, Little Leaf Farms, Local Bounti, Pure Harvest, 80 Acres Farms, and AeroFarms. Recent transactions are detailed in *Table 4* below.

Table 4. Recent investments into CEA companies and startups.

CEA	Investors	Funding	Date	Description
Babylon Micro-Farms[18]	• Venture South • Virginia Venture Partners • Hull Street Capital • New Theory Ventures	$8m Series A	Apr 2023	• Remotely managed vertical farming.
Local Bounti[19]	• Cargill Financial Services • Internally-managed net-lease real estate investment trust	$145m credit facility and sale-leaseback	Mar 2023	• Hybrid VF-GH • Expansion of facilities in Georgia, Texas, and Washington. • Sale-leaseback of facilities in California.
Plenty[20]	• Realty Income	Up to $1bn real estate deal	Feb 2023	• Real estate deal for investments into indoor farm space, which will be leased by Plenty.
AppHarvest[21]	• Mastronardi Produce • COFRA Holding	$127m sale-leaseback	Dec 2022	• High-tech indoor farm
Soli Organic	• CDPQ • Movendo Capital • Cascade Asset Management • S2G Ventures	$125m Series D	Oct 2022	• Soil-based vertical farms, organic herbs • Expand production with eight new farms in addition to current

[18] Marston, J. (2023, April 3). Babylon Micro-Farms: "Bigger doesn't mean better in vertical farming." AFN. https://agfundernews.com/babylon-micro-farms-lands-8m-series-a-bigger-does-not-necessarily-mean-better-in-vertical-farming.

[19] Manning, C. (2023). Local Bounti secures up to $145 million in financing. Produce Grower. https://producegrower.com/news/local-bounti-145-million-financing/.

[20] Marston, J. (2023a, February 23). Plenty lands partnership with "up to $1bn" for vertical farm development. AFN. https://agfundernews.com/plenty-lands-real-estate-deal-to-secure-up-to-1bn-for-vertical-farm-development-starting-with-strawberries.

[21] AppHarvest. (2022). AppHarvest completes deal with Mastronardi Berea LLC for $127 million sale-leaseback of Berea. Ky., farm and opens Richmond, Ky., 60-acre high-tech indoor farm achieving goal to quadruple number of operating farms in 2022 | AppHarvest. https://investors.appharvest.com/news-releases/news-release-details/appharvest-completes-deal-mastronardi-berea-llc-127-million-sale/.

				seven operational ones.
Gotham Greens[22]	• BMO Impact Investment Fund (IIF) • Ares Management • Commonfund • RockCreek • Kimco Realty • Mana Tree Partners • The Silverman Group	$310m Series E	Sep 2022	• High-tech hydroponic greenhouse, leafy greens. • Expansion of facilities, with projects in Texas, Atlanta, Colorado. • Partnerships with Whole Foods, Kroger, Albertsons, Amazon Fresh, etc.
Little Leaf Farms[23]	• The Rise Fund, TPG • BoA	$300m debt and equity	Jun 2022	• Expansion of greenhouse in Pennsylvania, leafy greens. • High-tech, hydroponic greenhouse, using rainwater and solar energy • No pesticides, herbicides, fungicides
Mucci Farms[24]	• Cox Enterprises	Significant strategic investment, undisclosed	Jun 2022	• Ontario-based high-tech greenhouse • Tomatoes, peppers, cucumbers, leafy greens, berries
Pure Harvest Smart Farms[25]	• Metric Capital Partners • IMM Investment Corp • Olayan Group	$180.5m	Jun 2022	• UAE-based high-tech hybrid farms. • Expansion in Middle East and Asia

[22] Gotham Greens, G. (2022, September 12). Gotham Greens Raises $310 Million in Fresh Funding To Accelerate National Greenhouse Expansion. GlobeNewswire News Room. https://www.globenewswire.com/en/news-release/2022/09/12/2513846/0/en/Gotham-Greens-Raises-310-Million-in-Fresh-Funding-To-Accelerate-National-Greenhouse-Expansion.html.

[23] Bank of America. (2022). Little Leaf Farms Raises $300 Million in Capital with Financing from TPG's The Rise Fund and Bank of America. Bank of America. https://newsroom.bankofamerica.com/content/newsroom/press-releases/2022/06/little-leaf-farms-raises--300-million-in-capital-with-financing-.html.

[24] Cox Enterprises. (2022). Cox Makes Strategic Investment in Controlled Environment Agriculture Company Mucci Farms. https://www.prnewswire.com/news-releases/cox-makes-strategic-investment-in-controlled-environment-agriculture-company-mucci-farms-301560651.html.

[25] Business Wire. (2022, June 30). Pure Harvest Smart Farms Secures USD $180.5 Million From Global Investors to Fund Expansion. https://www.businesswire.com/news/home/20220630005406/en/Pure-Harvest-Smart-Farms-Secures-USD-180.5-Million-From-Global-Investors-to-Fund-Expansion.

Plenty[26]	• Walmart • SoftBank • One Madison Group	$400m Series E	Jan 2022	• Vertical farming of leafy greens • Commercial supply agreement with Walmart
Bowery Farming[27]	• KKR	$150m credit facility	Jan 2022	• New farms in Atlanta and Texas, 100% renewables-powered. • Partnership with Wakefern
Dream Harvest Farming Company[28]	• Orion Energy Partners	$50m	Dec 2021	• Scale production with new facility in Houston • Wind energy-powered vertical farming • Leafy greens and herbs
InFarm[29]	• Qatar Investment Authority (QIA) •	$200m Series D	Dec 2021	• Europe-based vertical farming • Growing centre in Qatar targeting strawberries and tomatoes.
Iron Ox[30]	• Breakthrough Energy Venture • Crosslink capital • R7 Partners • Pathbreaker Ventures • Amplify Partners • Y Combinator	$50m Series C	Sep 2021	• Autonomous farming, robotics greenhouse • Construction of new farm in Texas • Leafy greens, berries, herbs
80 Acres Farms[31]	• General Atlantic	$160m Series B	Aug 2021	• Expansion of vertical farms

[26] Leigh Lore, K. (2023, January 25). Plenty partners with Walmart, secures $400M in funding. The Packer. https://www.thepacker.com/news/industry/plenty-partners-walmart-secures-400m-funding.

[27] Bowery Farming. (2022). Bowery Farming Secures $150 Million Credit Facility Led by KKR to Accelerate Growth. https://www.prnewswire.com/news-releases/bowery-farming-secures-150-million-credit-facility-led-by-kkr-to-accelerate-growth-301458918.html.

[28] Mistretta, A. J. (2023, May 31). Houston Indoor Farming Co. Secures $50M for Expanded Facility. https://www.houston.org/news/houston-indoor-farming-co-secures-50m-expanded-facility.

[29] Heater, B. (2021). Vertical farming startup Infarm raises $200M for international expansion | TechCrunch. https://techcrunch.com/2021/12/16/vertical-farming-startup-infarm-raises-200m-for-international-expansion/.

[30] Marston, J. (2021, September 22). Iron Ox raises $50m in Breakthrough Energy-led Series C round. AFN. https://agfundernews.com/iron-ox-raises-50m-in-breakthrough-energy-led-series-c-round.

[31] 80 Acres Farm. (2021). 80 Acres Farms Secures $160 Million in Series B Led by General Atlantic to Accelerate Global Farm Expansion & Product Development. General Atlantic. https://www.generalatlantic.com/media-article/80-acres-farms-secures-160-million-in-series-b-led-by-general-atlantic-to-accelerate-global-farm-expansion-product-development/.

	• Siemens Financial Services • Blue Earth • Barclays • Taurus			• Leafy greens, herbs, tomatoes, cucumbers, microgreens. • Partnership with Kroger
Pure Green Farms[32]	• Taylor Farms	Undisclosed	Aug 2021	• High-tech greenhouse • Leafy greens
Controlled Environment Foods Fund II, Equilibrium Capital[33]	• San Francisco Employees Retirement System • AP4 • Development Bank of Japan	$1.022bn	Jul 2021	• Investments in greenhouse facilities/operators, e.g. AppHarvest, Revol Greens, Fresh Farms, Houweling Group
Bowery Farming[34]	• Fidelity • GGV Capital • Temasek • Groupe Artemis	$300m Series C	May 2021	• High-tech vertical farming

However, over the last two years, the economic viability of CEA, especially high-tech vertical faming, has been subject to scrutiny. Multiple players in the sector have ran into financial difficulties and have either ceased operations or been forced to adopt drastic cost-cutting measures.[3536] Key challenges primarily relate to the mismatch between investor expectations and the ability of CEA to generate quick returns – the production of low-value crops such as leafy-greens do not generate sufficiently high enough revenues to comfortably offset the high costs of infrastructure and operations.[37] Indeed, c.90% of funding to farm operators ($5.49bn) have gone towards those growing leafy greens. In addition, CEA's huge consumption of energy

[32] Taylor Farms. (2021). Taylor Farms Announces Investment with Pure Green Farms—Taylor Farms. https://www.taylorfarms.com/newsroom/taylor-farms-announces-investment-with-pure-green-farms/.
[33] Equilibrium. (2021, July 7). Amid record heat, Equilibrium Capital raises $1 billion for second greenhouse fund » Equilibrium. Equilibrium. https://eq-cap.com/amid-record-heat-equilibrium-capital-raises-1-billion-for-second-greenhouse-fund/.
[34] Bowery Farming. (2021). Bowery Farming Secures $300 Million in Series C Funding to Accelerate Growth. https://www.prnewswire.com/news-releases/bowery-farming-secures-300-million-in-series-c-funding-to-accelerate-growth-301298237.html.
[35] Peters, A. (2023). Vertical farms tried to grow lettuce indoors. Now many are failing. https://www.fastcompany.com/90824702/vertical-farming-failing-profitable-appharvest-aerofarms-bowery.
[36] Sowder, A. (2023, April 5). Vertical farmer Kalera files for Chapter 11 bankruptcy. AgWeb. https://www.agweb.com/news/business/technology/vertical-farmer-kalera-files-chapter-11-bankruptcy.
[37] Peters, A. (2023).

also makes it highly vulnerable to energy price shocks, especially in Europe, which has been hit hard by the energy crisis stemming from the Russia-Ukraine conflict.[38]

Nonetheless, with the looming threat of climate change and other disrupting factors, there remains an urgent need to safeguard national food supply chains. CEA seems to be a promising solution that presents potentially attractive opportunities if approached with cautious optimism. Here, we identify opportunities in the sector by evaluating the market size, competitive forces, demand, and public funding.

[38] Vertical Farm Daily. (2023). Future Crops declared bankrupt: All equipment in online auction at Troostwijk Auctions. https://www.verticalfarmdaily.com/article/9518097/future-crops-declared-bankrupt-all-equipment-in-online-auction-at-troostwijk-auctions/.

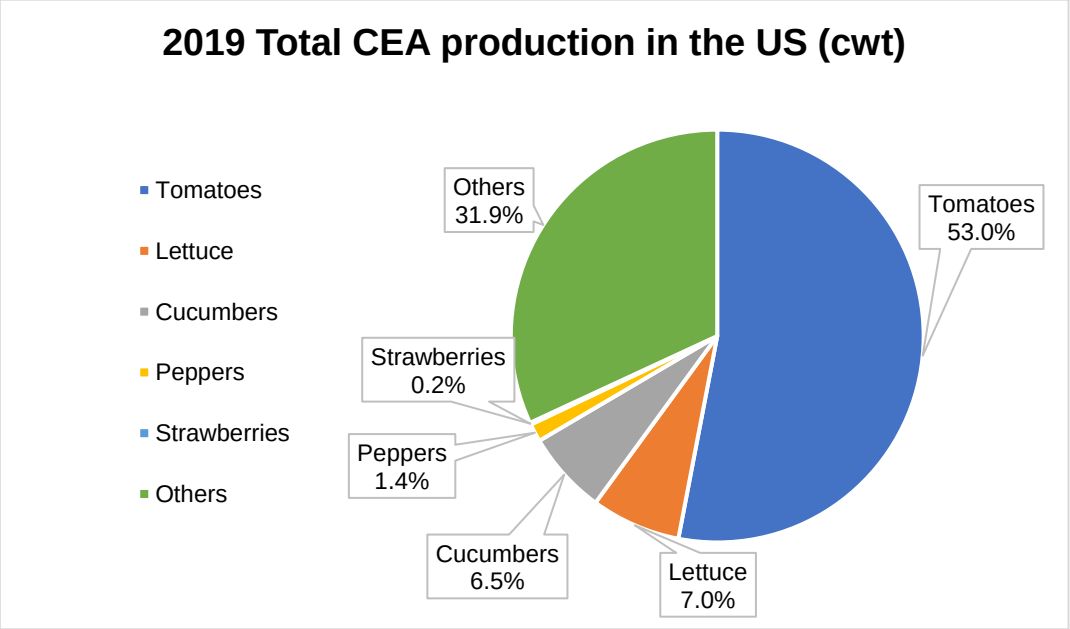
2. Industry Analysis – Opportunities and Attractiveness

2.1. Market Size

Given CEA's crop specificity and value proposition of providing fresh, localized produce (in particular vertical farming), to determine market sizes, we need to first identify specific crops of interest.

Out of total CEA production in the US, the most widely grown crops are tomatoes, lettuce, cucumbers, peppers, and strawberries (*Figure 2*).[39] Taking this as indication of their demonstrated economic and operational feasibility, we therefore focus on these crops.

Figure 2. CEA production (cwt) in the US by crop type



Comparing the US CEA production to the total US production by weight, it is clear that for the top CEA crops, CEA currently only contributes a very small proportion to total production

[39] USDA. (2019). 2019 Census of Horticultural Specialties. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Census_of_Horticulture_Specialties/index.php.

(*Table 5*). In anticipation of further disruptions to conventional farming production of crops, there seem to be ample opportunities for CEA production to gain market share.[40][41]

Table 5. US Total and CEA production of select crops by weight.

Crop	Total US production, cwt[42][43]	US CEA production, cwt	CEA % of Total
Tomatoes	17,852,679	4,165,635	23.3%
Lettuce	31,682,143	551,716	1.7%
Cucumber	3,817,857	510,300	13.4%
Peppers	9,427,679	110,739	1.2%
Strawberries	19,148,929	11,792	0.1%

In terms of value, much CEA produce, especially cucumbers, tomatoes, and lettuce, seems to be priced at a premium compared to non-CEA produce – CEA production has a higher % against total US production for value than for weight (*Tables 5 & 6*).

Table 6. US Total and CEA production of select crops by value.

Crop	Total US production value ($)	US CEA production value ($)	CEA % of Total
Tomatoes	885,492,857	345,025,000	39.0%
Lettuce	1,222,613,893	71,129,000	5.8%
Cucumber	112,245,000	45,691,000	40.7%
Peppers	440,272,589	8,577,000	1.9%
Strawberries	6,127,657,388	937,000	0.02%
Total	**8,788,281,727**	**471,359,000**	

Overall, there is a sizeable market for CEA produce, with the top CEA crops having a combined market annual sales value of $471.4m.

[40] Maureira, F., Rajagopalan, K., & Stöckle, C. O. (2022). Evaluating tomato production in open-field and high-tech greenhouse systems. Journal of Cleaner Production, 337, 130459. https://doi.org/10.1016/j.jclepro.2022.130459.

[41] Huang, K.-M., Guan, Z., & Hammami, A. (2022). The U.S. Fresh Fruit and Vegetable Industry: An Overview of Production and Trade. Agriculture, 12(10), Article 10. https://doi.org/10.3390/agriculture12101719.

[42] USDA. (2022). USDA ERS - Vegetables and Pulses Yearbook Tables. https://www.ers.usda.gov/data-products/vegetables-and-pulses-data/vegetables-and-pulses-yearbook-tables/.

[43] USDA. (2019).

2.2. Regional Competition

The feasibility of CEA in the US has to be considered against the backdrop of having major agriculture-producing competitors, Mexico and Canada, at its doorstep. Mexico is able to produce cheaper produce due to cheaper costs and more favourable weather down south, while Canada has more experienced and established CEA operations.[44] Over the past two decades, the volume of fresh vegetables imported primarily from Mexico and Canada has increased by c.200%.[45] As a result, in order for domestic CEA production to be feasible, it has to be competitive against imported produce from Mexico and Canada.

The US is a net importer of all top CEA crops from Mexico (*Table 7*).[46] However, Mexican produce is usually associated with lower and inconsistent quality. Meanwhile, for Canada, the US is a net exporter of cherry tomatoes and lettuce, but a net importer of cucumbers and peppers (*Table 7*). The main advantages of Canadian CEA are its expertise, high yields, and consistent quality. However, the lack of production during the winter in Canada is a major drawback, and may be a potential opportunity for domestic CEA production.[47]

Overall, a big reason for continued growing imports from Mexico and Canada stems from domestic production lagging increased US consumer demand for consistent and year-round availability of produce.[48] In terms of regional competition, there is a an opportunity for domestic expansion of the CEA industry to fulfil local demand.

[44] Lensing, C. (2018). Controlled Environment Agriculture: Farming for the Future? https://www.cobank.com/documents/7714906/7715347/Controlled-Environment-Agriculture-Report-May2018.pdf/d682de5f-7dd7-dcc9-2592-c80e9fd1a361?t=1607459642605.
[45] Davis, W. V. (2022). Vegetables and Pulses Outlook: December 2022. https://www.ers.usda.gov/webdocs/outlooks/105511/vgs-369.pdf?v=2679.
[46] USDA. (2023). USDA ERS - Vegetables and Pulses Data. https://www.ers.usda.gov/data-products/vegetables-and-pulses-data/.
[47] Lensing, C. (2018).
[48] Davis, W. V. (2022).

Table 7. Imports and Exports of CEA produce from and to main regional competitors, Mexico and Canada.

Crop	Mexico		Canada	
	Imports, 1,000 lbs	Exports, 1,000 lbs	Imports, 1,000 lbs	Exports, 1,000 lbs
Cherry tomatoes	20,633	778	2,951	9,554
Lettuce	1,032,144	99,999	80,529	548,884
Cucumbers	1,869,670	53	484,529	30,730
Peppers	1,405,537	4,192	334,405	90,149
Strawberries	551,806	50,804	9,715	200,253

2.3. Domestic Competitive Landscape

The CEA industry can be categorised into three main groups: Low to medium-tech greenhouses, medium to high-tech greenhouses, and high-tech vertical farming (*Figure 3*).

Many players have entered the CEA industry over the past few years and received huge amounts of funding, especially for those offering high-tech propositions. However, the high-tech vertical farming sector has since undergone a consolidation phase, where bigger players who have been able to achieve economies of scale and who have been able to secure partnerships with large distributors are performing better than others. The amount of investments into vertical farming has also fallen drastically after 2021. Instead, most funding after 2021 has either gone towards greenhouse companies or the larger vertical farming players (*Table 4*). Indeed, now there seems to be a general consensus amongst CEA experts, that vertical farming may not be the most viable option due to high costs and low margin.[49][50][51][52]

The low to medium-tech greenhouse category is currently dominated by several major players including Houweling's, Sunset Farms, NatureSweet, and Intergrow Greenhouses. They mostly

[49] Associate, Spring Lane Capital [Personal Interview, February 10, 2023].
[50] Vice President of Operations, IUNU [Personal Interview, April 13, 2023].
[51] CEO, A large CEA company [Personal Interview, April 14, 2023].
[52] Co-founder, A CEA company [Personal Interview, April 19, 2023].

focus on growing more traditional and established crops like tomatoes, cucumbers, and peppers.[53] Opportunities to enter this space is limited.[54]

Finally, the medium to high-tech greenhouse category has seen many new entrants exploring less traditional CEA crops, especially leafy greens. The category is currently still rather fragmented, with players trying to establish themselves across various geographies. Crop-wise, many new players are focusing on growing leafy greens instead of tomatoes, as it is less saturated and may fetch higher margins. In this regard, there may be opportunities to achieve higher margins with crops other than tomatoes.[55][56]

Figure 3. Main CEA players by technology

2.4. *Demand and Market Growth*

Demand for CEA produce is expected to grow along with population growth and increased urbanisation, increasing preference for local and fresh produce, and disruptions to conventional farming.

[53] Curran, J. (2023). Industry at a Glance—OD4012 Hydroponic Crop Farming in the US - MyIBISWorld. https://my-ibisworld-com.proxy.library.cornell.edu/us/en/industry-specialized/od4012/industry-at-a-glance.
[54] CEO, A large CEA company [Personal Interview, April 14, 2023].
[55] Ibid.
[56] Co-founder, A CEA company [Personal Interview, April 19, 2023].

According to the Congressional Budget Office (CBO), the US population is expected to increase by 10% from 336m in 2023 to 373m in 2042.[57]

There also seems to be relatively high demand for fresh, locally produced vegetables, where affordable and available. A survey carried out last year on fresh produce (with 1,899 18+ Internet users) found that majority of respondents would pay more for locally-grown produce.[58] A similar study done in 2021 (with 1,904 18+ Internet users) also found that freshness of produce was the top priority for 76% of respondents, followed by price (58%).[59]

Finally, climate change is expected to be a major disruptor of fresh produce supply over the next few years. For the 2022-2023 season, Florida's orange production is forecasted to decrease by 32% from previous year due to warmer weather and hurricanes, while California's tomato production is forecasted to be down by 10% due to drought.[60] Over the next thirty years, global open-field tomato production is also expected to drop by 6% due to impacts of climate change.[61]

2.5. Distribution Channels and Supply-Demand Gap

Identifying and establishing appropriate sales and distribution channels early on is essential to ensure that supply is supported by demand. Currently, the four main types of distribution/sales channels are: 1) Retail, 2) Restaurants, 3) Institutions, and 4) Wholesale Distributors. Securing retail partnerships, where possible, is suggested to be the most profitable route as retailers are not only willing to pay a premium for fresher, locally-grown produce, but are able to guarantee

[57] CBO. (2023, January 24). The Demographic Outlook: 2023 to 2053 | Congressional Budget Office. https://www.cbo.gov/publication/58612.
[58] Mintel. (2022). US Produce 2022.
[59] Mintel. (2021). US Produce 2021.
[60] Nowell, C. (2022). Waterlogged wheat, rotting oranges: Five crops devastated by a year of extreme weather | Drought | The Guardian. https://www.theguardian.com/environment/2022/nov/01/climate-crisis-us-food-system-five-crops.
[61] Cammarano, D., Jamshidi, S., Hoogenboom, G., Ruane, A. C., Niyogi, D., & Ronga, D. (2022). Processing tomato production is expected to decrease by 2050 due to the projected increase in temperature. Nature Food, 3(6), Article 6. https://doi.org/10.1038/s43016-022-00521-y.

large scale, consistent orders. Restaurants, on the other hand, are often inconsistent and unreliable partners who may cancel orders at the last minute, while institutions such as schools and hospitals do not provide as much profitability or scale as retail. Wholesale distributors provide the lowest profitability although they are able to purchase at scale. As seen in *Table 4*, many larger, more successful CEA players have been able to secure partnerships with major retailers and distributors including Krogers, Walmart, Whole Foods, Albertsons, and Amazon Fresh. In addition, surveys of produce buyers indicate willingness to purchase CEA produce at a premium of up to 10%, but some current challenges are the lack of suppliers in the region as well as the lack of relationships with CEA producers. There are therefore seems to be opportunities in terms of filling the retail supply-demand gap, as well as in securing partnerships with high-margin retailers as main sales and distribution channels.

2.6. Public Funding

Public funding is an important indicator of government priorities. Decision-making on public funding and policies are also often supported by rigorous research and consultations since they involve the use of taxpayers' money.

With regard to CEA, there seems to have been substantial amounts of federal and state funding into the sector post-2021. Three main federal agencies funding projects relevant to CEA are the National Institute of Food and Agriculture (NIFA)[62], the Agricultural Marketing Services (AMS)[63], and the USDA Partnerships for Climate-Smart Commodities.[64] Together they have put in at least $33.4m into funding CEA projects since 2022.

[62] NIFA USDA. (2023, February 9). NIFA Invests $70M in Sustainable Agricultural Research. National Institute of Food and Agriculture. http://www.nifa.usda.gov/about-nifa/press-releases/nifa-invests-70m-sustainable-agricultural-research.
[63] AMS USDA. (2022). Specialty Crop Block Grant Program | Agricultural Marketing Service. https://www.ams.usda.gov/services/grants/scbgp.
[64] USDA. (2022a). Partnerships for Climate-Smart Commodities. https://www.usda.gov/climate-solutions/climate-smart-commodities.

At state level, states including Virginia, Wyoming, and New York seem to have taken more interest in CEA than others, providing state funding for projects in the sector. In 2021, New York City established an Office for Urban Agriculture to oversee projects to address local food security and needs. Virginia has also been highly proactive in the CEA space, having partnered with Beanstalk Farms, Aerofarms, and Plenty to launch new CEA operations in the commonwealth.[65] Recent public funding in CEA at federal and state-levels can be seen in *Table 7*.

Table 8. Public funding in CEA at federal and state levels

Organization	Funding Amount	Date	Description
Federal-level			
NIFA Agriculture and Food Research Initiative (AFRI)	10m grant	Apr 2023	Clemson University project to develop an integrated hydroponics CEA platform for cultivation of salt-tolerant food crops using saline irrigation water by enhancing crop salt tolerance, developing new concepts in agricultural-sector desalting technologies, and optimizing salinity management.[66]
	$9.95m grant	Feb 2023	Grant for Auburn University project to reduce the demand for heating and cooling in CEA food-production environments, improve the overall efficiency of CEA climate-controlled environments, lower the carbon intensity of resource inputs, and shift consumer and producer behavior

[65] VDACS. (2023). Governor Glenn Youngkin Proclaims March as Virginia Controlled Environment Agriculture Month. Virginia Department of Agriculture and Consumer Services. https://www.vdacs.virginia.gov/press-releases-230302-controled-ag-month.shtml.

[66] NIFA. (2023). A Controlled Environment Agriculture Platform For Cultivation Of Salt-Tolerant Crops With Integrated Saline Water Irrigation And Salinity Management. https://cris.nifa.usda.gov/cgi-bin/starfinder/0?path=fastlink1.txt&id=anon&pass=&search=R=98248&format=WEBFMT6NT.

			surrounding CEA products and practices.[67]
AMS Specialty Crop Block Grant Program (SCBGP) [68]	$358k grant	Aug 2022	The University of Arkansas System Division of Agriculture will evaluate and develop spinach and arugula cultivars with high nutritional components and disease and pest tolerance suitable for sustainable open vegetable cultivation in Arkansas and other states under indoor/hydroponics.
	$614k in grant		Virginia Tech will evaluate the agronomic performance of 56 pepper cultivars grown in hydroponics under LED lights in a controlled environment. The researchers will also develop a protocol for measuring the aromatic flavor of pepper fruits and establish a breeding population to select new snacking pepper cultivars with compact plant size, early flowering, and improved fruit flavor. Developing snacking pepper cultivars suitable for vertical farming will make the snacking pepper become a new cash crop and create new job opportunities in Virginia.
	$1.37m		Twin Cities Berry Company LLC, a research and production farm, will be developing climate resilient practices for high-density strawberry production within protected culture structures,

[67] NIFA. (2023b). Reimagining Controlled Environment Agriculture In A Low Carbon World. https://cris.nifa.usda.gov/cgi-bin/starfinder/0?path=fastlink1.txt&id=anon&pass=&search=R=98242&format=WEBFMT6NT.

[68] AMS USDA. (2022b). Specialty Crop Block Grant Program Fiscal Year 2022 Description of Funded Projects – Farm Bill. https://www.ams.usda.gov/sites/default/files/media/SCBGPDescriptionofFunds2022.pdf.

			allowing new and emerging farmers to overcome spatial and environmental hurdles to financial sustainability.
	$1.44m		The University of Georgia Research Foundation will develop best management practices for the protected culture of water spinach using greenhouse hydroponic methods and in-ground high tunnel production.
USDA Partnerships for Climate-Smart Commodities	$5m	2022	The Coalition for Food Security (CFS) plans to implement climate-smart practices related to indoor hydroponic vertical farming and optimize environmental climate control management to create a voluntary climate-smart produce marketplace.
	$4.7m		Project participants would use innovative technology to convert crop residue into two high-value fertilizers for soil, foliar, or hydroponic use, and market resulting climate-smart commodities.
State-level			
Virginia Governor's Agriculture and Forestry Industries Development Fund[69]	$200k	Apr 2023	Grant for Better Future Farms to build a hydroponic greenhouse and processing facility in Louisa County.
Wyoming Business Council	$20m grant	Feb 2023	Grant to support development of the world's largest and most advanced vertical farming research center in Laramie.
New York Power Authority (NYPA)[70]	$250k	Nov 2022	Part of a multi-state demonstration funded by the New York Power Authority and led by energy R&D

[69] Area Development News. (2023, April 6). Better Future Farms Plans Louisa County, Virginia, Hydroponic Greenhouse-Processing Facility. Area Development. https://www.areadevelopment.com/newsitems/4-6-2023/better-future-farms-louisa-county-virginia.shtml.

[70] New York State. (2022a). Governor Hochul Announces Indoor Food Production System to Advance Urban Farming in Harlem | Governor Kathy Hochul. https://www.governor.ny.gov/news/governor-hochul-announces-indoor-food-production-system-advance-urban-farming-harlem.

			institute EPRI, the indoor farming pilot project in Harlem will increase the year-round availability of fresh fruits and vegetables for local underserved families and further national research about optimal indoor growing conditions and crop production. Harlem Grown, a local non-profit, will manage the food production and support distribution to the community. The project will also investigate how to increase yields and manage resources, while reducing associated greenhouse gas emissions and water consumption. The project helps advance the goals of the Climate Leadership and Community Protection Act, which requires New York to reduce its greenhouse gas emissions by 40 percent before 2030 and by no less than 85 percent by 2050.
Virginia Governor's Agriculture and Forestry Industries Development Fund[71]	$40k	Apr 2022	Grant for Area 2 Farms to build a new indoors farm in Arlington.

Taken together, the effects of a growing population, increasing demand for fresh and local produce, declines in open-field crop production, and public funding, may be indicative of the CEA market's growth potential.

[71] Area Development News. (2022, April 19). Area 2 Farms Plans Arlington County, Virginia, Organic Indoor Farm. Area Development. https://www.areadevelopment.com/newsitems/4-19-2022/area-2-farms-arlington-county-virginia.shtml.

3. Industry Analysis – Risks and Trade-offs

The attractiveness of the CEA market has to be weighed against potential risks and trade-offs, including business complexity, long return-horizon, and sustainability.

3.1. Business Complexity

CEA, both greenhouses and vertical farming, are extremely complex businesses that require extensive expertise, from development to operations, sales and distribution, to achieve success. Consequences for the lack of CEA expertise are evident in the failure of many companies including AppHarvest and Fifth Season. On the other hand, it has allowed major players to consolidate their position and dominate the market.

The development stage is particularly important as it determines and therefore requires consideration of many downstream factors including cost of operations, types of crops, consumer demand/preferences, and distance to distributors. Many operational issues including the optimal type of equipment, level of automation, and risks associated with labour, are also oftentimes difficult to anticipate without prior knowledge. In addition, many operational considerations tend to change at different scales, adding another layer of complexity – lessons learned at a smaller scale may not always be applicable at larger scales.[72]

Acquiring expertise in CEA requires years of cumulative experience and this process is certainly not helped by the lack of knowledge-sharing amongst players in the country due to fierce competition within a nascent industry. To address this shortfall in CEA expertise, many Dutch consultants have been brought in to share learnings from The Netherlands. Going forward, it is advised to work with experienced and reputable developers, builders, and growers in order to maximize the chances of success in CEA.

[72] Agritecture LLC (Director). (2017, April 3). Aglanta Panel: An Examination of Shuttered Vertical Farming Facilities. https://www.youtube.com/watch?v=1mB_8TE-t2E.

3.2. Long Breakeven Horizon

Many CEA failures have been attributed to the misalignment between investor returns expectations with reality – companies and investors have been overly optimistic about reaping quick returns in an industry which turned out to have a rather long breakeven horizon. Given the high costs of infrastructure and operations, and the relatively low margin of growing established crops, the current breakeven period for CEA is estimated to be at least 15 years (annualized returns of 6.67%).

Growing higher-margin crops may help to shorten the breakeven period but this comes with associated risks of entering unchartered territories such as crop failures due to limited operational know-how.

There is also the challenge of balancing between the need for scale to achieve higher returns, against not scaling up too quickly should production not be able to meet demand or vice versa. However, it is worth noting that larger scale facilities are able to achieve significantly higher energy and cost efficiencies due to more favorable production to greenhouse surface area ratio and lower energy loss rates per unit of operable bedspace.[73]

From a return on investment perspective, CEA is a sector which presents plenty of opportunities provided a long investment horizon. In addition, key factors that would improve the financial attractiveness of CEA are lower initial infrastructure costs, lower energy costs, and lower labour costs.

3.3. Sustainability

Although CEA has the potential to address food insecurity, its long-term viability is also dependent upon its alignment to other global, national, and state priorities, especially in terms

[73] Agritecture LLC, & Way Beyond Ltd. (2021). 2021 Global CEA Census Report. https://engage.farmroad.io/hubfs/2021%20Global%20CEA%20Census%20Report.pdf.

of carbon emissions. The current national goal is to achieve a net-zero emissions economy by 2050, and more regulations are expected to be developed over the upcoming years to reduce carbon emissions. In order for CEA to be viable in the long-term, it needs to be environmentally sustainable as well.

CEA is often perceived as being more sustainable compared to conventional farming. While this may be true for certain aspects of sustainability, including land-use, water-use, and food miles, the total carbon footprint for conventional farming remains significantly lower compared to all CEA types. This is primarily due to the huge energy inputs required for CEA operations. Although this problem may be offset through the use of renewable energy, the additional costs to infrastructure may not be feasible and requires careful consideration and planning.[74][75]

[74] Blom, T., Jenkins, A., Pulselli, R. M., & van den Dobbelsteen, A. A. J. F. (2022). The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. Journal of Cleaner Production, 377, 134443. https://doi.org/10.1016/j.jclepro.2022.134443.

[75] Casey, L., Freeman, B., Francis, K., Brychkova, G., McKeown, P., Spillane, C., Bezrukov, A., Zaworotko, M., & Styles, D. (2022). Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and field-based supply chains. Journal of Cleaner Production, 369, 133214. https://doi.org/10.1016/j.jclepro.2022.133214.

4. Conclusion and Future Perspectives

The CEA sector is undoubtedly an attractive one that has high growth potential. However, its current high CapEx and OpEx, business complexity, sustainability, and long breakeven horizon present major risks to viability.

Within CEA, greenhouse farming is a much more viable option compared to vertical farming in the US due to lower energy usage and costs, with the latter being widely acknowledged to struggle with profitability. To maximize success in greenhouse farming, key considerations include location (climate, costs, labour, demand), types of crops (low vs high value), and sales strategy (retail vs restaurants, partnerships).

Overall, the attractiveness of the CEA sector is highly dependent on future trends including climate change, cheaper renewable energy, and increasing demand for local, fresher produce, and the predicted detrimental impacts of these factors on conventional farming. In and of itself, CEA currently presents minimal advantages over conventional farming, and is instead less sustainable in terms of total carbon footprint. In order for the CEA industry to become more attractive for financial investments, some broad challenges have to be addressed.

Firstly, the high costs of set up and subsequently long breakeven horizon is a major deterrence for conservative investment into the sector. In addition, these high costs translate into higher prices, which are prohibitive to food-insecure populations. However, as with all nascent industries, continued investments by public funding and higher-risk financing can help to push CEA to a point where there is sufficient sectoral expertise and mass market adoption such that costs are drastically reduced. Subsequently, CEA produce will be able to achieve price parity with conventional farming produce be better able to serve as a solution to address food insecurity.

Next, high energy consumption is another major obstacle for CEA both in terms of financial costs and environmental sustainability. While numerous studies are underway to improve the resource-use efficiency of CEA technologies, perhaps a more addressable solution is to look to the energy sources. Most CEA facilities are currently powered by non-renewable sources, resulting in high vulnerability to energy price shocks. Looking ahead, more rapid development of renewable energy infrastructure could potentially help augment CEA's value proposition by reducing energy costs and carbon footprint.

Finally, labour makes up the largest contributing cost to CEA. While technology continues to be developed to reduce reliance on manual labour, the costs of technology may be prohibitive, especially for smaller CEA players looking to enter the sector. Labour shortage is currently a big problem in the sector and there is therefore a need to upskill populations in conjunction to CEA development to address the labour gap, bring down labour costs, and reduce the risk of labour-related inefficiencies.

Taken together, as the CEA industry gradually develops and matures, opportunities may arise – continued monitoring of key trends in costs, supply, and demand, would be helpful to identifying these opportunities quickly.