Controlled Environment Agriculture: Growing Local Food, Capturing Carbon with Flexible Onsite Power and Advanced Controls

Thomas Bourgeois, Pace Energy and Climate Center
Joseph O'Brien-Applegate, Natural Resources Defense Council
Jack Ventura, Elisabeth Haub School of Law at Pace University
Professor Jim Freihaut, Penn State University

Abstract

Controlled environmental agriculture (CEA) in both high tech greenhouses and vertical growhouses offer a potentially extraordinary yet underdeveloped opportunity to support the conference theme "Climate Solutions: Efficiency, Equity, and Decarbonization". Equity is at the heart of the CEA story as it offers locally grown produce to promote food resiliency, shrink food deserts, and support job creation. With appropriate business models, it may stimulate entrepreneurship or community ownership in historically underserved communities as well as rural, ex-urban, or "rust-belt" cities and towns that have suffered years of declining economic activity.

This paper will comprehensively address technologies, design, operations, and industry trends in CEA. CEA requires onsite power tightly integrated with advanced controls, sensors, communications, climate management, lighting, and mechanical systems within a multi-factor constrained optimization ecosystem. CEA may use natural gas, but properly designed and operated systems can do so in an environmentally superior manner, capturing carbon from onsite generation and using it as a resource to accelerate plant growth. Focusing on the Northeast US context, we take full account of CEA research at Cornell, the GLASE Center, and RD&D innovations at other Northeast Land Grant institutions. With distributed generation and advanced controls, these needs can be addressed, and power exports can provide a separate revenue stream, which the Dutch have demonstrated to be a linchpin of economically viable business models. This revenue can make CEA price competitive with non-locally sourced food, providing sustainability and resiliency to local food supplies.

Introduction

There are few things more important to creating resilient, sustainable communities than food, heat, and electricity. By marrying high-tech controlled environmental agriculture (CEA) operation with the electric grid, communities can secure both food resiliency and resilient, reliable electricity and heat. Our focus will be high-tech greenhouses, and how they might be designed for optimal societal benefits when paired with on-site generation of heating and electricity through combined heat and power (CHP). CHP systems have long been recognized for their ability to provide resiliency at critical infrastructure sites and locations like multifamily senior complexes, hospitals, and center of refuge stations (Hampson et al. 2013). CHP systems can also play a key role in providing food resiliency to communities. Recent disruptions, including those caused by the COVID-19 pandemic, supply chain issues, exacerbated by the war in Ukraine have highlighted the tenuous nature of the world's food supply. Catastrophic occurrences, whether man-made or natural, can seriously disrupt world food supplies and inventories.

In the same way that decentralized energy systems can be decoupled from the risks that threaten highly centralized energy generation and transmission approaches, localization of food production markedly enhances the resiliency of a region's food supplies. CHP is a critical enabling technology to support high efficiency, low emissions, and economically viable local food production in the Northeast while also providing support to the electric grid.

The Dutch, who are recognized world leaders in CEA, have nearly 4,000 MWs of CHP systems operating at greenhouses across the country. In 2020 the production of electricity using natural gas fired CHP in greenhouse horticulture in the Netherlands was 10.3 billion kWh. By deploying CHP in greenhouse horticulture, the Dutch have reduced total CO_2 emissions by approximately 1.76 million tons (Smit and van der Velden 2021).

Efficiency is a central feature of greenhouses, enabling increased crop yields and reduced energy, land, fertilizer, and pesticide usage compared to traditional farming. Equity is also potentially addressable with CEA technologies and systems from several perspectives. There are plans to use locally sited greenhouses as a pathway for addressing food deserts, areas with little or no access to quality fresh foods that are an important contributor to good health. CEA with CHP provides carbon saving benefits by utilizing the CO_2 from the engine exhaust to stimulate further plant growth, instead of purchase and import of CO_2 from other sources. A proportion of the CO_2 injected into the greenhouse is absorbed by the plants, decreasing total emissions. This efficiency is what enables the Dutch to be the second largest vegetable exporter in the world on a tiny surface area, as shown in Figure 1.

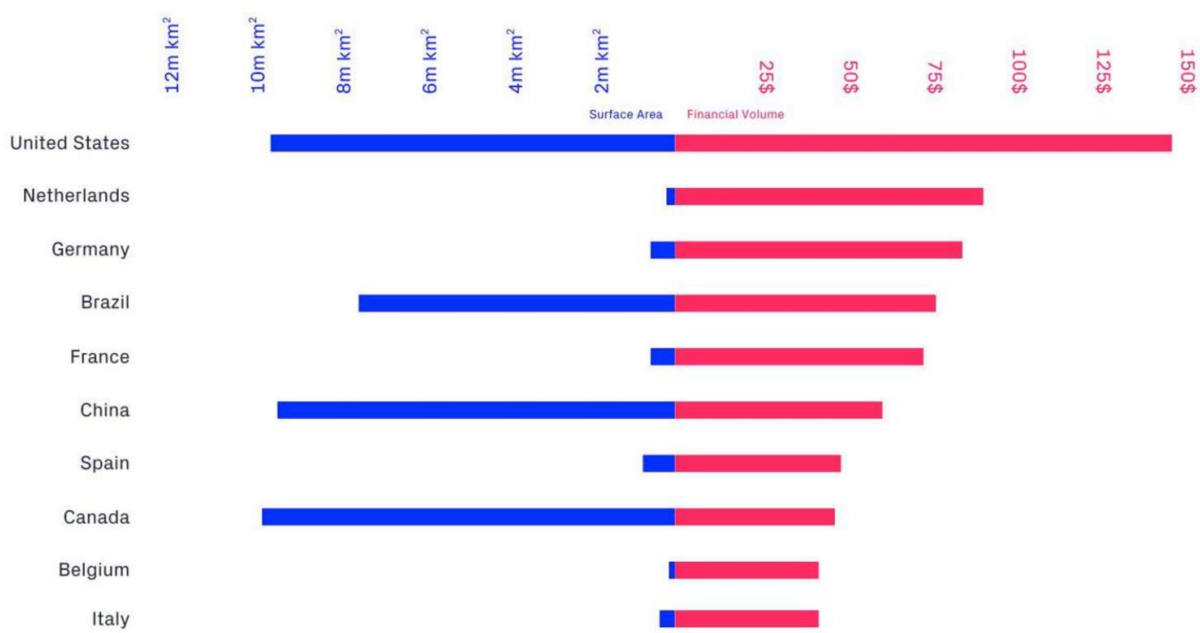

Figure 1. Country Food Production in Dollars by Land Area. (Dutch Greenhouse Delta 2021)

A resilient and sustainable community is one that exhibits high rates of productivity, producing abundant quantities with minimal use of resources and with as little environmental impact as possible. It is also capable of controllable rapid recovery in the context of externally based disruptions. Using the example of tomatoes, information from Dutch Greenhouse Delta (DGD) indicates that on one hectare of land the high-tech greenhouse can produce 750,000 kg of tomatoes with just 6,500 m^3 of water usage, as seen in Figure 2. Open field production of tomatoes on the same amount of land yields just 150,000 kg of tomatoes while requiring 28,500 $m^3$of water. Put in other terms, the high-tech greenhouse delivers 5 times the output while consuming nearly 78% less water. Resiliency and sustainability are advanced by producing a far more abundant food supply vis-à-vis the status quo alternative, while using significantly less and increasingly limited fresh water resources.

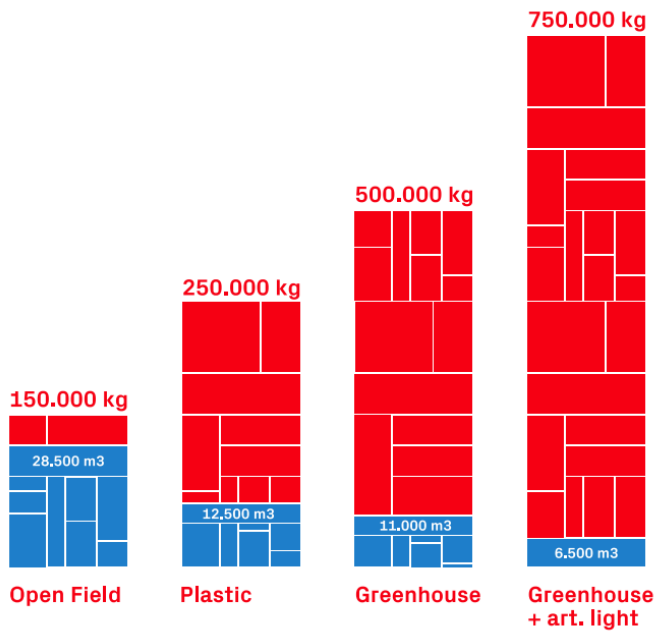

Figure 2. Tomato production on one hectare vs. water consumption for open field farming, plastic-covered greenhouses, glass greenhouses, and glass greenhouses with artificial lighting. (Dutch Greenhouse Delta 2021)

To find what policies lead to the growth of CHP with CEA, we examine the Netherlands, where both greenhouse farming and utilization of CHP in greenhouses are widespread. We then compare the conditions that led to the spread of CHP adoption in Dutch greenhouses and those in the Northeast and Mid-Atlantic US. Advances in greenhouse technologies may further help bolster the economics of CEA with CHP in the conditions expected to develop in the Northeast and Mid-Atlantic in the near future. Finally, the potential social and environmental benefits widespread adoption of this technology may bring are evaluated.

Energy Policy and Investment in CHP at Greenhouses

Development of the Dutch Market for CHP in Greenhouses

Usage of CHP in CEA is widespread in the Netherlands, with over 60% of Dutch greenhouse acreage served by CHP, totaling 6400 ha of greenhouses and over 4 GW of installed CHP (van der Velden and Smit 2009). Half of Dutch greenhouse acreage produces vegetables, such as tomatoes and peppers, while the other half is used for growing flowers and ornamental plants (Wetzels, van Dril, and Daniëls 2007). CHP is uniquely suited to the needs of CEA, in that it provides heat, electricity and CO_2 for crop cultivation, replacing the need for grid electricity, boilers for heat, and purchasing CO2 to inject into greenhouses.

The adoption of CHP by the greenhouse industry was rapid, with 2 GW of CHP added between 2003 and 2009 (van der Veen and Kasmire 2015). This adoption was driven in large part by the extremely favorable conditions for export power generation in the Netherlands at the time. In 2002, the Netherlands liberalized their electric energy market, allowing participation by private generation asset owners. Greenhouses were eligible to participate, and growers began to install CHP systems with participation in the electric market in mind (van der Veen and Kasmire 2015).

The economics of generating electricity for grid export were favorable from 2003 to 2009, with low natural gas prices and high electricity prices creating a favorable spark-spread. This also coincided with the removal of environmental permitting requirements for CHP systems in greenhouses, allowing fast and streamlined installation of CHP systems. Greenhouse CHP operators could either sell electricity directly into hourly supply markets, or arrange long-term contracts with municipalities for power purchasing. Greenhouse owners were installing oversized CHP units with selling excess power in mind, creating an additional revenue stream for growers and reducing the payback time of their CHP investment (van der Veen and Kasmire 2015).

In addition to a favorable power export market, the Netherland's provides a robust suite of programs and incentives for CHP installation. One of the major programs that enabled CHP is the Stimulation of Sustainable Energy Production and Climate Transition (SDE++) program. Renewable heat and CHP are eligible for this program, and it is intended for multiple industries (Netherlands Enterprise Agency 2022). The program is a yearly subsidy program that adjusts to the source's actual production rates and corrective amount. The subsidy is provided for implementing the technology and it incentivized companies to use CHP.

The Canadian Greenhouse Market

Greenhouses have proliferated in Canada with Ontario, British Columbia and Quebec by far the dominant provinces, as shown in Table 1.

Table 1. Number of greenhouse vegetable operations in Canada by province.

	2016	2017	2018	2019	2020	2020 Share, %
Atlantic provinces	52	52	51	49	49	5.90%
Quebec	247	250	238	235	230	27.50%
Ontario	323	330	325	315	315	37.60%
Prairie provinces	107	101	102	94	95	11.40%
British Columbia	160	154	150	150	148	17.70%
Canada	**894**	**889**	**866**	**843**	**837**	**100.00%**

Source: Crops and Horticulture Division 2021, 3.

Among these three provinces, the bulk of the production in the greenhouse vegetable sector is situated in Ontario (71% of the total production), followed by British Columbia and Quebec, with 16% and 6% respectively. Canada's technologically advanced indoor agriculture sector is an important contributor to the national economy with $1.8 billion in farm gate sales and approximately $1.4 billion in exports in 2020 (Crops and Horticulture Division 2021, 1). Vegetable crop production is highly concentrated with tomatoes, peppers and cucumbers accounting for 93.7% of total harvested area as shown in Table 2.

Table 2. Harvested area of greenhouse vegetables by commodity in square meters

	2016	2017	2018	2019	2020	2020 Share, %
Tomatoes	5,990,278	6,356,198	6,579,782	6,346,327	6,063,023	33.50%
Peppers	5,385,939	5,625,383	5,615,729	5,760,318	5,895,708	32.60%
Cucumbers	4,005,746	4,321,832	4,559,877	4,739,726	4,985,780	27.60%
Lettuce	174,696	209,183	236,813	417,302	432,272	2.40%
Strawberries	N/A	N/A	N/A	N/A	318,003	1.80%
Eggplants	90,123	109,631	110,519	121,641	137,450	0.80%
Fine herbs	26,922	90,429	69,737	103,655	115,880	0.60%
Microgreens and shoots	N/A	16,773	69,479	61,663	56,846	0.30%
Other fruits or vegetables	194,393	85,214	131,831	97,715	35,204	0.20%
Chinese vegetables	55,471	48,740	43,396	37,850	30,979	0.20%
Beans (green and wax)	4,526	6,630	6,998	8,914	10,499	0.10%
Sprouts	N/A	8,181	6,685	5,734	4,330	0.00%
Total	**15,928,094**	**16,878,194**	**17,430,846**	**17,700,845**	**18,085,974**	**100.00%**

Source: Crops and Horticulture Division 2021, 4.

Unlike the Dutch experience with nearly 4 GWs of onsite power, just a handful of greenhouses in Ontario were utilizing CHP as of 2019. Those that did were floriculture, not vegetable growing, facilities (Posterity Group 2019). A key factor here is the overriding importance of the local energy market, regulation, rates, and incentives. The electricity prices paid by the vegetable growers in Ontario is quite low. The low prices are a disincentive to onsite generation, including CHP. The low prices are in-part an artifact of rates setting at the provincial level. Greenhouses are tightly clustered in a small corner of the province (Posterity Group 2019).

In 2015, a CHP standard offer program (CHPSOP) was introduced in Ontario. The program made it possible for greenhouses to benefit significantly and justified the installation of cogeneration projects. In the years following, as many as 7 greenhouses have successfully secured contracts with the Independent Electric System Operator (IESO) and proceeded to construct cogeneration projects. These projects have ranged from 2.7 MW to 13.3 MW, showing success amongst multiple projects (U Gaat Bouwen 2021). Cogeneration systems were also installed specifically in greenhouses to supply electricity back to the grid to back up their wind energy projects (Kuack, 2021).

The IESO program supporting CHP at greenhouses was designed as a measure to encourage new sources of power generation that would facilitate replacement of coal across the system (H. Ng, Supervisor Market Analysis, IESO, pers. comm., May 24, 2022). In 2019, the province moved toward phasing out incentives for natural gas equipment and systems. This effectively ended provision of capital or operating benefits for distributed power systems at greenhouses (V. Gagnon, Business Manager Public Sector Conservation, IESO, pers. comm., June 2, 2022).

A significant portion of the rates are set based on power consumption during the peak summer months. For most greenhouse operation this is the time of year when less electricity for lighting and less heat are needed warming greenhouses for plant growth. Only large greenhouse operations requiring plant cooling conditions for specific plant type that would not be obtainable by window opening alone could potentially activate a CHP system by using a hybrid combination of electric and absorption cooling for greenhouse temperature regulation. Appropriately sized CHP systems could be available to provide export power to a stressed grid during that time, but that capital investment would need to be incentivized by the utility regulator and independent system operator.

The experience of Ontario offers another example that U.S. states can examine. It's an example that again spotlights the importance of the regulatory framework and the energy policy incentives. Introduction of the CHPSOP brought forth interest in investment in onsite power at greenhouses. Without the policy driver, investment is muted as electric prices are low. "Ontario growers observed that the Dutch could undercut them on price, in vegetable markets, because they are earning revenues in the Energy Markets" (V. Gagnon, Business Manager Public Sector Conservation, IESO, pers. comm., June 2, 2022). The implementation of energy policies, the design of market rules, and electric rate setting are key drivers of investments. States, utilities, and grid operators can consciously design policies, energy markets, and rates in a manner which supports resilient sustainable communities via the marrying of food and energy resiliency with the usage of CHP systems.

CHP Policy Landscape in Northeast and Mid-Atlantic US

Northeast and Mid-Atlantic States, especially New York, Massachusetts, and Pennsylvania, have historically provided incentive programs for qualified CHP systems. However, in recent years, these incentives programs have ended or been proposed for reduction and phase-out in some States. In New York, the long-running NYSERDA Catalog Program for CHP ended in 2019 (NYSERDA, 2019). Massachusetts provides CHP incentives through its Alternative Portfolio Standard for environmentally beneficial, but not renewable, technologies. Similar to renewable energy credits (RECs), CHP received one alternative energy credit (AEC) per MWh of generation. In 2020, Massachusetts released a straw proposal for public comment that phased out the AECs CHP receives, reducing to 0.7 AEC per MWh in 2023, then 0.1 per year until it reaches 0 in 2030 (Daymark Energy Advisors 2020).

Pennsylvania Act 129 has encouraged major utilities to incentivize CHP in application sites that have the appropriate thermal and electric demand profiles that lead to primary energy efficiency increases as well as emissions reductions compared to the conventional use of the utility grid and a separate boiler and/or furnace configuration. ACT 129 seeks to have investor-owned utilities reduce baseload electric demand by 1% and peak electric power demand by 3%, relative to a given reference year (Pennsylvania General Assembly 2008). Nearly all investor-owned utilities in PA have CHP incentivized programs that include paying for part of the CHP first costs based on the electrical output size of the CHP engine and, depending on the local utility, a given reimbursement amount for each kwh produced by the CHP system for a given amount of time. The total reimbursement is capped at a given utility specified total amount or percentage of the total system installation costs (Pennsylvania General Assembly 2008).

Resiliency and Community Benefits of CEA with CHP in the Northeast

Northeast Energy Market Opportunities

Northeast states, especially New York and Massachusetts, have adopted ambitious goals for integrating a high percentage of, or operating entirely on, renewable energy. This means that the grid of the future will be dominated by variable energy resources. There are certain functions, important to reliability needs, that cannot be performed by variable energy resources. Because of the significant and rapid deployment of variable grid resources, the NYISO is looking at comprehensive changes to how they pay for resource adequacy (Swider 2022).

With the anticipated asset mix in New York, it is expected that electricity itself will be relatively cheap. However, the demand for and the prices paid to a variety of reserves will be quite high as the services they provide become ever more critical. This represents a revenue opportunity that will be developing in the near future.

At a recent webinar Mike Swider, Senior Market Design Specialist at the New York Independent System Operator (NYISO), delivered an informative and illuminating presentation describing several NYISO market initiatives with potential implications for CHP (Swider 2022). Swider noted that within the class of dispatchable resources, the most reliable resources are those that are already online. Particular value will be paid for assets that are online, serving a load, and are able to shed some load and inject into the grid. New market initiatives will likely create revenue opportunities in the future for CHP as a dispatchable electric resource. Swider points out that "to the extent that a Combined Heat Power resource can follow a NYISO dispatch signal it can participate by selling energy, reserves and capacity" (Swider 2022). Furthermore, these resources will be needed in significant capacity, which means that the opportunity created is extensive.

Flexibility of CEA with Advanced Controls

CEA requires onsite power tightly integrated with advanced controls, sensors, communications, climate management, lighting, and mechanical systems within a multi-factor constrained optimization ecosystem. Sophisticated controls are a necessary component of a successful CEA system. Sites where production process control variables can be time or intensity shifted, with little to no impact on the quality or the quantity of the output are ideal candidates for serving as dynamic grid assets. CEA sites are particularly attractive for the co-design and deployment of grid support investments. In the Netherlands greenhouses with CHP are proven in their ability to respond to electricity pricing, and further advances in greenhouse controls and integration with energy management will allow response to more complex and nuanced needs for balancing the grid with intermittent generation. The incremental expense of adding grid functionality is small, since the expenses are already largely incurred as a part of the high-tech greenhouse package. CEA is an ideal candidate for serving as a dynamic grid asset, as its production process control variables can be time or intensity shifted with little to no impact on the quality or the quantity of the output. The general relationship between CEA's need for onsite power and process flexibility is illustrated in Table 3 below.

Table 3. Industry needs for onsite power and ability to time-shift electric and thermal load.

	Low Flexibility	Medium Flexibility	High Flexibility
Low On-Site Need	Commercial	-	-
Medium On-Ste Need	-	Manufacturing	-
High On-Site Need	Hospitals	-	CEA

Plants grown with CEA are flexible in the amount, intensity, and timing of light they receive, with the optimal total amount and amount of variance determined by the specific plant. Study results indicate that lettuce can tolerate a wide range of fluctuating light levels if the fluctuations are not extreme (Bhuiyan and van Iersel 2021). Other studies indicate process control variables that can be shifted, for example the timing of blow down fans used to open the boundary layer on lettuce and using alternating red and blue lighting for energy efficiency in growing tomatoes, peppers and cucumbers (Nicholson et al. 2022; Hao 2021). Several anecdotal examples of time flexible electric loads are enumerated in Table 4 and others are explained below.

Table 4. Time-flexible electric loads in greenhouses.

Lighting	LED lighting can be ramped more easily than HPS lighting. Plants can tolerate variations in lighting amount and schedule. Alternating red and blue light with tomatoes to reduce peak demand.
Ventilation and Fans	Horizontal and vertical fans are utilized to create different crop zones in the same greenhouse. The use of variable flow drive fans allows flexible usage. Vertical fans that provide boundary separation in lettuce crops can be flexibly timed.
Thermal Energy	Thermal batteries allow decoupling greenhouse thermal generation and utilization allowing flexible timing of cogenerated heat and power.

Source: Afzali et al. 2021; Bhuiyan and van Iersel 2021; Frijns 2022; Hao 2021; Nicholson et al. 2022.

Conversion to LED lighting. LED grow lights consume far less electricity than traditional high-pressure sodium (HPS) lighting systems. However, greenhouse growers have been reluctant to switch to LED due lingering uncertainty as to whether or product quality will be adversely affected. Recent research conducted at Wageningen University Research suggests that certain forms of tomatoes grown under full spectrum LED lighting had 3% to 11% higher yield than with HPS (Fluence 2021). LED lighting reduces energy usage and power demand at greenhouses and is much more amenable to flexibility in operation than HPS lighting systems. A team of University of Georgia researchers are designing new lighting systems capitalizing on the flexibility of LEDs. that could reduce a greenhouse's electrical demand without hurting the plants. Their system utilizes sensors and controls to measure current weather conditions, along with light-predicting algorithms to predict the amount and timing of natural light. This enables optimization of the lights inside the greenhouse to provide plants the correct amount of light with much greater efficiency (Afzali et al 2021). This level of flexibility can likewise be utilized to respond to electric grid market signals.

Thermal batteries. In the case of processes that produces more heat than it can consume, like greenhouses, thermal batteries allow for greater efficiency and lower greenhouse gas emissions by storing unused heat in one period and displacing the need for energy to deliver heat in a future period. Thermal batteries can reduce greenhouse heating needs by 5% to 15% (Frijns 2022). This translates to an estimated 10 to 30 percent reduction in natural gas consumption (Frijns 2022).

This decoupling of thermal generation and utilization further increases a greenhouse's ability to respond to electric grid signals, especially in combination with CHP.

The Potential Equity and Public Health Benefits of Growing Local Food

The equity benefits of CEA are quite real but will not occur organically. There are significant public health benefits that might be realized by providing fresh, high-quality foods in neighborhoods which presently have no access to these goods. However simply siting a commercial CEA operation within or near a food desert is offers no guarantee that the local community will have better access than before.

In a presentation on Controlled Environment Agriculture and Food Security, Cornell Professor Chuck Nicholson notes that food security has many dimensions. Two important dimensions are physical access and economic access (Nicholson 2021). Food security in the United States has little to do with a lack of sufficient supplies of food and more to do with physical and economic access. According to Nicholson, anecdotal reports and conversations suggest CEA in 'food deserts" has not increased access to fresh fruits and vegetables. This is because the products themselves are still sold through the traditional retail outlets (Nicholson 2021).

When implementing CHP into CEA projects, it is important to keep in mind who is reaping the food and monetary benefits of the project. Primarily, the goals for these projects should be to keep the benefits in the community rather than larger corporations or entities. To achieve this, it will require a conscious effort from the industry and those organizing these projects. Food security also should be consciously considered when making decisions on future CEA projects.

Unfortunately, there is some doubt on the effectiveness of CEA in providing food security to individuals as well as the benefits reaching the immediate community. This doubt is fueled by high energy costs, supply chain costs, and the need for more evidence (Nicholson 2021). To improve food security, it is imperative to consider business models which maintain availability, access, and utilization of food over time (Jones et al. 2013). A combination of the proper business model with the implementation of CHP is key. Three structures this section will focus on are (1) benefit corporations, (2) nonprofits that would qualify under 501(c)(3), and (3) municipality partnerships.

A benefit corporation is a corporate structure where the corporation does not only have a fiduciary responsibility to shareholders but is also required to pursue a social benefit. This means that if the corporation is not upholding their community benefit responsibilities, the shareholders have the right to act (Noked 2012). The idea would be to have the CEA project ensure the benefit that the community would be well served and reap the rewards of the project. Such a business structure could attract investors who would be attracted to the positive community impact. Also, an LLC can be written into a benefit corporation, making the structure rather simple and accessible.

However, business corporations have flaws in their current structure. A primary concern is that there is no external enforcement mechanism in place when the benefit corporation does not adhere to their established community benefit. This means that enforcement must be done solely within the company and amongst shareholders, which can cause a conflict of interest. Also, the CEA project would likely have to rely on loans and funds from wealthy donors to get started due to their initial cost. Such a barrier can make ownership by an underserved community tough (Nicholson 2021). These flaws must be kept in mind when wanting to consider a benefit corporation.

Another option is for the CEA project to be considered a 501(c)(3) nonprofit, or a charitable organization. In order to qualify, the organization must not adhere any of its earnings to a private shareholder or individual (IRS 2022). By having this structure, the CEA project would not have any responsibility to shareholders. The sole purpose would be to provide food for the community. While this project is ideal, there are issues to consider. First, the organization would rely solely on funding. Also, qualifying as a 501(c)(3) may be problematic. Half of food markets qualify, but the IRS does not see selling food as a charitable enterprise (IRS 2022). There are possible loopholes as an "educational organization" but nevertheless qualifying as a 501(c)(3) would be difficult. The CEA project would have to find a way to be noncommercial in order to qualify. In sum, a 501(c)(3) structure could bring the most direct benefit to the community, but the means of qualifying would be difficult.

A third option to consider is the CEA party partners with the community municipality in creating the project. This structure would ensure the community reaps the benefits since the CEA project would be run by the town. There are some examples of this, such as the GrowNYC Food Hub (GrowNYC 2022). One problem with this structure is that, as with the other two business models, outside funding is needed. Taxpayers to the municipality alone would not be able to fund the project. Also, the project is riskier than a standard energy project, which may have municipalities hesitant to approve such a project. Regardless, this is a possible business model for a new CEA facility.

Carbon Reduction Benefits

In 2020 the production of electricity using natural gas fired CHP in greenhouse horticulture in the Netherlands was 10.3 billion kWh (Smit and van der Velden 2021, 10). By deploying CHP in greenhouse horticulture, the Dutch have reduced total CO_2 emissions by approximately 1.76 million tons (Smit and van der Velden 2021, 10). While the Dutch report significant CO_2 savings, we find little peer reviewed published evidence on CO_2 savings in New York, or the Eastern States generally. There is a Cornell Study that shows greenhouse gas impacts for greenhouses, roughly similar to lettuce, grown and consumed in New York City vis-à-vis field grown lettuce, grown in Salinas CA and trucked into New York City (Nicholson et al. 2020). However, the water usage benefit of greenhouses is outstanding vis-à-vis the field grown scenario.

The authors of the Cornell study note the relative dearth of research in this area: "Although a number of previous studies have examined the environmental impacts of lettuce supply chains (e.g., Emery & Brown, 2016; Rothwell, Ridoutt, Page, & Bellotti, 2016), we are not aware of any previous study that has compared both landed costs and environmental outcomes of lettuce supply chains to major US urban areas" (Nicholson et al. 2020, 35). The Cornell study describes a life cycle analysis (LCA) comparing the cumulative energy demand, global warming potential, water use, and total landed cost of 1 kg of saleable leaf lettuce delivered to a representative wholesale market location in both New York City and Chicago. The study compared a conventional, field-based production supply chain to two types of CEA-based supply chains (Nicholson et al. 2020, 38). The CEA based supply chains fared better water usage and identified several factors that would undoubtedly change the global warming potential and total life cycle cost results in favor of Greenhouses. For example, the type of design we encourage in this paper, one using onsite power for the CEA facility at high but plausible total system efficiency, recapturing the exhaust for use in the greenhouse, extensive greenhouse controls and thermal batteries.

There is a critical need for determining how much CO_2 is captured and recycled for acceleration of plant growth, in the case where the CO_2 emissions from onsite CHP generation is used to provide CO_2 for the greenhouse. More research is needed to provide accurate figures for carbon capture and reuse. There are many claims by greenhouse CHP system providers attesting to a significant CO_2 savings, with correct design, equipment configuration and operation. An analysis of the empirical data from actual operations is required for moving the status of equipment manufacturers and grower claims, from anecdotal to hard evidence.

There are some filings available pursuant to a benefit-cost analysis (BCA) to support a Commercial Property-Assessed Clean Energy (C-PACE) financing arrangement at Wheatfield Gardens in Tonawanda, NY. To secure the C-PACE financing, the greenhouse with CHP was analyzed on several factors. It was reported that the CO2 savings (over the base case) were very important to this site in achieving at high BCA score (G. Higgins, Transaction Manager Commercial Energy Efficiency, Nuveen, pers. Comm., June 8, 2022).

In another instance of unbiased, third-party verified assessments of CO_2 reductions in the Northeast, we were directed to a New York Green Bank (NYGB) Transaction Profile Supporting Deployment of Controlled Environment Agricultural Assets in New York State for the company Agbotic, Inc (S. Davidson, Director, NY Green Bank, pers. Comm., June 9, 2022). The Sponsor, Agbotic Inc. is a New York State-based CEA agritech company that builds regenerative “SmartFarms” with robotic greenhouse automation to produce organic food with an ecologically restorative model. The Client in this transaction profile is Agbotic Project #1 LLC. According to the analysis Accompanying the NYGB Transaction Profile the operation of this CEA proj“ct was projected to have the outcomes shown in Table 5.

Table 5. Projected Environmental Impacts of Agbiotic Project #1

Energy/Environmental Impacts	Lifetime Low Estimate	Lifetime High Estimate	Annualized Low Estimate	Annualized High Estimate
Electricity savings (MWh)	65,223	79,717	3,261	3,986
Fuel savings (MMBtu)	231,876	593,206	11,594	29,660
Estimated GHG emission reductions (metrics tons)	44,601	70,504	2,230	3,525

Source: NYGB 2020.

Energy efficiency technologies that were identified by the NY Green bank were the on-site cogeneration plant, LED lighting, and heat sinks (NYGB 2020). The transaction profile notes that total electricity savings comprise electric generation from the CHP engine, as well as secondary electric impacts attributable to use of an absorption chiller to satisfy cooling load that otherwise would have been satisfied with an electric chiller (NYGB 2020, 4). NYGB’s minimum investment criteria require that NYGB-supported transactions have the potential for energy savings and/or clean energy generation that will contribute to greenhouse gas emission reductions in support of New York’s energy policies.

Conclusion

When utilized with high-tech CEA, food resiliency is added to the menu of CHP benefits. Recent events including the disruptions caused by the COVID-19 pandemic, supply chain issues, and the Russian invasion of Ukraine have highlighted the tenuous nature of the world's food supply. These occurrences, whether man-made or natural, can disrupt world food supplies and inventories. In the same way that decentralized energy systems can decouple from the risks that threaten centralized energy generation and transmission approaches, localization of food production enhances the resiliency of a region's food supplies. CHP is a critical enabling technology to support high efficiency, low emission, and economically viable local food production while also providing support to the electric grid.

As shown in the Dutch CEA with CHP, participation in energy markets can be key to making CEA competitive with traditional agriculture in more hospitable climates with lower labor prices. While the policy landscape in the Northeastern United States is not as conducive to direct electric sales as the Netherlands, the increased penetration of renewable generation may generate valuable markets for grid reliability support and other ancillary services. Advances in greenhouse technology and controls, as well as research in plant and agricultural science, have demonstrated the potential greenhouses have to load shift for both electric and thermal energy. These technology innovations are apt to allow the flexible response necessary to make CEA an ideal candidate to operate in energy markets.

CEA offers a potentially extraordinary yet underdeveloped opportunity to support resiliency in both the energy and food supplies of communities. With the profitability from capturing additional value streams from the electric market, CEA can deliver on a promise to expand economic access to better, fresher, higher-quality foods. Through the local production of food and energy, CEA with CHP can enable communities with resilient sources of food and electricity, while reducing carbon directly and allowing for the greater penetration of renewable energy in the rest of the grid.

References

Afzali, S., S. Mosharafian, M. van Iersel, and J. M. Velni. 2021. "Development and Implementation of an IoT-Enabled Optimal and Predictive Lighting Control Strategy in Greenhouses." *Plants* 10 (12): 2652. https://doi.org/10.3390/plants10122652.

Bhuiyan, R. and M. van Iersel. 2021. "Only Extreme Fluctuations in Light Levels Reduce Lettuce Growth Under Sole Source Lighting." *Frontiers in Plant Science 28.* https://doi.org/10.3389/fpls.2021.619973

Crops and Horticulture Division. 2021. *Statistical Overview of the Canadian Greenhouse Vegetable Industry, 2020.* Ottowa, ON: Agriculture and Agri-Food Canada. https://agriculture.canada.ca/sites/default/files/documents/2022-02/GreenhouseVegetable_Report_2020_en.pdf

Daymark Energy Advisors. 2020. *Alternative Energy Portfolio Standard Review.* Worcester, MA: Daymark Energy Advisors. https://www.mass.gov/doc/alternative-energy-portfolio-standard-review/download.

Fluence. 2021. *Researching the Future: Tomato Production in Greenhouses.* Austin, TX: Fluence. https://fluence.science/science-articles/wageningen/.

Frijns, R. 2022. *Thermeleon makes greenhouse horticulture more sustainable with smart thermal battery*. Delft: Thermeleon. https://innovationorigins.com/en/thermeleon-makes-greenhouse-horticulture-more-sustainable-with-smart-thermal-battery/.

GrowNYC. 2021. *New York State Regional Food Hub*. New York, NY: GrowNYC. https://www.grownyc.org/hub-temp.

Hampsen, A., T. Bourgeois, G. Dillingham, and I. Panzarella. 2013. *Combined Heat and Power. Enabling Resilient Energy Infrastructure for Critical Facilities*. Washington, DC: ICF, International. https://www.osti.gov/biblio/1219963-combined-heat-power-enabling-resilient-energy-infrastructure-critical-facilities. ORNL/TM-2013/100 6161.

Hao, X. 2021. *Dynamic Long-Photoperiod, Low Intensity Lighting Strategies.* Ottowa, ON: Harrow Research and Development Centre, Agriculture and Agri-Food Canada. Canadian Greenhouse Conference.

Intergrow. 2021. *Our Farm.* Ontario, NY: Intergrow. https://www.intergrowgreenhouses.com/our-farm/.

Internal Revenue Service (IRS). 2022. *Exemption Requirements - 501(c)(3) Organizations.* Washington, DC: Internal Revenue Service https://www.irs.gov/charities-non-profits/charitable-organizations/exemption-requirements-501c3-organizations

Jones, A., F. Ngure, G. Pelto, and S. Young. 2013. "What Are We Assessing When We Measure Food Security? A Compendium and Review of Current Metrics" *Advances in Nutrition* 4 (5): 481–505. https://doi.org/10.3945/an.113.004119.

Kuack, D. 2021. *Cogeneration systems can deliver the electricity, heat and supplemental carbon dioxide that controlled-environment growers can use to produce edible, ornamental and medical cannabis crops more efficiently and more profitably.* Ithaca, NY: Greenhouse Lighting and Systems Engineering. https://glase.org/interviews/controlled-environment-growers-power-their-operations-with-cogeneration-systems/.

Netherlands Enterprise Agency. 2022. *Stimulation of sustainable energy production and climate transition (SDE++).* The Hague, NL: Netherlands Enterprise Agency. https://english.rvo.nl/subsidies-programmes/sde.

Nicholson, C. 2021. *Controlled Environment Agriculture and Food Security.* Ithaca, NY: Cornell University. https://blogs.cornell.edu/urbancea/2021/10/06/new-video-controlled-environment-agriculture-and-food-security/

Nicholson, C., K. Harbick, M. Gómez, and N. Mattson. 2020. "An Economic and Environmental Comparison of Conventional and Controlled Environment Agriculture (CEA) Supply Chains for Leaf Lettuce to US Cities." *Aktas, E. and M. Bourlakis (eds) Food Supply Chains in Cities.*

Nicholson, K., J. Swartz, and N. Greens. 2022. "Polygreens Podcast Episode 063." https://www.nickgreens.com/podcast/episode/7b3d4a97/063-round-table-discussions-dr-greenhouse-kelley-nicholson

Noked, N. 2012. *Benefit Corporations vs. "Regular" Corporations: A Harmful Dichotomy*. Cambridge, MA: Harvard Law School. https://corpgov.law.harvard.edu/2012/05/13/benefit-corporations-vs-regular-corporations-a-harmful-dichotomy/.

New York Environmental Conservation Law of 2021. State of New York § 6599.

New York Green Bank (NYGB). 2020. *Supporting Deployment of Controlled Environment Agricultural Assets in New York State: Agbotic, Inc.* Albany, NY: New York Green Bank. https://greenbank.ny.gov/-/media/greenbanknew/files/NYGB-Transaction-Profile_Agbotic.pdf.

NYSERDA (New York State Energy Research and Development Authority). 2019. *CHP Program Program Opportunity Notice (PON) 2568.* Albany, NY: New York State Energy Research and Development Authority. https://portal.nyserda.ny.gov/servlet/servlet.FileDownload?file=00Pt000000AixE4EAJ.

Pennsylvania Act 129 of 2008. https://www.legis.state.pa.us/cfdocs/legis/li/uconsCheck.cfm?yr=2008&sessInd=0&act=129

Posterity Group. 2019. *Greenhouse Energy Profile Study.* Ottowa, ON: Posterity Group. https://www.ieso.ca/-/media/Files/IESO/Document-Library/research/Greenhouse-Energy-Profile-Study.ashx

Smit, P. and N. van der Velden. 2021. *Energiemonitor van de Nederlandse glastuinbouw 2020. Wageningen Economic Research Rapport 2021-127.* Wageningen, NL: Wageningen University and Research. https://library.wur.nl/WebQuery/wurpubs/589447

Swider, M. 2022. *Grid in Transition: DEFRs and Dispatchability*. Albany, NY: NYISO. January 27, 2022.

U Gaat Bouwen. 2021. *Taking Standardization of Greenhouse Cogeneration to The Next Level*. Weert, NL: U Gaat Bouwen B.V. https://www.ugaatbouwen.com/news/taking-standardization-greenhouse-cogeneration-next-level.

van der Veen, R. and J. Kasmire. 2015. "Combined Heat and Power in Dutch Greenhouses: A Case Study of Technology Diffusion." *Energy Policy* 87: 8–16. https://doi.org/10.1016/j.enpol.2015.08.040

van der Velden, N. and P. Smit. 2009. *Energiemonitor van de nederlandse glastuinbouw 2008.* The Hague, NL: LEI Wageningen UR. https://edepot.wur.nl/15538

Wetzels, W., A. van Dril, and B. Daniëls. 2007. *Kenschets van de nederlandse glastuinbouw*. Petten, NL: Energy Research Centre of the Netherlands. http://resolver.tudelft.nl/uuid:4914d69a-c781-40c5-a19c-8e68e860e979. ECN-E–07-095.

Flexibility of the Production Process: Ability to Time and/or Intensity Shift		
Activity	Example	Citation
Lighting	Lettuce	*Only Extreme Fluctuations in Light Levels Reduce Lettuce Growth Under Sole Source Lighting*. Ruqayah Bhuiyan* and Marc W. van Iersel. Frontiers Plant Science, 28 January 2021 | https://doi.org/10.3389/fpls.2021.619973
VFD's with Horizontal Air Flow (HAF), Vertical Air Flow (VAF), power tubes.	Different vegetable zones: plants at different growth stages, heights, size	Round Table Discussions - Dr. *Greenhouse* - Kelley Nicholson. Polygreens Podcast. Mar 4, 2022. Episode 063. https://www.nickgreens.com/podcast/episode/7b3d4a97/063-round-table-discussions-dr-greenhouse-kelley-nicholson
Top Down air flow	Head lettuce to improve yield (boundary layering)	Round Table Discussions - Dr. Greenhouse - Kelley Nicholson. Polygreens Podcast. Mar 4, 2022. Episode 063.
Thermal Battery makes greenhouse horticulture more sustainable	"Smart" thermal battery decouples production of thermal energy from time of usage of thermal energy. Adding operational flexibility to greenhouse	*Thermeleon makes greenhouse horticulture more sustainable with smart thermal battery*". By Roelant Frijns. January 22, 2022. Innovations Origin. Source: https://innovationorigins.com/en/thermeleon-makes-greenhouse-horticulture-more-sustainable-with-smart-thermal-battery/
Lighting: Dynamic Long-Photoperiod Low Intensity Lighting Strategies	utilizing red lighting for 12 hours during the day, and 12 hrs of blue light at night, it is possible to save 20-35% peak electricity, while not negatively impacting the plants (20% in tomatoes and peppers, 35% in cucumbers).	*Dynamic Long-Photoperiod, Low Intensity Lighting Strategies. Xiuming Hao, Ph.D. Harrow Research and Development Centre, Agriculture and Agri-Food Canada. Canadian Greenhouse Conference. October 6,2021*