Energy, Greenhouse Gases and Production Agriculture in New York State

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ABSTRACT

Producing fresh vegetables and fruits in controlled environments is a sector of New York State agriculture that could experience explosive growth. The goal of the Government/University partnership described in this report has been to identify energy management opportunities, both energy efficiency and electric peak load management strategies, to minimize the burden of CEA (Controlled Environment Agriculture) facilities on the utility grid in New York State. This collaboration has resulted in a system of fruit and vegetable production that offers many environmental and energy advantages to our current system in the U.S. Initial work resulted in development of a (patented) daily light integral control algorithm that has been tested and proven in a working greenhouse. A second stage has ended with a (patented) control algorithm to optimize the synergy between light and CO_2 for plant growth. Computer simulations based on the algorithm predict greenhouse lighting can be reduced by half when CO_2 is controlled optimally, with little change of crop productivity. Implementing the algorithm in a working greenhouse is planned. A next stage, yet to be started, would be to install a small refrigeration system in a working greenhouse, for limited air conditioning and humidity control, to prevent ventilation in response to modest cooling loads and permit yet more hours of CO_2 supplementation. A concurrent effort involves analysis of the energy and carbon footprints of several CEA and seasonal outdoor products grown in New York for local consumption, with comparison to the same crops when imported.

Introduction

This paper will present one example where critical questions of energy and environmental constraints are being addressed. Specifically, America and the world are facing the twin problems of global oil depletion and global climate change. Many people would add a third related issue - that of overpopulation. All these issues represent a complex interplay of politics, religion, policy and technology. In addition, there is no consensus, today, that all these issues require society's attention. One issue where there is consensus is that energy, especially oil, will become increasingly expensive in the coming decades. Concomitantly, there is growing interest on the part of consumers for locally-grown food and part of this interest is based on an awareness of the negative energy and environmental implications of our global food system. As a complement to seasonal field production of produce in New York State for local markets, Controlled Environment Agriculture (CEA, i.e., greenhouses) represents a potential growth industry for production of fresh fruits, vegetables, herbs, and other, high-value crops, year round, for local and regional markets. CEA represents an industry where a combination of policy and technology will help advance the industry while creating a sustainable, and geographically dispersed, agricultural base focused on local food production for local consumption. Fresh fruits and vegetables available in New York State have typically traveled great distances prior to sale and shipping distances appear to be increasing. Pirog and Benjamin (2003) studied fresh produce arriving at the Chicago Terminal Market. In 1981 the weighted average travel distance was 1,245 miles. In 1998 the average distance was 1,518 miles.

Because the West Coast dominates the fresh produce market, average travel distances to New York State are likely to be greater and to show a similar temporal increase.

From an energy perspective, locally-grown vegetables produced in CEA facilities are more dependent on electricity and less dependent on liquid fuels in their production and transportation to (local) markets. The energy for CEA production is almost entirely electricity (space heating is minimized - reduced by approximately half - by heat from supplemental lighting). Fourteen percent of New York State electricity in 2005 was generated from oil. That number is expected to decline in the future as non-oil (and non-carbon) fuels take over more of the generation mix in New York State. For transportation of vegetables from a local CEA facility to local markets, oil requirements will be the same as those for transporting local field crops to local markets, or for the local distribution of long haul produce from the West Coast. If one compares local CEA production and transportation to imported vegetable production (much is air freighted from Europe), the energy advantage for production and transportation in local CEA is more than 3 to 1 (Reinhardt, 1994).

This represents an extreme departure from the U.S. conventional (global) food production and distribution system based on cheap oil and very large, and increasing, distances between growers and consumers. Horticultural products from CEA facilities will have consistent high quality, will be available year-round, will be safe to eat, and can be grown pesticide-free with limited environmental discharge. These crops will not be organic because they require synthetic fertilizer, but the fertilizer can be used very efficiently with no run-off. Reliable production of CEA crops will depend on considerable electric energy use for supplementary lighting in the winter and ventilation in the warmer months.

There is a variety of reasons why a shift to CEA production around the world is happening. These reasons include increasing water quality problems and field crop contamination issues in major vegetable growing states, health and safety concerns stemming from food security considerations, increasing pressures for land development, and in response to rising energy and fertilizer costs. While many of the reasons driving this production shift are just now becoming important issues in the minds of consumers, many of these issues have been recognized and studied over the last 15 years by NYSERDA and Cornell University in association with several business partners. One overriding objective for the Cornell researchers and our business partners has been to optimize crop production so as to maintain product quality and maximize revenue for the grower.

At that time, NYSERDA's interest in CEA was based on two energy factors over and above the economic and environmental factors cited above. These two energy factors were the following:

1. CEA for local markets requires relatively little oil. The traditional production and delivery of produce from far-off production centers to eastern markets uses oil in both production and long-haul transportation of the product to market, usually in refrigerated trucks. CEA requires less oil input, mostly for fertilizer, some for electricity generation, perhaps some for greenhouse heating, and usually for relatively short-haul distribution of product to local or regional markets. Typical supplies of fresh produce from Sunbelt states will travel over 1500 miles in a truck to reach eastern market distribution centers.
2. As an expanding industry in New York State, CEA could have a significant impact on electricity use and the utility grid. Most energy use in CEA is electricity to run grow lights, fans, pumps, and other motors. How much electricity is required and whether this electric load is on-peak or off-peak are questions that might have significant implications for the State's utility system. In addition, NYSERDA has been interested in opportunities for on-site power production using solar or biomass energy sources to reduce impacts on the

electric utility system. Microturbines provide yet another possibility. NYSERDA has undertaken several alternative energy projects with CEA facilities, but they have been outside NYSERDA's collaboration with Cornell.

Because the potential impact on electric utilities in New York was a factor, NYSERDA began its support of CEA research at Cornell in partnership with the State's electric utilities. The Cornell research supported by NYSERDA had two specific energy objectives. First, to identify energy management opportunities in operating CEA facilities for energy efficiency and, second, for electric peak load management (including renewable on-site power generation) to minimize operating energy costs for growers and minimize peak load growth for electric utility systems.

The development and growth of CEA production of fresh produce in New York State in future years will be the result of many actions by NYSERDA, other New York State entities such as the Department of Agriculture and Markets, Empire State Development, The Farm Bureau, The New York State Farm Viability Institute, various local agricultural and business development organizations, and numerous academic institutions in New York State. This paper will focus on the collaboration of NYSERDA and Cornell University, an effort that has set the stage for the dynamic growth of a CEA industry in New York State. This collaboration has resulted in a system of vegetable production that offers many environmental and energy advantages to our current system of vegetable and fruit production and distribution in the U.S. This presentation will summarize past, current and anticipated future collaborations of the NYSERDA/Cornell team.

Environment Control Algorithms to Optimize Energy Use

The daily light integral, occasionally termed the "light sum", is defined as the number of photons received during one day, per unit area of plant growing area, where the photons are characterized by wavelengths within the region of the light spectrum effective for photosynthesis (400 to 700 nm). The heart of the CEA system developed at Cornell has been control algorithms to provide a pre-determined daily light integral (kept the same from day-to-day for consistent growth and quality), and to apply carbon dioxide in a way that optimizes the efficiencies of natural and supplemental lighting. Controlling the daily light integral in real time, and adding CO_2 concentration control, have been ground-breaking research at Cornell. Many references can be found in the extant research literature that describe plant responses to light (but only a few to light integrals) and many others that describe plant responses to carbon dioxide enrichment. None have described efforts to optimize daily light integral control or simultaneously control the two.

Daily light integral control requires two environmental modification systems be installed and controlled in a greenhouse: supplemental lights and deployable shades. Supplemental lights are grids of High-Pressure Sodium (HPS) or Metal-Halide (MH) luminaires mounted over the growing area. The preferred light source is HPS because of its greater efficiency. Deployable shades are typically made of cloth aluminized in strips that transmit 25 to 75 percent of the natural light. Shades can be stowed by retraction into an accordian-folded configuration, or rolled. The former is more typical with shade sections that are relatively short, such as deployment from roof truss to roof truss, or one side of the greenhouse to the other. Shades are frequently closed at sunset for some energy retention during nights.

Daily light integral control is based on providing the same total number of photosynthetically-active photons every day to the growing crop. Light is the only form of energy plants can use and consistent lighting leads to consistent production. The efficacy with which light is used depends on whether light, or some other factor, limits growth. When light availability is not limiting, and nutrient availability is optimized through proper hydroponic practices, carbon dioxide concentration will likely be the first factor to limit growth. Increasing carbon dioxide concentration above the natural ambient level makes light more effective and can lead to significant increases of growth, productivity and, frequently, quality.

Development of the light integral control algorithms may be viewed as progression along a three stage continuum. The first stage (only daily light integral control) has been proven in practice, the second stage (optimized and synchronized daily light integral and CO_2 control) has been demonstrated in computer simulation but not yet in practice, and the third stage (humidity control) has been partly demonstrated in simulation but needs further refinement. Development of the stages is described in the remainder of this report.

Daily light integral control. The first algorithm (Albright, 1998) was developed to control supplemental lights and movable shades to provide consistent (day-to-day) daily light integrals while using off-peak electricity to the greatest extent. Several years of using the algorithm in a commercial demonstration lettuce greenhouse originally owned by Cornell (www.cornellcea.com) and now owned and operated by Challenge Industries, Inc., (www.fingerlakesfresh.com) have shown it controls supplemental lights and movable shades accurately. The algorithm provides consistent daily integrals without conflicting use of shades and lights and delays supplemental lighting, as much as possible, into the off-peak electric rate time of day. Several years of operating experience, plus an energy audit conducted four years ago, provide a sound data base for CEA operation with supplemental lighting and daily light integral control. Operating experience with the light control protocol shows control and energy use closely follow predictions of the computer simulations that accompanied the algorithm development.

As a perspective on daily light variability, in Figure 1 is a graph showing one year of daily solar integrals for Ithaca, NY. The data are expressed in units of Photosynthetic Photon Flux Density (PPFD), which is the measure of light that relates most closely to plant growth. The PPFD is the flux density of photons between wavelengths of 400 and 700 nanometers, expressed in $\mu mol\text{-}m^{-2}\text{-}s^{-1}$. The great day-to-day variability of the data shows the difficulty of obtaining consistent plant growth on a daily basis and, in addition, the low probability of being able to use historical averages of insolation as a basis of accurate daily light integral control strategies anywhere in climates similar to upstate New York. Furthermore, even if available, weather forecasts of a day's expected insolation are not likely to be accurate when made at sunrise. These two difficulties were the motivation to develop the rule-based daily light integral control algorithm mentioned above.

Figure 1 also contains a graph showing one year of simulated control based on the actual data shown in the graph. Control during winter is noticeably more precise because there is the entire night (until the next sunrise, or end of the off-peak period) to achieve the goal. When days are bright, and the movable shade partly transmissive, exceptionally bright days and sudden changes of sky conditions can lead to slight overshoots that can not be overcome by removing light later in the day. However, seldom was the control error more than ten percent.

Quantified energy needs and supplemental lighting costs for a typical greenhouse (descriptive data for the greenhouse construction are in Albright, et al., 2000) are summarized in Table 1. It should be noted that, even in Ithaca when a high daily light integral was desired, two-thirds of the plant lighting for the year was obtained from the sun and, of the remaining one-third obtained from supplemental lighting, more than two-thirds came during off-peak lighting hours when electricity is less expensive and the CO_2 footprint of combined electricity generation may be smaller

Figure 1. Simulated Daily Light Integral for One Year Inside a Greenhouse with and without Daily Light Integral Control, Daily Goal of 17 mol-m^{-2}, and 70% Greenhouse Transmissivity

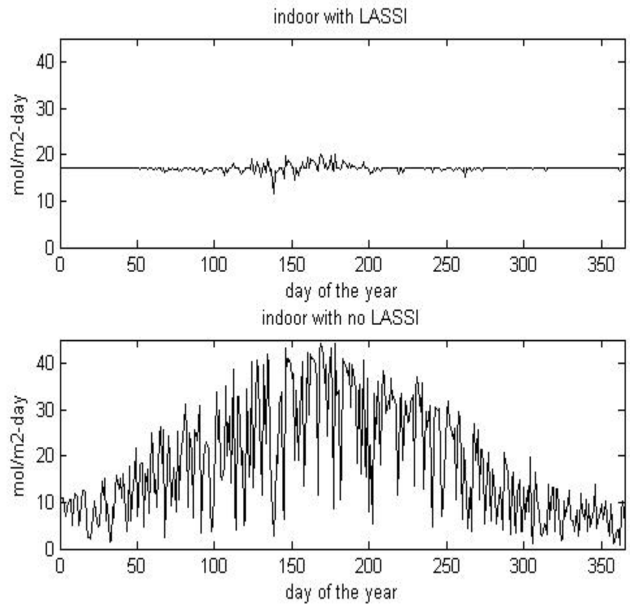


Table 1. Yearly Heating and Lighting Requirements, As Affected by Supplemental Lighting Daily PPFD Integral Target, Based on Simulation and 1988 Hourly Weather Data for Ithaca, N.Y.

Parameter	Daily PPFD Integral Target, mol-m^{-2}				
	None*	10	14	17	20
Yearly Heating, GJ-m^{-2}	2.87	2.38	1.92	1.49	1.17
Yearly Heating Reduction, %	-	17	33	48	59
Yearly Total PPFD, mol-m^{-2}	4385	4135	5286	6260	7233
Yearly solar PPFD, mol-m^{-2}	4385	3512	4000	4376	4760
Yearly Added PPFD, mol-m^{-2}	0	623	1286	1884	2473
Yearly Lighting, kWh-m^{-2}	0	282	583	855	1122
Lighting Off-Peak, %	-	93	78	68	63
Yearly Hours Heating	6289	5433	4867	4326	3718

* Daily PPFD integral target of 17 mol-m^{-2} for movable shade operation

Using supplemental lights obviously affects a greenhouse's thermal environment. Luminaire efficacy determines the partition of electricity between light and heat, virtually all of which is added to the greenhouse air (remote ballasts are not common with greenhouse luminaires and are impractical for large greenhouses). Thermal energy convected from luminaires and ballasts adds heat to the air. Radiant energy striking plants and other surfaces adds both sensible and latent (after evaporation or transpiration) heat to greenhouse air. Solar energy (that transmitted through the greenhouse glazing) is partitioned approximately equally between sensible and latent heat.

Table 1 contains calculated values of heating requirements summarized for a "typical" greenhouse. No use of the movable shade as a nighttime thermal screen is included in the calculations. Heating data in Table 1 show yearly benefits of supplemental lighting as a heat source. More detailed data show there is little benefit during summer, for days with heavy cloudiness when lights are needed are usually warm at night and little heat is needed. Late autumn days showed the greatest benefit of heat from supplemental lighting. In November, for example, approximately 90% of the heat from lighting was useful at a daily PPFD target of 20 mol-m^{-2}, due to characteristics of the local climate where late autumn is especially cloudy but only moderately cold. Comparable weather characterizes much of the Northeast and northwestern Europe, for example.

Table 1 provides data for an overall view of lighting and heating interactions for the year of weather data used. All unit area results are based on floor area. Of interest is the non-linearity of electricity needed for lighting as the daily light integral target increases from 10 to 17 mol/m^2. For example, when the daily target is reduced from 17 to 14 mol/m^2 the total light received is reduced by 18% (6260 to 5286 mol/m^2) while the electricity for lighting is reduced by 47% (855 to 583 kWh/m^2) because natural light plays a larger role in reaching the target.

However, it must be noted that additional adjustments for lighting design would be required in a more complete design. For example, the assumed movable shade system provided 60% shade when closed. This was inadequate to limit the daily PPFD integral target to 10 mol-m^{-2} during many summer days, thus the yearly average daily PPFD was significantly above the target (which was not important for the purposes of this simulation). Furthermore, the design PPFD of 200 μmol-m^{-2}-s^{-1} was insufficient to achieve the target of 20 mol-m^{-2} on the darkest winter days and the yearly averaged daily PPFD integral missed the target by one percent. These slight differences, however, are expected to make no noticeable difference in conclusions inferred from the general results.

It is obvious from the data that supplemental lighting can greatly influence greenhouse heating loads in moderately cold and cloudy climates such as Ithaca, N.Y. For the assumed weather data and greenhouse characteristics, natural light provided the majority of the PPFD daily target when averaged over the year. However, supplemental lights offset heating by about half at a daily target of 17 mol-m^{-2}, for example. Electricity is a more costly source of heat than typical heating fuels. However, in evaluating the benefits of supplemental lighting for greenhouses, the data suggest reduced heating loads should be considered among the benefits in a total economic analysis, especially when off-peak electricity rates are modest and heating fuels are expensive. Note that most lighting occurred during off-peak hours, which are times of greatest heating need. This is in contrast to electricity for fan ventilation – which is primarily during on-peak hours (Albright, 1994).

Month-to-month fluctuations of lighting energy use and cost are large. Nevertheless it can not be generalized that, for a solar climate such as in central New York State, all summer supplemental lighting needs will be limited to off-peak hours. Supplemental lighting is needed much less during summer, but some summer days have natural light totals similar to totals characterizing the depths of winter. These dark summer days cause on-peak metered demand during summer equivalent to on-peak metered demand during winter. Major demand cost savings can be achieved if lighting control is modified to preclude on-peak lighting during any summer months (at least June through August), with deficits compensated by raising target integrals for the following days when more natural light is likely to be available. Plant growth data obtained at Cornell (as yet unpublished) as part of the initial research showed plants, at least lettuce, can integrate daily light integrals over approximately three days as long as day-to-day variations are not more than 25% of the daily target. Precluding on-peak lighting should benefit any summer-peaking utility, as well as reducing demand on liquid fossil fuel power stations. Simulations incorporating this factor into the control algorithm resulted in slightly greater day-to-day variations of light integral (because the daily target was not constant) but the averages for the summer months were almost exactly on the target because seldom are there two very dark days in a row.

Thermal environments in greenhouses are determined by many interacting elements. Some are under the control of a greenhouse systems designer, some are not. Supplemental lighting is becoming increasingly important as CEA grows more "sophisticated" and light control should be a matter of close attention for greenhouse engineers. Light is as important as air temperature for plant growth but has traditionally been neither designed nor controlled well. Greenhouse operators do not tolerate widely (and randomly) varying air temperatures from day to day. Nor should they tolerate widely varying PPFD integrals if they have installed supplemental lights and deployable shades. The work described above has provided a practical means to implement simple computerized light control to achieve accurate and consistent daily light integrals.

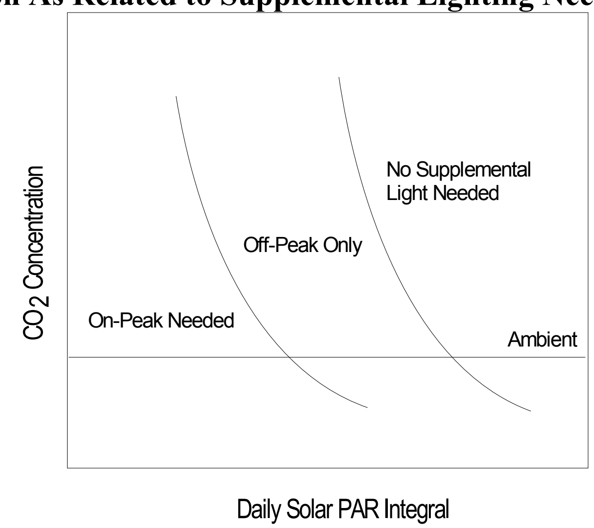
Integrated daily light integral and CO_2 concentration control. A second algorithm (Albright, et al., 2007) extended the PPFD integral control algorithm to add CO_2 concentration control. Carbon dioxide supplementation makes light, in effect, more effective. The algorithm is yet to be tested in an operating greenhouse but computer simulation suggests greenhouse lighting can be reduced by half for lettuce production in Ithaca.

Increasing aerial CO_2 concentration (within limits) improves photosynthetic efficacies of C3 plants. Supplemental lighting is typically expensive to operate, whereas CO_2 resources are generally inexpensive. However, air infiltration and ventilation are CO_2 loss paths whereby supplementing CO_2 may become more costly than electricity for supplemental lighting to achieve comparable growth. Whether it is cost effective to add CO_2 or operate supplemental lighting, and what is the optimum combination of CO_2 concentration and light integral for the next decision period, are important questions that must be answered to implement optimized computer control and test the algorithm.

Numerous models have been proposed (e.g., Ferentinos, et al., 2000) that explore optimized combinations of the daily light integral and CO_2, but generally they are not configured for real-time control purposes. In Figure 2 is a graph containing the conceptual aspects of integrated light integral and CO_2 control. When the daily natural light integral is high, ambient CO_2 suffices. When the daily natural light integral is modest (central region of the graph), only off-peak lighting hours are needed, possibly augmented by CO_2 above ambient to increase light use efficiency. When the daily natural light integral is low, both on-peak and off-peak supplemental lighting will be needed, with less needed when CO_2 is supplemented than when it is not.

Additionally, higher CO_2 concentrations delay the need for on-peak lighting. This is important for more than energy or cost savings. In New York State, with its relatively high dependence on hydropower and nuclear energy, which generate continuously, all reductions of electricity use will lower use of fossil fuels and reduce discharge of CO_2 into the atmosphere. Shifting more use to the off-peak period reduces demand on peaking generating stations that rely on petroleum fuels and natural gas. Finally, by delaying supplemental lighting into the late afternoon, or later, provides a better match between need for space heating and this, in turn, expands the potential to obtain CO_2 from the greenhouse heating system flue gas. This is a well-accepted technology, particularly in Europe (de Zwart, 1998). If CO_2 is obtained from (cleaned) flue gas, its cost is likely to be so low that CO_2 supplementation to the upper boundary will be economically attractive, further reducing need for supplemental lighting.

Figure 2. State Spaces (Conceptual) of Daily Light Integral and Carbon Dioxide Concentration As Related to Supplemental Lighting Need and Timing



Careful control of the daily growth rate becomes possible when light and CO_2 are controlled within tight limits (Both, et al., 1998; Albright, et al., 2000). Coordinated management of the two can substantially increase yields and lower production costs beyond levels achievable with practices based on adding supplemental light only, supplementing CO_2 only, supplementing each independently, or simply accepting what the sun provides.

A generic greenhouse was assumed for simulation purposes (see Albright, et al., 2004). The greenhouse and its design were based on the CEA lettuce greenhouse operated at Cornell University (www.cornellcea.com). The model was programmed as an application in Java and one year (1988) of hourly weather data from Ithaca, NY, was used for calculations.

A base case scenario without CO_2 supplemented provided the data in Table 2. Table 3 contains comparable data but with supplemental CO_2 enabled. The most obvious result of the simulations is the predicted savings of both energy and operating cost. Nearly 40% costs savings are realized by adding carbon dioxide to make both natural and supplemental lighting more efficient.

Table 2. Yearly Lighting Requirements with No CO_2 Supplementation, Based on Simulation and 1988 Hourly Weather Data for Ithaca, N.Y.

Parameter	Value
Total cost of lighting	US$18,670
Lighting cost/m^2	US$25.12
Hours of lighting	2766
Mol/m^2 from supplemental lighting	1792

Table 3. Yearly Lighting Requirements with CO_2 Supplementation Capability up to 1600 ppm, Based on Simulation and 1988 Hourly Weather Data for Ithaca, N.Y.

Parameter	Value
Total cost of lighting	US$9630
Lighting cost/m^2	US$12.96
Total CO_2 cost	US$1860
CO_2 cost/m^2	US$2.50
Total Lighting + CO_2 cost	US$11,500
Total Lighting + CO_2 cost/m^2	US$15.50
Cost savings compared to base case	US$9.60/$m^2$ (38%)
Hours of lighting	1451
Mol/m^2 from supplemental lighting	940

A secondary benefit is that less supplemental lighting was needed during on-peak hours. The base case, with CO_2 supplemented and coordinated light control, shows an energy savings of 47% and an operating cost savings of 37%. A lower greenhouse light transmittance raises costs. If the greenhouse is less air tight, costs increase significantly – both for heat and CO_2, if supplemented.

The majority of hourly CO_2 control decisions were to provide either the maximum allowable concentration of CO_2 (1600 ppm in the simulation) or the minimum (ambient). Relatively few hours resulted in optimum CO_2 concentrations between the two extremes; the base case showed 237 of 1451 hours of supplemental lighting were with an optimum CO_2 concentration between the extremes. These hours were characterized by a required ventilation rate (for temperature control) so small as to be only slightly above the assumed air infiltration rate.

More sophisticated greenhouse air temperature control could be implemented to improve the simulation presented here. For example, the program was written to keep greenhouse air temperature at the set point by using ventilation. The prediction errors where actual outdoor air temperature was one or two degrees above the predicted value would lead to increased ventilation and CO_2 venting. Most greenhouse air temperature control includes a “dead band” of no control actions between the heating and cooling temperature set points, followed by temperature steps of two or more degrees between ventilation/cooling stages. Permitting such temperature drifting would improve the efficacy of the control algorithm. However, even without adding this nuance, results show integrated control of supplemental light and CO_2 can significantly reduce both energy use and operating cost.

Potential use of limited mechanical air conditioning and dehumidification. A further step of temperature and CO_2 concentration control has been explored by computer simulation (only). Although the simulations for light integral and CO_2 concentration indicate considerable potential to save energy and electricity, and reduce atmospheric release of CO_2 from power generating stations, the simulations showed there were many other hours when ventilation was required above the threshold where the cost of lost CO_2 more than offset the value gained. One situation was during cool and moderately bright fall and spring days. On these days, natural light was insufficient to provide the entire daily light integral need, yet, ventilation for temperature control was above the threshold, at least during late mornings and afternoons. The other important situation was during winter days and at night at other times of the year when outdoor air temperature was only moderately cold. The greenhouse structure, when the outdoors is cold, provides a vigorous passive dehumidification of the greenhouse air. Humidity limits are important for plant growth. High relative humidity encourages development of plant diseases such as mildew. Additionally, particularly with lettuce, insufficient plant transpiration leads to a physiological disorder termed “tip burn” that distorts growth and makes the crop unmarketable. If outdoor air is not sufficiently cold for passive dehumidification, normal greenhouse control imposes ventilation for humidity control.

Neither of these situations creates a large cooling or dehumidification load. The concept is not to air condition greenhouses on hot summer days with bright sunshine; daily light integrals on such days suffice at ambient CO_2. The concept is to keep the vents closed when modest ventilation is needed for temperature control, but at a flow rate that makes CO_2 supplementation uneconomical.

An extensive computer study was completed (Henderson and Albright, 1995) to simulate operating a greenhouse with a small refrigeration system. Several mechanical cooling systems were considered: conventional air conditioning, air conditioning with condenser reheat, air conditioning with a controllable heat exchanger and condenser reheat, and a desiccant system. Results showed the expected mix of sensible and latent loads in a greenhouse can be met with a conventional air conditioning system and the added cost and complexity of reheat and heat exchanger options are not likely to be economically worthwhile. Results showed, for a greenhouse such as the commercial production module described above, mechanically cooling the greenhouse leads to lower operating cost than other options. Annual savings due to mechanical cooling were predicted to be $0.85 per square foot of greenhouse at on- and off-peak electric rates of $0.10 and $0.05 per kWh. Today’s costs are higher, of course. Simple payback of the added cooling was calculated to be 12 years at an installed refrigeration cost of $750 per ton. Many scenarios of costs are possible, but in general the conclusions were that the concept of modest refrigeration capacity may be well worth considering for CEA facilities as a means to reduce energy requirements, reduce adding CO_2 to the atmosphere, and reducing operating as well as total costs.

Energy and CO_2 footprint scoping study. Coincident with the computer simulation and greenhouse experimental efforts described above, a paper study has begun of the energy types and quantities required to grow and ship selected types of fresh produce into New York State from open-field sites outside the state. From data available in governmental data bases and published literature, indices for each of the crops are being developed, weighted as to impact by field production outside the state, for comparison to local production in CEA facilities. The two indices consider energy and CO_2 production. Weighting is based on several factors: the amount of produce shipped from each source, the distance to the source, production methods at the source, and shipment requirements (such as refrigerated trucks) from the source to central New York State. This study is a collaborative effort of NYSERDA and the Cornell University CEA program.

Conclusions

Many factors are combining today that could lead to the emergence of a vigorous CEA industry in New York State and other places in the Northeast. Additionally, certain fresh vegetable and fruit growers (such as in California), faced with water shortages, pressures for land development, farm labor shortages, food safety issues, food security concerns, and energy issues, may consider a retreat from large centralized production facilities originally sited to take advantage of good weather and soil, and relocate into CEA facilities nearer population centers on the East coast where they can focus on local food production. A long collaboration between NYSERDA and the Cornell University CEA program has led to an enhanced production system for greenhouse vegetables that provides high quality products every day of the year while optimizing energy use. Central to the system are patented light and carbon dioxide concentration control algorithms capable of reducing energy requirements for supplemental lighting to the level where the crops have a net energy advantage compared to similar outdoor crops grown elsewhere and shipped into New York State. Local production of CEA crops in New York will require more electricity and less liquid fuels for production and transportation. This shift makes control of CEA facility electricity demand and use important for local utilities because of the ability to shift the majority of use to off-peak hours and smooth demand during operating hours.

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