Conjoining Food and Grid Resiliency with CEA

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Abstract

Controlled environmental agriculture (CEA) offers an extraordinary, yet underdeveloped, opportunity to support resilient and healthy communities. We analyze the opportunity high-tech CEA utilizing onsite power has to operate as a dynamic grid asset. Advanced control systems enable CEA to provide many benefits including local food supply and significant reductions in water and land usage. Combined Heat and Power (CHP) can efficiently provide onsite thermal and electric power while recycling the CO_2 for supplementation in the CEA facility, advancing plant growth. Flexibility in the CEA demand and dispatchability of CHP supply uniquely positions CEA operations to contribute to energy and food resiliency.

This paper aims to inform and engage policymakers, regulators, CEA operators, grid operators, market participants, and other key stakeholders. We argue that CEA has a unique capacity to alter the timing and intensity of energy use, without sacrificing the quality or quantity of the output. This paper further investigates CEA's feasibility to conjoin the need for grid and energy resiliency, via onsite power, with local food production. Flexible generating assets are an absolute necessity for meeting New York's decarbonization plans. The supply-demand energy gap with a 100% renewable grid must be filled by a large-scale addition of distributed and Dispatchable Emissions-Free Resources (DEFRs). According to the NY Independent System Operator (NYISO), DEFRs will be ever more valuable and well compensated. This incremental revenue stream should incentivize business models that make CEA more price competitive with non-locally sourced food, thereby providing sustainability and resiliency to local food systems.

Meeting Future Food Supply Challenges: Efficiency, Sustainability

There are few things more important to creating resilient, healthy communities than access to fresh nutritious food. However, there are several critical challenges facing access to food. In a macro sense, meeting future food supply requirement alone is a daunting task. According to an often-cited FAO report the world will require a 60% increase in food production by 2050 over 2010 levels (Alexandratos & Bruinsma, 2012). A recent meta-analysis of 57 global food security projection and quantitative scenario studies identified a range of outcomes of +30% to +62% expected increase in the total global food demand between 2010 and 2050.

The matter of meeting future food demand is further complicated by the widespread consensus that our current food systems are unsustainable. Conventional agriculture practices are water intensive, use many chemical inputs affecting ecosystems, and are a major source of greenhouse gas (GHG) emissions. As such, implementing more sustainable solutions is critical. Current practices exacerbate the impacts of climate change, and climate change adds significant new risks to current practices. Recent disruptions, including those caused by the COVID-19 pandemic, and 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.

Efficiency is a central feature of greenhouses, enabling increased crop yields and reduced energy, land, fertilizer, and pesticide usage compared to traditional farming. Environmental justice can also be addressed by CEA technologies and systems from multiples perspectives. For example, 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. With additional steps the site can even produce for sale a food grade CO2. This displaces purchase and import of CO_2 from other sources. A proportion of the CO_2 injected into the greenhouse is absorbed by the plants, used in commences thereby decreasing total GHG emissions, which are traditionally higher in environmental justice communities.

A resilient and sustainable community incorporating CEA is one that exhibits high rates of productivity, producing abundant quantities of output with minimal use of resources, and as little environmental impact as possible. One hectare of land devoted to a high-tech greenhouse can produce 750,000 kg of tomatoes with just 6,500 m^3 of water usage, while open field production of tomatoes, on the same amount of land, yields just 150,000 kg, while requiring 28,500 $m^3$of water (Eric Egberts, 2022). Accordingly, 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 conventional agriculture, while taking significantly less from an increasingly limited water supply. As noted below, the potential social and environmental benefits that widespread adoption of CEA may bring are extensive.

By connecting high-tech CEA operations with the electric grid, communities can simultaneously secure food resiliency, and resilient, reliable electricity and heat. This paper's focus will be high-tech greenhouses, and how they might be designed for optimal societal benefits when paired with onsite generation of heating and electricity through combined heat and power (CHP). CHP has proven to be a critical enabling technology to support high efficiency, low emissions, and economically viable local food production in the Netherlands, Flanders, Ontario, and elsewhere while also providing support to the electric grid.

1. CEA and CHP Perfect Together

CEA utilizing CHP is a concept that is tested, proven, economic, reliable, and clean. In the Netherlands where the development of the high-tech greenhouse has reached the greatest levels of efficiency, productivity and scalability, there are currently more than 3,000 MWs of onsite CHP systems powering and heating greenhouses. In 2021 more than 11% of all the electricity consumed by businesses, homes and industry was generated onsite at high-tech greenhouses (Smit & van der Velden, 2021). Approximately 22% of the CHP capacity in Flanders is installed in greenhouse horticulture, a sector that has been driving significant growth in installed capacity in recent years. In 2021, the total CHP capacity in Flanders reached 2.6 GWe, contributing to nearly 23% of the region's electricity generation.

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. Generating electricity onsite at the greenhouse provides reliable power and with CHP, the thermal energy from the generator is used for heating the greenhouse. In certain instances, heat is also used with absorption chillers to deliver air conditioning to the greenhouse as well. Some sites engage in "quad generation" utilizing the generator for heating, cooling, electricity, and CO_2 supplementation for plant growth and even conversion to food grade CO2 for sale and utilization in other business processes.

2.1. CEA in High Tech Greenhouses is the Most sustainable Method Today

Studies have shown that CEA in high-tech greenhouses is one of the most sustainable forms of agriculture currently available (Zhou et al., 2021). Such studies have evaluated sustainability on a more holistic approach than is traditionally utilized and have considered performance against the Sustainable Development Goals ("SDGs") introduced by the United Nations in their 2030 Agenda for Sustainable Development. Specifically, agricultural forms were compared against the following SDGs: (i) SDG 2- Zero Hunger; (ii) SDG 3- Good Health and Well-being; (iii) SDG 6 -Clean Water and Sanitation; (iv) SDG 7 – Affordable and Clean Energy; (v) SDG 12 – Responsible Consumption and Production; (vi) SDG 14 – Life below Water; and (vii) SDG 15- Life on Land. As demonstrated by the SDGs considered, both environmental and social aspects of sustainability were considered as part of this evaluation. This holistic assessment concluded that high-tech greenhouse CEA systems outperform organic, low-tech greenhouse systems and conventional forms of open field agriculture relating to sustainability.

2.2. The Unique Characteristic of CEA with CHP: Generation Flexibility Meets Process Flexibility

CEA holds a special place among industries and sectors because it possesses both a high need for onsite power and a high degree of process flexibility. Many industries and economic sectors have little need for a dedicated onsite power generation resource. For many forms of business enterprises there are not significant economic or operational advantages to be gained by investing in and operating onsite generation. We characterize their demand for onsite power as LOW. There are other forms of businesses, hospitals being a prime example, where the demand for onsite power is HIGH. A hospital is a "critical infrastructure" site, an enterprise that must always have power available for the safety of the patients. Furthermore, hospitals are energy intensive and have a large power need and consistent demand (24 hours a day, 365 days per year). Hospitals can productively utilize the waste heat from electric power generation, making them a top prospect for a CHP system. However, a hospital does not possess a high degree of energy demand flexibility. That is, a hospital cannot redirect the consumption of electricity from lifesaving medical equipment and provide that power to support the grid. Figure 1 illustrates how the relationship between CEA's need for onsite power and process flexibility makes it "the best" type of grid asset.

Figure 1. CEA's need for onsite power and ability to time-shift load.

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

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 (Swider, NYISO Webinar 1/29/2022.

2.3 Factors Accounting for CEA's Flexible Demand

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. Crops grown in greenhouses often have a target Daily Light Integral (DLI), meaning the total amount of light energy they receive over a day. Crops respond to the photoperiod, or the length of the day and night (similar to humans responding to the amount and length of sleep they get). Depending on the specific crop, growers may target a length of uninterrupted light or darkness. For example, researchers at Ohio State have thoroughly studied ideal environments for strawberry production. The optimal DLI is 20-25 mol/m^2 with a recommended minimum of 12 mol/m^2 and maximum of 30 mol/m^2 (*Photosynthetic Lighting | Controlled Environment Berry Production Information*, n.d.). If natural light provides 13mol/m^2 on a particular day over 12 hours, the grower may target supplementing 7 mol/m^2 over 6 more hours, still allowing for 6 uninterrupted hours of darkness.

While these plant characteristics provide some constraints, many plant scientists believe the timing and intensity of the light application is flexible otherwise. The amount of light they receive at any one instantaneous moment, or the *intensity* of light, can range significantly without affecting plant growth. One study revealed that lettuce can tolerate a wide range of non-extreme fluctuating light levels (Bhuiyan & van Iersel, 2021). Considering this relative demand flexibility, a CEA facility's demand can respond to energy market conditions. Some facilities aim to coincide artificial lighting and off-peak electricity rate times as much as possible (A.J. Both, 2015). In addition to demand-response, CEA with onsite generation also offers energy during grid stress.

LED lighting. Light Emitting Diode (LED) lighting enables greater demand flexibility in the greenhouse and is much more efficient than other common types of lighting. Unlike High Pressure Sodium (HPS) lights, LEDs can turn on and off instantly without significantly affecting their operating life. While most operate on an on/off basis, LEDs are capable of dimming, while HPS lights are not (Llewellyn et al., 2020). Therefore, LEDs can respond in real time to sunlight and electricity market signals while maintaining desirable conditions for plant growth.

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. This system utilizes sensors and controls to measure current weather conditions, along with light-predicting algorithms to predict the amount and timing of natural light, thereby enabling optimization of the lights inside the greenhouse to provide plants the correct amount of light with much greater efficiency (Afzali et al., 2021).

LEDs have other advantages over HPS lights. LEDs have a much higher energy-to-photon conversion rate (>3.0 μmol/J) compared the HPS lights (1.0-1.7 μmol/J), making LEDs 2-3 time more efficient (*Photosynthetic Lighting | Controlled Environment Berry Production Information*, n.d.). Research conducted at Wageningen University Research also suggests that certain forms of tomatoes grown under full spectrum LED lighting had 3% to 11% higher yield than with HPS (Researching the Future: Tomato Production in Greenhouses, 2021).

Thermal storage. Thermal storage with thermal batteries can temporally decouple the thermal requirements in the greenhouse from the thermal energy generation. This is especially helpful with CHP at CEA sites since CHP produces heat and electricity simultaneously but the demand for the two energy types is often asynchronous. Thermal batteries allow for greater efficiency and lower GHG 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% (Frijins, 2022). This translates to an estimated 10 to 30% reduction in natural gas consumption. 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 integrated CHP system can provide electric energy to the grid during peak grid demand hours and charge the thermal energy storage system with the bi-product heat generated. The heat can be used to meet CEA demand later to avoid the need for an additional boiler or CHP production.

Agriculture and Agri-Food Canada's Harrow Research and Development Centre (Harrow, Ontario) has been conducting research on Optimal Lighting Recipes using overhead lighting (HPS, LED, or a hybrid system of HPS and LED). Authors Al-Daoud and Hao summarize findings at Harrow from recent research on lighting recipes for various crops. They state, "in regions such as Ontario with large fluctuations in electricity prices at different times of the day, longer photoperiods will allow much more flexibility to use cheaper electricity" (Al-Doud and Hao, 2023)

Other Process Control Flexibility. Other studies indicate that process control variables, such as fans and alternating red and blue lighting, can be strategically utilized, enabling elasticity in adjusting power levels (Hao 2021). Figure 2 lists examples of time flexible energy loads, which are also discussed below.

Figure 2. Time-flexible electric loads in greenhouses.

Lighting	LED lighting can be ramped more easily than high pressure sodium lighting. Plants can tolerate variations in lighting amount and schedule. Alternating red and blue light with tomatoes to reduce peak demand (Hao, 2021).
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.

3. Renewable Powered Grids and the Need for DEFRs

3.1. 100% Renewable Grid by 2040

New York passed the sweeping Climate Leadership and Community Protection Act (CLCPA) requiring a 70% renewable grid by 2030 and a 100% renewable grid by 2040. New York also adopted a Scoping Plan to effectuate the goals of the CLCPA. The Scoping Plan is one of the most ambitious climate change mitigation plans in the world and distinguishes New York as a climate leader. The Scoping Plan calls for the phaseout of fossil generating resources on or before January 1, 2040. The Scoping Plan anticipates a renewable resource supply mix that includes 9 GW of Offshore wind by 2035, 6 GW of solar PV by 2025, and 3 GW of energy storage by 2030.

The Scoping Plan anticipates electrification of nearly all sectors of the state's economy. Currently the vast majority of the state's homes, businesses, industry, and government buildings are heated by fossil fuels. Sectoral electrification has several profound outcomes on the magnitude and the seasonality of the state's electric power demands. NYISO projects that the New York Power system will switch from a summer peak to a winter peak in the mid-2030s, with the magnitude of winter power demand nearly tripling in 2040.

The NYISO uses the term DEFR to refer to system resources, over and above anticipated renewable generation capacity that will be needed to ensure the reliable operation of the state's renewable powered electric grid. These DEFRs will be necessary to bridge the **gap** that will occur during periods of wind lulls that occur simultaneously with periods of insufficient solar PV output. In its 2021-2040 System Outlook the NYISO projects a need for 111-124 GW total by 2040. According to the NYISO, DEFRs must be developed and added at scale to reliably serve demand when intermittent generation is unavailable. New York's Scoping Plan states that analysis and current studies show that the climate goals require the development and deployment of 15 GW to 45 GW of electricity from zero-emission, dispatchable resources in 2040 to meet demand and maintain reliability, although that **gap** may change over time depending on forecasted demand.

3.2. The Magnitude and Time / Geography Occurrences of the Gap

The magnitude, timing, and locational occurrences of the gap were explored in a Technical Conference hosted by NY DPS on December 11-12, 2023. A panel with expertise in modeling the NY grid was convened to characterize the potential "gap" with respect to resource adequacy, transmission security, and grid stability arising from shuttering fossil fuel-fired resources When asked by the moderator, "is there a gap?", Dr. Lindsey Anderson of Cornell responds, "yes, we do find that there's going to be a gap." Dr Anderson conducted a study using a digital twin of the New York system where all resources were in the ideal locations, adding electrification of transportation and buildings and taking account of weather history. The Cornell study performed a simulation of NY grid operations; dispatched on real weather / load conditions, operated hour-by-hour for 22 years and concluded that there are very few situations in which we do not see load shedding. Furthermore, these gaps occur in the worst times, on cold days and hot days.

All panel members were unanimous in their conclusions that as New York moves towards a 100% renewable grid the state becomes increasingly reliant on weather dependent supply resources. We consistently find this gap, most prominent during winter weeks when electric demand will be much higher than it is today. The weather record shows several days where solar output is low occurring with multiday wind lulls. To compensate for this gap the state needs DEFRs, resources that do not need to be recharged, and that can operate over periods of extended duration.

Con Edison's modeling of the New York City grid corroborates these findings in its 2023-2032 Comprehensive Reliability Plan white paper where they note that wind lulls lasting 24 hours or more happen a dozen times per year. The gap is most prominent during the winter, when demand is high, due to heating electrification, transportation and electric power. Con Edison's modeling shows low wind and solar output over multiple days.

There is a critical spatial feature at play that we can't lose sight of - It's essential that we understand not only how much of these DEFRs are needed, but where, geographically, they are required. NYISO has stated, "that's another important thing that we should highlight *where* on the system these resources are necessary from a reliability deliverability standpoint. Deliverability meaning that if you can't get the energy which is needed in Long Island can't get it there from Albany you better have some reserves or resources in Long Island for example."

3.3. What are the Characteristics of the Resources Needed to Fill the Gap

The NYISO has identified a set of 10 attributes required to operate the grid of the future safely and reliably. Zach Smith NYISO VP System and Resource Planning presented a mapping of these attributes to sample technologies.

Figure 3. Attributes of Sample Technologies: from NY PSC Dec 11, 2023 Technical Conference. Presented by Zach Smith, VP System and Resource Planning

Attributes of Sample Technologies

Sample Technology	2023 NYCA Summer Capacity (MW)	Energy Attributes						Other Reliability Attributes			
		Carbon Free	Dependable Fuel Source	Non-Energy Limited	Dispatchable	Quick Start	Flexible	Multi Start	Inertial Response	Dynamic Reactive Control	High Short Circuit Current
Fossil	25,667	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hydro	4,265	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pumped Storage	1,407	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hydrogen Fuel Cell	0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Hydrogen Combustion	0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nuclear	3,305	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes
Modular Nuclear	0	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
Battery	0	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No
Solar	154	Yes	No	No	No	Yes	Yes	Yes	No	Yes	No
Wind	2,051	Yes	No	No	No	Yes	Yes	Yes	No	Yes	No
Demand Response	1,234	Yes	Yes	No	No	No	Yes	No	No	No	No
Synchronous Condenser	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes	Yes	Yes	Yes

*see figure 39 of the CRP report for more detail

New York ISO

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For the purposes of this paper, only hydro and hydrogen technologies satisfy all these essential attributes. Biogas, though capable of satisfying all attributes, with carbon-free designation yet to be determined, is not included among these technologies. Fossil technologies, currently representing 25.7 GW of NYCA Summer Capacity, must be retired by 2040. In their place some set of technologies must be deployed that will satisfy the grid's requirements for energy and other reliability attributes.

3.4. The Incremental Cost of Adding Grid Connectivity is Small

High-tech CEA integrates advanced controls, sensors, communications, climate management, lighting, and mechanical systems within a multi-factor constrained optimization ecosystem. Environmental factors including temperature, light, CO_2, humidity, and airflow, along with fertigation, are some of the most important determinants of plant growth, thus careful resource and system deployment control is imperative. The high costs associated with controlling these variables also means efficiency and optimal control is crucial to the financial success of a CEA operation. Studies have demonstrated potential for a 29% cost reduction at a Netherlands greenhouse using optimal energy dispatch control (van Beveren et al., 2020)Another study modeled optimized energy input to the greenhouse to produce the same environmental conditions achieved in practice by the grower at the same Netherlands greenhouse, realizing a 47% reduction in heating, 15% reduction in cooling, and 10% reduction in CO_2 injection (van Beveren et al., 2015).

It is important to note this control optimization becomes more complicated when attempting to dynamically optimize resource and system deployment in the context of rapidly changing grid conditions.

Utilizing smart control frameworks, CEA sites are particularly attractive for the co-design and deployment of dynamic 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.

3.5. Time and Intensity Flexibility May Surpass Other Viable DEFR Alternatives

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

At a January 2022 webinar hosted by the NY/NJ CHP TAP, Mike Swider, Senior Market Design Specialist at the 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 are those 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".

Resources that can perform when called; for the longest period of time, with quick start non-energy limited, dispatchable, flexible, quick ramping will provide the most societal value and be compensated in markets that are in development now or in the near to mid-term.
The New York ISO has identified a list of critical attributes for reliability.

Figure 4. Attributes for Reliability (NYISO) presented at NY DPS Technical Conference by Zach Smith, NYISO VP of System and Resource Planning

1. **Dependable Fuel Sources** that are carbon free and allow these resources to be brought online when required
2. **Non-Energy Limited** and capable of providing energy for multiple hours and days regardless of weather, storage, or fuel constraints
3. **Dispatchable** to follow instructions to increase or decrease output on a minute-to-minute basis.
4. **Quick-Start** to come online within 15 minutes
5. **Flexibility** to be dispatched through a wide operating range with a low minimum output
6. **Fast Ramping to inject or reduce** the energy based on changes to net load which may be driven by changes to load or intermittent generation output
7. **Multiple starts** so resources can be brought online or switched off multiple times through the day as required based on changes to the generation profile and load
8. **Inertial Response and frequency control** to maintain power system stability and arrest frequency system stability and arrest frequency decline post-fault
9. **Dynamic Reactive Control** to support grid voltage
10. **High Short Circuit Current** contribution to ensure appropriate fault detection and clearance

Except for attribute #1, carbon (and emission) free, an appropriately designed, configured and operated CEA site can deliver on this entire suite of critical attributes. In the next section we discuss prospects for and examples of renewably powered CEA sites and urge that policymakers, regulators and key stakeholders adopt a "circular economy" framework to consider an expanded role of CEA in a decarbonization roadmap.

4. Developing Renewable Energy Powered CEA Sites (Circular Economy)

CEA coupled with CHP in a high-tech greenhouse, is the most sustainable way of growing food today. Currently, most CEA facilities utilize natural gas, but stakeholders and end-users alike are seeking renewable energy solutions, including biomass powered CEA. Thoughtful utilization of biomass-based feedstocks as a CEA fuel source provides a zero-emissions method to ensure decarbonized grid resiliency and promote local food production.

With anaerobic digesters providing the heating/power/cooling and CO_2 source pro-active policies, designed with from a circular economy perspective can simultaneously encourage food production, innovative waste management, and power/grid resiliency. The necessary organic materials that serve as the digestor's resource base, such as animal manure, wastewater biosolids, and food, prunings, and other clean waste, are available nationwide in varying compositions and total amounts. State organic waste policies are crucial here in shaping the utilization of CEA in conjunction with anaerobic digestors, in that these policies may dictate what organic materials may be used and in what manner. For example, New York State food waste law regarding the recycling of food waste and food scraps, made applicable to large generators of food scraps, including some grocery stores, restaurants, and colleges, are required to send food scraps to an available organics recycler, such as an anaerobic digester, if the generator is within 25 miles. This law should expand the utilization of food waste processing to generate renewable biogas that could be used to power CEA.

Food waste processing and anaerobic digestion is already being utilized to generate renewable biogas for local clean energy buyers by companies like Trenton Renewable Power, LLC, who describes their process as "partner[ing] with cities and businesses of all sizes to recycle food waste into premium compost, organic fertilizer and renewable biogas. The compost and fertilizer are sent to local farms and the biogas is used onsite to produce electricity that powers the facility and contributes renewable energy to the grid when it's needed most." Such a process could be replicated to provide onsite power to CEA facilities.

Recognizing the seasonal variability of food waste composition, some facilities have co-digested their food waste with other feedstock sources, such as animal manure or wastewater biosolids. For example, the Downers Grove Sanitary District Wastewater Treatment Plant in Downers Grove, Illinois powers its 750 kW engine-driven CHP system with biogas from co-digesting wastewater solids with fats, oils, and grease. Co-digesting feedstocks to produce biogas requires smaller amounts of any resource base and changes in composition would lessen the impact on a system's sensitivity, thereby mitigating problems arising seasonal feedstock variability.

Renewable energy powered CEA is currently being utilized in Ontario, Canada by Foothill Greenhouse. The site produces 20 kW of onsite power through PV, and a 3.2 MW CHP system. In addition to capturing and recirculating 100% of its irrigation water to use fertilizer more efficiently, the site utilizes wood-waste as a primary fuel source and recycles CO_2 to be consumed by plants in the greenhouse. This 15-acre farm can produce about 2400 tons of cucumbers, approximately 8 times more than field grown cucumbers. Recently, this site received unanimous approval from its local government to build a new 1.2 MW CHP to serve as a grid asset in Ontario.

A biomass-fired CHP plant recently commissioned in Andijk, Netherlands produces heat and electricity from prunings and yard waste, delivering renewable heat to six greenhouse companies. Independently conducted emission measurements certify this biomass plant's NOx emission reduction to be greater than 99%. Achieved using HoSt's ultra-low NOx innovative combustion technology, precise combustion temperature control, and highly automated control, CO_2 from flue gases is captured for use in greenhouses to stimulate crop growth. Excess heat and electricity can be sold to district thermal or electric microgrids (David Van Holde, 2023).

We've interviewed several sites in New York who are interested in developing a zero carbon CEA facility, powered by a waste fuel. Empire State Greenhouse has plans to build a 7-acre greenhouse at SUNY Cobleskill, situated about 40 miles west of Albany. The 300,000-

square-foot greenhouse slated to be built on a farm owned by the college, will run on renewable energy, grow vegetables year-round, create more than 150 full time jobs, and provide a living laboratory for student research (Jim Poole, 2022).

Ramsay Agriculture, LLC is developing an indoor hydroponic farm utilizing recycled gases from various waste sources in Jamestown, NY. Ramsay is currently soliciting partners from whom they would acquire specific feedstock to be utilized in an anaerobic digester that will produce methane gas fueling generators to produce heat and electrical power to power an indoor hydroponic farming operation. Ramsay's solicitation is somewhat unique in that they seek long-term agreements for either the provision of fresh produce to the site, or collection of suitable organic wastes from the site.

4.1. District Energy Systems Resilience and Circular Economy

The National Climate Resilience Framework defines resilience as the ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and disruptions. Climate change will bring extreme weather events that are more frequent and more severe. The attribute of resilience will be ever more valuable.

District Energy Systems ("DES") provide a platform for aggregating the demand and supply of a heterogeneous set of customers and energy sources. This reduces risks by providing multiple options for managing demand and delivering heating, cooling, and power services. DES has proven to be more robust by actively managing, across property lines, broad portfolios of energy demands and supplies. DES also provides a platform for technically feasible and economically viable thermal energy networks. New York State recently passed the Utility Thermal Energy Networks and Jobs Act (2022), which requires that all investor-owned utilities in New York begin developing pilots to test the technology.

Research conducted in European countries with high penetration of DES, such as Denmark, have demonstrated the ability to be more resilient in the face of the dual economic shocks caused by COVID-19 pandemic and the Russian war in Ukraine. DES has demonstrated the ability to lower price and supply volatility with the ability to switch to alternative fuels, large storage capacity, and combination of electricity producing and consuming unit. DES systems with storage being actively run, a mix of heat and power production optimally managed to the situation smooths price adjustments (Stochel, 2023).

DES enables the transport of thermal energy with less waste and higher energy efficiencies. Within a DES, connected electric power generating resources can be managed, coordinated, and optimized in sync with thermal energy needs. An illustrative case study is the Danish District Energy Company Hvide Sande, where the performance of an electric and thermal energy company actively managing a broad resource portfolio exhibited significantly superior performance in navigating energy price shocks. Production units included two CHP units at 3.7 MWe and 4.9 MWt, three 3 MWe Wind Turbines, Heat Pump 5 MWt, PV 9,500 m^2, and 3,200 m^3 hot water storage.

Data centers integrated with CEA are being implemented elsewhere. Such an application holds significant promise for this thesis of "conjoining" energy and food production and resiliency, with DES as an efficient resource aggregator. In Sweden, a $27.8 million agreement between Agtira and Greenfood has been signed for a cucumber cultivation plant in Boden, which facility will be the first of ten in the country. "The potential to recover residual heat from data centers and other industries is a huge and often unused resource." Another such example from Lévis, Quebec, is the Q-Scale data center, which claims that it will "produce 2,800 tons of small fruit and more than 80,000 tons of tomatoes per year" in greenhouses to be constructed adjacent to the facility utilizing residual heat rejected by the data center.

Also located in Quebec, Toundra Greenhouse is an agrothermic industrial park where heat and CO_2 produced from Resolute Forest Product's pulp mill are used to heat and supplement greenhouse CO_2 in an 8.5-hectare greenhouse. While not an example of coupling data centers with CEA, this agrothermic industrial park nicely illustrates a template for circular economy structures.

A circular economy can be described as a change in emphasis from profit seeking without regard to externalities, to economies that promote "a flourishing web of life, so that we can thrive in balance" (Raworth, 2017). There is increasing interest in adopting such solutions towards this end as the circular economy is included in national climate pledges. Each of the DES discussed above fit the criteria as they utilize the waste heat from a facility such as a data center, to realize the benefit in growing food at another facility, such as a greenhouse. Encouraging the adoption of technologies in furtherance of a circular economy that reuse resources that would otherwise be lost, is beneficial to both the environment, and the economic bottom line.

5. CEA with CHP Can Deliver a Suite of Ancillary Benefits

Growing local food in or near urban centers can have a number of "ancillary" benefits in addition to the central features mentioned above, including: addressing food deserts; public health; community engagement; skills training; community development; entrepreneurship; and local ownership.

5.1. The Potential Public Health Benefits of Growing Local Food

The environmental justice 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 that do not currently have access. However, simply siting a commercial CEA operation within, or near, a food desert offers no guarantee that the local community will have better access than before.

When implementing CHP into CEA projects, a policy goal for these projects should be to keep the benefits in the community rather than those benefits being passed on to larger corporations or entities. To achieve this will require a conscious effort from the industry and those organizing these projects. Food security should also be consciously considered when making decisions on future CEA projects. In a presentation on CEA and Food Security, Cornell Professor Chuck Nicholson noted that food security has many dimensions - Two important dimensions are physical access and economic access (Nicholson, 2021). According to Nicholson, CEA in food deserts has not increased access to fresh fruits and vegetables because the products themselves are still sold through traditional retail outlets. The industry must do better.

The ineffectiveness of CEA in providing food security and benefits to the immediate community 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 that maintain availability, access, and utilization of food over time (Jones et al., 2013). A potential benefit of CONJOINING food and energy resiliency, with onsite power, grid support and CO2 production, is the possibility that new revenue streams improve the economics of local food growing

5.2. Mixed Evidence of Carbon Reduction Benefits

There's mixed evidence on the CO_2 reductions from the high-tech greenhouse. The 2020, the electricity produced using natural gas fired CHP in greenhouse horticulture in the Netherlands was 10.3 billion kWh and by deploying CHP in greenhouse horticulture, the Dutch have reduced total CO_2 emissions by approximately 1.76 million tons (Smit & van der Velden, 2021). While the Dutch report significant CO_2 savings, we find little peer reviewed published evidence of CO_2 savings in New York, or other states in the northeastern United States. A Cornell study shows GHG impacts for greenhouses are roughly similar to those from 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., 2023). 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., 2023). 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, and compared a conventional, field-based production supply chain to two types of CEA-based supply chains (Nicholson et al., 2020). The CEA based supply chains fared better in terms of water usage and identified several factors that would undoubtedly change the global warming potential and total life cycle cost results in favor of greenhouses. Specifically, the type of design supported by 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, is ideally suited to realize these benefits.

More research is needed to provide accurate figures for carbon capture and reuse. There is a critical need for determining how much CO_2 is captured and recycled for acceleration of plant growth, where the CO_2 emissions from onsite CHP generation is used to provide CO_2 for the greenhouse.

Conclusion

CHP can provide food resiliency when utilized with high-tech CEA. 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. 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 Netherlands, participation in energy markets can be key to making CEA utilizing CHP competitive against traditional agriculture in more hospitable climates while lowering costs. While the current policy landscape in the Northeastern United States is not as conducive to direct electric sales as that of the Netherlands, the increased penetration of renewable generation may result in 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 technological 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 communities' energy and food supplies. 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 at an affordable price point. Utility regulators, grid operators and policymakers ought to send the right market signals so that the CEA industry will make required, incremental investments in controls, sensors, optimization algorithms that maximize societal values. Through the local production of food and energy, CEA with CHP can enable communities with resilient sources of food and electricity, while reducing carbon and allowing for the greater penetration of renewable energy in the grid.

This paper addresses two pillars of "*Resilient and Healthy Communities"*: (i) food resiliency, including fresh, local, high-quality food; and (ii) energy/power resiliency, including supporting critical infrastructure, and protecting vulnerable populations. We cojoin these pillars of resiliency, noting that some forms of CEA are unique insofar as they have both a high need for onsite power, and high flexibility in the production process. Further and quite importantly, we hypothesize that CEA is quite unique in that it has a considerable ability to time and/or intensity shift its energy use, without damaging the goods being produced.

Our objective with this paper is to lay out the case as to why CEA deserves greater public recognition and support. We've cited numerous working examples of CEA operating simultaneously in food and in power markets. We have pointed to research that has identified how utilizing dynamic lighting recipes and long photoperiods CEA demonstrates elasticity in power demand shifting from high price to lower priced periods. Finally we urge that across numerous agency jurisdictions: power markets, food and organic waste management, community planning far more attention must be given to the prospect of moving towards a circular economy. CEA can be an integral tool for communities looking to implement solutions that grow local, fresh, healthy food, integrating smart waste management, while generating onsite power and serving as a dynamic grid asset.

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