Abstract

Plant factories (PFs), multi-layer production in opaque warehouses, are novel production systems with many potential benefits and some key impediments, notably, energy consumption. The economic viability and environmental footprint of PF facilities depend on energy consumption associated with lighting, heating, ventilation, and cooling to the production space. Light and energy-system modeling can inform designers and investors about the energy requirements and economics related to a proposed or existing facility. Previous models have focused on comparing energy consumption between PFs and greenhouses (GH) in a limited number of production scenarios. There is little information regarding water consumption and carbon emissions at PF facilities and how energy conservation measures (ECMs) may impact water use efficiency, upstream emissions and purchased carbon-dioxide. The objective of this study is to model energy and water use in PFs growing lettuce in five U.S. locations (New York, NY, Los Angeles, CA, Seattle, WA, Chicago, IL, and Atlanta, GA) with three types of ECMs: installing lighting fixtures with high photon efficacy, introducing outdoor air for cooling through use of an air-side economizer, and maintaining elevated levels of carbon dioxide in the crop production space to enhance photosynthesis. Building energy modeling (BEM) software EnergyPlus was employed to simulate environmental conditions and associated energy consumption. Energy consumption ranges from 6.2 to 12.0 kWh kg^{-1} fresh weight of lettuce produced depending on design and operational choices. Water consumption for irrigation and production operations ranges between 2.0- and 9.8-liters of water per kg (FW) lettuce produced. Beyond operating parameters, the primary emissions associated with energy consumption at the facility varies widely due to the energy mix of each location’s grid, ultimately ranging between 0.6 and 3.9 kg carbon dioxide equivalent emissions per kg (FW) lettuce produced. We conclude that locating PFs in areas with a cleaner grid and employing these ECMs can reduce the energy consumption associated with growing lettuce indoors, though there are important tradeoffs to consider between water, energy, and supplemental carbon-dioxide in design.

Keywords

Energy Modeling, Plant Factory, Energy-Efficiency, Water-Use-Efficiency, Indoor Food Production

Nomenclature

Abbreviations	Descriptions
ACH	Air changes per hour
ACR	Air Change Rate
AHU	Air handling unit
BEM	Building energy modeling
CAV	Constant air volume
CEA	Controlled Environment Agriculture
CO_2	carbon dioxide
COP	Coefficient of Performance
DLI	Daily Light Integral
DOE	Department of Energy
DW	Dry-Weight
ECM	Energy Conservation Measure
EPA	Environmental Protection Agency
FW	Fresh-Weight
GH	Greenhouse
HVAC	heating, ventilation, and air-conditioning
LAI	Leaf Area Index
PAR	Photosynthetically active radiation
PF	Plant factory
PPFD	Photosynthetic photon flux density
TMY	Typical Meteorological Year

1. Introduction

The global population is projected to reach 9.7 billion by year 2050 with two-thirds of the population expected to live in urban centers (United Nations, 2019), increasing food demand and further concentrating demand in urban areas. Controlled environment agriculture (CEA) and urban agriculture are increasingly popular models proposed to supplement traditional agricultural production methods in this context of a rapidly increasing human population. CEA refers to a variety of technology-based crop-production systems (typically soilless) that aim to facilitate plant growth by controlling one or more environmental factor such as light, temperature, humidity, or nutrient supply (Gómez et al., 2019). CEA can also serve as a measure to increase food security for areas with limited land resources, harsh growing environments, or strong dependence on food imports (Lamalice et al., 2018). Global interest in CEA has risen dramatically and the vertical farming market was projected to experience 25% compound annual growth through from 2021 to 2026 (Fujiwara et al., 2016; Wood et al., 2020; MarketsandMarkets, 2021).

All types of CEA operations aim to influence environmental conditions or nutrient supply of crops to support productivity, though there are various types of CEA facilities with a range of operational complexity. For example, high tunnels are relatively inexpensive structures that allow a grower to extend their growing season, but do not offer much opportunity for active environmental control since they are typically unheated and not enclosed. Greenhouses (GHs) are more enclosed structures, which provide more opportunity for control over environmental variables by employing heating, lighting, shading, ventilation, and cooling. Plant factories (PFs) or PFALs (PFs with artificial lighting) are multi-layer production facilities in opaque warehouses which offer complete control over the climate and lighting systems at the cost of higher energy consumption and higher initial investment (Kozai and Niu, 2016; Lubna et al., 2022; Nicholson et al., 2020). Skyscraper farms have been proposed to maximize space-use efficiency while utilizing natural light (Despommier, 2011), though the light resource may not be sufficient to make a large impact on reducing energy consumption (Eaton et al., 2021). The economic viability and environmental impacts of CEA facilities like GHs and PFs are largely dependent on the energy consumption associated with providing lighting, heating, ventilation, and cooling to the production space (Nicholson et al., 2020). While there is decades of research in greenhouse climate modeling, controls optimization, and energy consumption (Zwart, 1996; B.H.E. Vanthoor et al., 2011; B. H. E. Vanthoor et al., 2011; Vanthoor et al., 2012; Rodríguez et al., 2015; Iddio et al., 2020; Katzin et al., 2022); given the short history of research into PFs, there are relatively few publications dedicated to characterizing PF energy-system models and modeling production scenarios (Graamans et al., 2018; Harbick and Albright, 2016; Kozai and Niu, 2016; Weidner et al., 2021; Zhang and Kacira, 2020).

PF energy modeling efforts have largely focused on studying the relative energy intensity of PFs as compared to GHs without studying a large range of potential configurations, instead comparing selected configurations in different geographic locations. (Harbick and Albright, 2016; Graamans et al., 2018; Weidner et al., 2021). Harbick and Albright (Harbick and Albright, 2016) used building energy modeling (BEM) software EnergyPlus to model the PF environment, comparing PF to GH energy consumption in 4 US locations. Benis et al (Benis et al., 2017) used BEM software to develop a decision support workflow for studying indoor agriculture in urban contexts, providing case studies for tomatoes grown in indoor farms and urban greenhouses. Li et al (Li et al., 2020) developed another high-level decision support framework for the design and operation of more sustainable urban farming systems, building a technoeconomic optimization problem to maximize the net present value of a given production facility and provides a case study in Singapore, comparing several farming options with renewable energy integration. Graamans et al (Graamans et al., 2018) conducted a lettuce PF vs GH comparison in several locations, calculating unit resource consumption and energy loads of a chosen PF configuration to two GH configurations. Weidner et al (Weidner et al., 2021) compared PF food production to two GH configurations, optimizing the setpoint parameters to different climatic conditions across ten geographic locations. Zhang and Kacira (Zhang and Kacira, 2020) compared energy consumption of PFs and GHs growing lettuce in 6 geographic locations. Though several PF configurations were considered, the scope of analysis was restricted to energy while leaving important operational parameters unexplored including essential humidity controls, supplementing CO_2 to the production space and higher lighting targets for more crop yield, all of which can affect the unit resource consumption

Most previous studies did not characterize a large range of potential configurations, instead comparing selected configurations in different geographic locations. Moreover, the analyses from these studies did not gain consensus as to resource use intensity of PF food production, or the most efficient configuration; with different studies reaching conflicting conclusions. For example, (Graamans et al., 2018) found that PFs were more energy efficient than even the most efficient GHs, while (Weidner et al., 2021) found that open GHs were substantially more energy efficient than plant factories in all ten locations studied. (Zhang and Kacira, 2020) found PFs superior to greenhouses in cold climates and vice versa in hot climates, while (Harbick and Albright, 2016) found PFs to be inferior in all cases. The findings are in tension in part due to the high variability in PF design, modeling parameters, and scope of analysis. Assumptions about building construction, lighting efficacy, HVAC configuration and level of CO_2 supplementation can impact predicted resource consumption, and the expected viability of PF food production. More recently, studies have investigated how energy conservation measures (ECMs) can impact the resource use efficiency of PFs. (Graamans et al., 2020) characterized potential energy savings of early stage design decisions, considering a range of building façade designs, finding that facility energy consumption can be reduced by around 10%. (Wang and Iddio, 2022), conducted an energy audit at an existing PF and identified energy conservation measures related to addressing equipment malfunction and controls to yield 48% savings of natural gas in an existing PF.

Design decisions will not only affect energy consumption but can also affect water use efficiency, supplemental CO_2 consumption, and upstream carbon emissions. However, knowledge of the environmental impacts of many PF design options and operational choices remains limited (Engler and Krarti, 2021). The interactive effects of PF design options on energy consumption, water-use efficiency, and CO_2 emissions have not been evaluated. Characterizing the effects of a range of inputs on predicted resource consumption in terms of energy, water, and carbon impacts of different design options can provide important knowledge for PF designers to tailor production to meet specific constraints (e.g., locations with water-scarcity) and environmental goals (e.g., reduced CO_2 emissions). The objective of this study is to assess resource use and upstream emissions of multiple PF lettuce production scenarios in five U.S. metropolitans. Three design alternatives or energy conservation measures (ECMs) were evaluated: installing lighting fixtures with higher photon efficacy, introducing outdoor air for cooling through use of an air-side economizer, and maintaining elevated levels of CO_2 in the crop production space to facilitate photosynthesis. The energy, water, and carbon impacts of these design alternatives are quantified and compared.

2. Methods

Investigations into PF resource consumption have employed building energy modeling (BEM) software to model the climate dynamics of the production space and quantify energy consumption associated with meeting lighting and HVAC needs (Harbick and Albright, 2016; Benis et al., 2017; Graamans et al., 2018; Zhang and Kacira, 2020). BEM is a technique that uses mathematical models to quantify building performance related to design, operation and control. Buildings such as offices, hospitals, and schools can be modeled using commercially available software such as EnergyPlus™ (Bartlett et al., 2003), however, modeling the environment of indoor agriculture facilities using existing BEM software requires additional sub-models to account for crop growth and crop effects on the building environment (Graamans et al., 2018; Zhang and Kacira, 2020).

The workflow described here for modeling PF environments uses EnergyPlus™ for model definitions and building energy simulation and python for crop modeling and post-processing simulation data. Inputs to the model include weather information for each of the five locations, building construction details, equipment and light fixture efficiencies, and control setpoints. Outputs of the building model include calculated energy consumption for different systems, water loss from the facility, purchased CO_2, and upstream emissions. Weather data for each location is supplied from the Typical Meteorological Year Dataset (TMY3) (Wilcox and Marion, 2008). The scope of this study exclusively focuses on modeling resource consumption associated with lettuce production spaces, to the exclusion of co-located offices, bathrooms, and hallways, due to the energy demand in the production spaces being much larger than common spaces.

2.1 Plant factory model

2.1.1 Building model details

The total building area of the PF modeled is 4095 m^2, with rectangular construction, length of 65 m, width of 63 m, height of 8.3 m, and four walls oriented in cardinal directions. Each face of the building is made of typical warehouse construction materials: that is, an insulated concrete slab floor, and insulated metal walls and roof. Lettuce is grown on tiered-shelves with 10-levels, that are set apart in rows divided evenly by space for walking, and equipment movement. The area footprint of the growing units is 50% of the total floor space, making the ratio of canopy to building floor area is 5 to 1.

The production space energy balance is described in Equation 1 and depicted in Figure 1.

$$\acute{Q}_{air} = \sum_{i=1}^{N_{sl}} \acute{Q}_{L_i} + \sum_{j=1}^{N_{surfaces}} \acute{Q}_{surface_j} + \acute{Q}_{sys} + \acute{Q}_{inf} \qquad (1)$$

Where $\acute{Q}_{air}$ is the time rate of change of energy stored in the zone air, $\sum_{i=1}^{N_{sl}} \acute{Q}_{L_i}$ is the sum of internal loads from lighting, zone equipment, and the latent contribution at the crop canopy, $\sum_{j=1}^{N_{surfaces}} \acute{Q}_{surface_j}$ is the sum of convective heat transfer from wall surfaces, $\acute{Q}_{sys}$ is the energy flow associated with supply and return air to and from the production space, $\acute{Q}_{inf}$ is the energy flow associated with infiltration air-exchange which is set to zero for the purposes of this study. In EnergyPlus^{TM}, the room air heat and mass balance equations are coupled with those of the building systems balance and solved simultaneously to obtain zone conditions, energy consumption, and equipment status.

2.1.2 Heating ventilation and air-conditioning (HVAC)

The building equipment consists of a packaged constant-air-volume (CAV) air handling unit (AHU) to control the thermal load in the growing space. CAV systems maintain a constant supply air volume while varying the supply air temperature to meet the heating and cooling loads of a thermal zone. A dehumidifier with a closed refrigerant loop and electric reheater was added to the production space to manage the large dehumidification load, with a rated efficacy of 3.42 kWh/L water removed. The cooling system performance metric is the coefficient of performance (COP), the dimensionless ratio of net transported heat to the input energy. The nominal COP for the cooling system here is assumed as 4.0, and scales depending on outdoor conditions (condensing temperature) and part-load efficiency of the equipment using the default relationships in EnergyPlus™.

2.1.3 Lighting

Lettuce crop total dry mass is directly proportional to the accumulated photosynthetically active radiation (PAR) received by the canopy (L. D. Albright et al., 2000), referred to as the light integral. Daily Light Integral (DLI) control is a common CEA lighting strategy which aims to achieve a target number of photons reaching the crop canopy each day (L. D. Albright et al., 2000). The lighting systems modeled here maintained a daily light integral of 17 mol m^{-2} day^{-1} which has been found to be near the optimal DLI for some varieties of lettuce (*Lactuca sativa L.*), as this amount of light drives fast growth without inducing a physiological disorder known as tipburn (Both, 1995). A 24-hour photoperiod is adopted in this study, to minimize the required installed lighting capacity and investment costs to meet a 17 mol m^{-2} daily target. The corresponding photosynthetic photon flux density (PPFD) of the 17 mol daily target is 197 µmol m^{-2} s^{-1}. Purchasing lighting fixtures with higher lighting efficacy will reduce the amount of energy required to meet a desired lighting target.

Model input details can be found in Table 1.

Table 1: General model input parameters. Curly brackets "{}" indicate a set or range of values for different scenarios.

Category	Parameter	Value	Units
Facility Information	Building footprint	4,095	m^2
	Building Height	8	m
	Space Utilization	50%	%
	Layers	10	#
	U-Value (Walls/Roof)	0.28 / 0.21	W m^{-2} K^{-1}
Environmental Control	HVAC System type	Packaged CAV unit	-
	Nominal Cooling COP	4.0	-
	Heating Efficiency	80%	%
	Heating/Cooling Setpoint	19 / 24	ºC
	Min/Max Humidity Setpoint	50 / 85	%
	Dehumidifier efficiency	3.42	kWh L^{-1}
Crop Parameters	Crop type	Lettuce	-
	Evapotranspiration rate	{37-57}	ml $head^{-1}$ day^{-1}
	Crop Area Coverage	90%	%
	Leaf Area Index	2.1	-

Lighting Systems	Lighting Fixture Type	LED	-
	Daily Light Integral	{17,14}	mol m^{-2} day^{-1}
	PAR Lighting Efficacy	{2.0, 2.5, 3.0}	μmol J^{-1}
	Photoperiod	24	hours
	PPFD	{196.8, 162}	μmol s^{-1} m^{-2}
	Installed Lighting Capacity	{55-98.6}	W m^{-2}

2.2 Crop Model

2.2.1 Crop yield

Crop growth rate is calculated according the Van Henten lettuce model (Van Henten, 1994) which defines a system of differential equations for lettuce growth as a function of crop-specific parameters, and environmental conditions including temperature, light, and CO_2 concentration; Equations 2 and 3.

$$\frac{dX_{nsdw}}{dt} = c_a * f_{phot} - r_g X_{sdw} - f_{resp} - \frac{(1 - c_b)}{c_b} r_g X_{sdw} \tag{2}$$

$$\frac{dX_{sdw}}{dt} = r_g X_{sdw} \tag{3}$$

Where X_{sdw}, and X_{nsdw} are the structural and non-structural dry weight, respectively; c_a is a conversion factor for CO_2 to sugar; f_{phot} is the gross canopy photosynthesis, r_{gr} is the specific growth rate; and c_b a factor for respiration and synthesis losses of non-structural material due to growth. The supporting terms and parameters are calculated using recommended parameter values for lettuce according to (Van Henten, 1994).

PFs targeted a fresh-weight (FW) of 150 g for a single head of lettuce, achieved in a 35-day growth-cycle with 17 mols m^{-2} day^{-1} of light. Other modeling studies have calculated growth cycles between 30 and 38-days depending on temperature, light intensity, and CO_2 concentration (Graamans et al., 2018; Zhang and Kacira, 2020). The dry-weight (DW) to FW ratio at harvest is assumed to be 4% in which aligns with the range of values for lettuce reported in experimental findings and other studies, 3-7% (Gent, 2014; Graamans et al., 2017; Koudela and Petříková, 2008). To maintain high space-use efficiency, younger plants can be spaced more closely than mature plants; we calculate the space allocation for continuous cropping (i.e. daily planting and harvesting equal number of plants) with details supplied in supplemental materials. For a 35-day crop cycle, and average spacing of 48 lettuce heads m^{-2}, 38,265 heads of lettuce at weights of 150 grams $head^{-1}$ can be harvested daily at the facility. This yields 103.6 kg m^{-2} $year^{-1}$ (canopy area) or 2,121,210 kg (FW) of lettuce produced at the facility annually.

2.2.2 Crop evapotranspiration

Modeling the environment of indoor agriculture using existing building energy software requires the addition of a sub-model to account for the thermodynamic effects from the crop canopy on air temperature, and humidity due to evapotranspiration in the growing space (Graamans et al., 2018; Harbick and Albright, 2016; Liebman-Pelaez et al., 2021; Zhang and Kacira, 2020).

The present study implemented the procedure described in (Graamans et al., 2017) which combines evapotranspiration models i.e. modified Penman Monteith (Monteith, 1965), Stanghellini (Stanghellini, 1987), with a canopy heat balance (Campbell and Norman, 1998; Monteith and Unsworth, 2013) and the assumption that air at the leaf surface is saturated (Graamans et al., 2017). Equations (4-7) were iteratively solved for the latent and sensible heat contributions and leaf temperature.

$$R_n - H - \lambda E = 0 \tag{4}$$

$$H = \frac{LAI * \rho_a * c_p * T_s - T_a}{r_a} \tag{5}$$

$$\lambda E = \frac{LAI * \lambda_{fg} * (\chi_s - \chi_a)}{r_s + r_a} \tag{6}$$

$$\chi_s \cong \acute{\chi}_a + \frac{\rho_a * c_p}{\lambda} \varepsilon * (T_s - T_a) \tag{7}$$

Where R_n is net radiation, H is the sensible heat term, λE is the latent heat term. Leaf Area Index (LAI), which is the ratio between total area of leaves to the area footprint of an individual plant, is assumed to be the average of all present growth stages 2.1 in accordance with the *big leaf model* assumption (Monteith, 1965) and values adopted in similar studies (Graamans et al., 2017; Liebman-Pelaez et al., 2021) . ρ_a, c_p are the density and specific heat capacity of the air. T_s and T_a are the leaf surface temperature, and air temperature. λ_{fg} is the latent heat of phase-change for water vapor. The vapor concentration of air at the canopy level, χ_s, is approximated using χ_a, the saturated vapor concentration of the air at temperature, T_a. Calculations for supporting terms in equations 4-7 are shown in supplemental materials. The thermodynamic effects of the canopy are introduced by defining pieces of zone equipment to emit moisture and remove heat according to this canopy heat balance.

2.3 Parameter studies

To understand the range of annual energy consumption of PFs, multiple energy conservation measures (ECMs) were included as varying parameters including, investing in lighting fixtures of higher efficacy, the use of an air-side economizer, and providing the production environment with supplemental CO_2.

2.3.1 Lighting efficacy

The photosynthetic photon efficacy (PPE) of horticultural lighting fixtures is defined in terms of photosynthetically active radiation (PAR), which is the portion of the light spectrum (between 400 and 700 nm wavelength) used in photosynthesis (McCree, 1971). The photon efficacy of horticultural lighting fixtures is defined as the ratio of the output number of photons in the PAR waveband (units of µmols), to the input electrical energy in Joules. Lighting is the dominant energy use in PFs (Graamans et al., 2017; Harbick and Albright, 2016; Weidner et al., 2021; Zhang and Kacira, 2020) and the PAR efficacy of lighting has a major impact on the electricity consumption and cooling loads. Recent publications measuring the efficacy of horticulture lighting, found PAR efficacies ranging between 1.3 and 2.1 µmol J^{-1}, though advances in LED lighting technology (Both et al., 2017; Shelford and Both, 2021), have increased efficacy with some manufacturers declaring efficacies up to 4.0 µmol J^{-1} (DLC Horticultural Lighting Database, 2021). The lighting systems considered in this study model three light efficacies {2.0, 2.5, 3.0} µmol J^{-1}, Table 2.

2.3.2 Air-side economizer control

Introducing an air-side economizer into the HVAC system allows a facility to cool the production space using outdoor air when it is advantageous. An economizer will make decisions about the fraction of outdoor air mixed into the ventilation system based on required cooling. An enthalpy economizer compares the enthalpy of outdoor air and return air to determine when outdoor conditions are more favorable than the prospect of reconditioning return air.

2.3.3 Supplemental CO_2 levels

Supplementing CO_2 to the production space can reduce the total lighting required to get a desired growth rate. The relation between elevated CO_2 levels and relative growth rate is derived from (Both, 1998) and reported as the 'virtual DLI' (Equation 8, Fig. 2), which is the DLI that would achieve an equal relative growth rate without CO_2 supplementation.

$$DLI_{virtual} = DLI_{delivered}\frac{ln(2.66E4) - ln(400)}{ln(2.66E4) - ln(X_{CO2})} \quad (8)$$

Where $DLI_{virtual}$ (mol m^{-2} day^{-1}) is the 'virtual DLI'; $DLI_{delivered}$ (mol m^{-2} day^{-1}) is the actual delivered DLI, and X_{CO2} is the CO_2 concentration of the production space (ppm).

Delivered DLI (and consequently installed lighting capacity) can be reduced at elevated CO_2 levels while maintaining a desired growth rate, Figure 2.The elevated level of CO_2 modeled (839 ppm), was chosen to achieve equivalent growth between production scenarios providing a DLI of 17 mol m^{-2} day^{-1}, while only supplying 14 mol m^{-2} day^{-1} of light. This strategy allows for the installed lighting capacity and PPFD to be reduced correspondingly with the lower lighting target.

There are 12 scenarios per location, with different combinations of varied parameters: lighting efficacy, economizer use, and CO_2 levels, Table 2.

Table 2: Scenario details with values of varied parameters.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Lighting Efficacy	2.0	2.0	2.0	2.0
CO_2 level	ambient	ambient	839	839
Economizer	No	Yes	No	Yes
	Scenario 5	**Scenario 6**	**Scenario 7**	**Scenario 8**
Lighting Efficacy	2.5	2.5	2.5	2.5
CO_2 level	ambient	ambient	839	839
Economizer	No	Yes	No	Yes
	Scenario 9	**Scenario 10**	**Scenario 11**	**Scenario 12**
Lighting Efficacy	3.0	3.0	3.0	3.0
CO_2 level	ambient	ambient	839	839
Economizer	No	Yes	No	Yes

2.3.4 Geographic location and CO_2 emission factors

In addition to the efficiency measures listed, the geographic location was varied to understand the environmental impacts of upstream emissions, and environmental dependence of PFs. The impacts of location are also relevant when considering air-side economizer control because the conditions of the outdoor air will impact the free-cooling efficacy. Five U.S. metropolitan areas were chosen as sites for PFs across three diverse climate zones, Table 3.

Table 3: Modeled PF sites with parameter details.

Location	Abbreviation	CO_2e Emissions Factor (kg/MWh)	ASHRAE Climate Zone
Atlanta, GA	ATL	400.4	3A
Los Angeles, CA	LA	176.0	3B
New York, NY	NYC	171.9	4A
Seattle, WA	SEA	136.0	4C
Chicago, IL	CHI	329.9	5A

2.3 Post-processing calculations

The amount of water recovered, CO_2 emissions associated with production, and replacement CO_2 required for each case were calculated using the results of the building energy simulations. Water recovered was calculated based on the latent cooling load on the HVAC system and Equation 9.

$$m_w = \sum_{i=1}^{8760} \frac{L_i}{\lambda_{fg}} \tag{9}$$

Where L_i is the latent cooling provided at hour "i", and $\lambda_{fg}$is the latent heat of phase-change for water condensation.

The total water consumption associated with irrigation can be calculated by conducting a mass balance, where water entering the system will be divided among system losses, assumed to be 10% of water supplied in accordance with previous literature (Graamans et al., 2017), plant uptake, modeled as a portion of fresh-weight (FW), and plant evapotranspiration. The transpired water is either condensed out of the air in the HVAC system or exhausted outside based on the ventilation strategy. The total water consumption is calculated according to Equation 10.

$$m_{total} = m_{lost} + m_{plants} + m_{exhausted} - m_{recovered} \tag{10}$$

Where, m_{total} is total facility water consumption, m_{lost} is lost in irrigation system, m_{plants} is the water imbibed by the plant, $m_{exhausted}$ is the water vapor lost with the exhaust air stream, and $m_{recovered}$ is the water recovered by condensation.

Greenhouse gas emissions associated with energy production depends on the mix of energy generating sources in a specific location, Table 3 ("Emissions and Generation Resource Integrated Database (eGRID).," 2022); Equation X was used to calculate emissions associated with production and presented in carbon dioxide equivalent emissions CO_2e according to Equation 11.

$$CO_{2_e} = AEU \cdot E_f \tag{11}$$

Where, AEU is the annual energy usage (MWh), and E_f (kg/MWh) is the CO_2 equivalent emission factor for the location (kg).

In the case of maintaining elevated levels of CO_2 in the production space while introducing outdoor air for cooling, CO_2 must be supplied to replace the high concentration exhaust air. The replacement CO_2 is equal to the CO_2 loss which is calculated using a mass balance in the space at each time-step according to Equation 12.

$$CO_2 = \frac{\acute{m}_{outdoor_{air}} \cdot (ppm_{out} - ppm_{in})}{\frac{M_{air}}{M_{co2}}} \tag{12}$$

3. Results and Discussion

3.1 Energy consumption

Due to finding that given enough insulative materials, plant factory energy consumption is largely insensitive to location (Graamans et al., 2018; Harbick and Albright, 2016; Zhang and Kacira, 2020), one location, NYC, is selected for discussion here Figure 3, and energy results for all locations can be found in the supplemental materials. Though geographic location becomes more relevant due to using outdoor air for cooling, the relative magnitudes of lighting and cooling loads remain consistent across locations with only about 5% difference between scenarios in different locations. Ultimately, the energy consumption of PFs are highly dependent on system design decisions around lighting, HVAC, and supplemental CO_2 where specific energy intensity of production ranges between 6.2 and 12.0 kWh energy consumed per kg (FW) of lettuce produced and the most energy efficient scenarios consumes 46-49% less energy than the least efficient scenario.

To discuss the relative performance of different scenarios, we define the baseline scenario as a PF growing ten layers of lettuce in NYC, using a lighting efficacy of 2.0 μmol J^{-1}, an HVAC system without air-side economizing, and maintaining ambient levels of CO_2 (400 ppm) in the production space (Scenario 1). Facility energy consumption in our baseline PF is made up of about 70% lighting, and 30% HVAC.

For all scenarios, lighting makes up between 58 – 88% of total facility energy consumption depending on light efficacy and whether the cooling load is reduced through economizing, with the total lighting energy consumption ranging between 1,703 and 3,100 MJ m^{-2} of canopy or 4.6 to 8.3 kWh kg^{-1} lettuce produced, Figure 3. Investing in high efficacy lighting results in facility energy savings from both the reduced lighting energy consumption and part of the cooling load. Increasing the lighting efficacy from 2.0 μmol J^{-1} to either 2.5 or 3.0 μmol J^{-1} saves 15% and 24% of facility energy consumption, respectively. The incremental energy savings of upgrading from 2.5 μmol J^{-1} to 3.0 μmol is 11% of the total building energy consumption and 20% of the lighting energy. The energy required to meet zone conditions by cooling and dehumidifying air in the production space in this study is found to be a significant portion of the energy budget for all production scenarios ranging between 12% and 42% of the total energy demand. After introducing an airside to the baseline model, HVAC energy consumption is reduced by between 40 - 69%, depending on location, and lighting configuration and ratio of sensible to latent cooling.

Maintaining elevated levels of CO_2 reduces the annual energy consumption from our baseline model without compromising crop growth (Both, 1998). Energy savings for implementing this measure alone reduces facility energy consumption by between 13%-14% as compared to the case with identical light efficacy without CO_2 supplementation. Maintaining elevated CO_2 levels with an air-side economizer results in the highest energy savings with respect to the baseline PF, though this combination increases the carbon dioxide consumption associated with production due to replacing lost CO_2 when outdoor air is introduced. Previous studies have assumed an elevated level of CO_2 as part of their simulations but did not detail tradeoffs between energy and CO_2 use. When considering these tradeoffs, the most energy efficient cases are not necessarily optimal in terms of water use, or total CO_2 emissions.

3.2 Water consumption

Water consumption for irrigation and production operations (excluding washing/cleaning) ranges between 2.0 and 9.8-liters of water per kg (FW) lettuce produced. In open PF systems (i.e. those with economizers), water consumption increases to 4-5 times ranging between 6.0 and 9.8 kg water per kg lettuce produced, due to humid air from the production zone being exhausted outdoors with a high ventilation rate. In closed PF systems (i.e. those without air-side economizers), the total water consumption remains consistent and depends only on the system losses which track irrigation and transpiration rate. In scenarios with airside economizing water efficiency is slightly better with lower installed lighting capacity due to a lower outdoor air fraction and a higher reliance on the zone dehumidifier which collects condensate rather than exhausting. There is a slight location dependence for water consumption in open PF systems where in Seattle and Los Angeles, the water use is higher due to higher average outdoor air-fractions mixed into the airstream.

3.3 CO_2 consumption and emissions

Primary emissions associated with energy consumption at the facility ranges between 0.6 and 3.9 kg CO_{2e} for every kg (FW) lettuce produced depending on location and operational parameters. In general, lower onsite energy consumption results in lower annual emissions rates (Figure 4), however when combining economizing with elevated CO_2 levels (scenario 4, 8, and 12), CO_2 exhausted from the facility becomes significant ranging between 0.4 and 1.1 kg of replacement CO_2 per kg lettuce produced. Interestingly, combining these two measures results in lower onsite energy consumption and upstream emissions but higher level of exhausted CO_2. The amount of replacement CO_2 required indicates that the cost of CO_2 can be an important consideration for some operational choices.

3.4 Comparison with other studies

Energy

Comparing expected performance across modeling studies is challenging due to differences in modeling scope, assumed parameter values, crop type, lighting strategy, HVAC system, and environmental setpoints, which impact building energy usage and crop productivity. In addition to differences between models, the scope and units of reported performance metrics in existing literature contain variation, confusing comparisons. The energy consumption of indoor production facilities can be reported in terms of annual facility energy consumption, energy consumption per unit area of building footprint, per unit area of canopy, or per unit of crop produced annually. Unifying reporting methods and metrics can reduce confusion between conclusions and build understanding about the relationship between operating parameters and resulting performance.

The most relevant comparisons will be made using energy consumption per unit of crop yield in kWh kg^{-1}, considering those studies which conducted annual energy simulations of PFs growing leafy green vegetables. Harbick and Albright (Harbick and Albright, 2016) reported performance in terms of total facility energy consumption and did not report annual yield, calculating 3,651 MJ m^{-2} of canopy. Assuming equal yield with this study, their predictions are between 19-23 kWh kg^{-1}, Their energy usage was dominated by HVAC system making up 50-55% of the total energy, where lighting was found as the dominant energy usage in this study making up between 57-85% of total energy consumption. The higher overall usage and HVAC proportion is explained by their lower lighting efficacy and higher evapotranspiration rates, which required more cooling and reheating of conditioned air. Graamans et al (Graamans et al., 2018) modeled PFs targeting a relatively fast growth cycle of 30 days, reporting unit energy consumption of 232 kWh kg^{-1} dry-weight or 17.3 kWh kg^{-1}, made up 91% lighting and 9% HVAC. Their lower HVAC proportion is explained by a more efficient cooling system, and a dedicated high efficiency heat pump for removing waste heat from the light fixtures. Zhang and Kacira (Zhang and Kacira, 2020) performed simulations of multi-level plant factories targeting a lower DLI of 13, and 15 mol m^{-2} day with unit energy consumption of 7-8 kWh kg $^{-1}$ made up of around 80-90% lighting. Differences in the absolute magnitude of HVAC consumption can be explained by their lower DLI target and because some of their scenarios omitted humidity controls which can have a big impact on HVAC performance. They noted HVAC energy savings from economizer usage between 13% and 67%, which agrees with values calculated in this study. Higher savings were found in Seattle PFs as compared to other U.S. locations, matching our observations

Water

Previous studies have calculated the water inputs required for PF lettuce production in a closed system finding that water use in PFs is quite low compared to GHs (Graamans et al., 2018) and open field (Nicholson et al., 2020). The water-use intensity calculated in the closed-system PF configurations are higher here than (Graamans et al., 2018) which calculated water use of 1.0 liters of water per kg (FW) lettuce produced, approaching the theoretical water-use efficiency of plant factories (Kozai, 2013). The present model assumed 10% system losses in water supply and irrigation, accounting for this difference in the closed systems. Other studies have considered production scenarios which include airside economizing in PFs to reduce the energy consumption, though the water-efficiency implications were not discussed in detail (Harbick and Albright, 2016; Zhang and Kacira, 2020). The tradeoff between energy consumption and water consumption by introducing outdoor air into an open greenhouse system is a notable outcome in (Weidner et al., 2021), with water consumption ranging between 2 and 26 liters per kg produced of a mixed crop variety depending on location and time of year. The annual range presented here for PFs aligns with the findings in (Weidner et al., 2021), though differences in exact values may be due to crops exhibiting higher transpiration rates in greenhouses, and differences in crop water uptake assumptions as they model a mix of vegetables including tomatoes, where this study models only lettuce.

CO_2 consumption and emissions

Replacement CO_2 in an open greenhouse was calculated in (Weidner et al., 2021) at 0.35 kg replacement CO_2 per kg produced. This result is lower than what was found here (0.4 -1.1 kg) due to different ventilation rates, and their CO_2 setpoint varying hour-to-hour where here, one setpoint was maintained throughout the year.

4. Conclusion

This study provides details on constructing building energy models of multi-layer PFs using EnergyPlus, simulates production scenarios, and analyzes tradeoffs in energy consumption, water use efficiency, and carbon impacts of different ECMs. Improving lighting efficacy in our baseline PF reduced facility energy consumption by 24%. Introducing an air-side economizer alone can reduced HVAC energy consumption by 40 - 69%, although this adversely impacts the water efficiency of the facility. Maintaining elevated levels of CO_2 in the production space enabled the reduction of delivered lighting for a desired growth rate, and reduced energy consumption by 13-14%. Combining all efficiency measures resulted in 45 - 49% energy savings compared to the baseline facility, with trade-offs identified between energy, water, and carbon emissions. The specific energy intensity of production ranges between 6.2 and 12.0 kWh energy consumed per kg (FW) of lettuce produced. Water consumption for irrigation and production operations ranges between 2.0- and 9.8-liters of water per kg (FW) lettuce produced. Primary emissions associated with energy consumption at the facility ranges between 0.6 and 3.9 kg CO_{2e} per kg (FW) lettuce produced depending on location and operational parameters. Additional CO_2 consumption is associated with maintaining elevated levels in the production space while cooling with outdoor air. We conclude that locating PFs in areas with a cleaner grid and employing these ECMs can significantly reduce the environmental impacts of growing lettuce indoors, and that there are important tradeoffs to consider between water, energy, and supplemental carbon-dioxide in design.

Acknowledgements

Funding for this project is provided by the National Science Foundation under award number 1739163.

References

Bartlett, R., Halverson, M.A., Shankle, D.L., 2003. Understanding Building Energy Codes and Standards (No. PNNL-14235, 900221). https://doi.org/10.2172/900221

Benis, K., Reinhart, C., Ferrão, P., 2017. Building-Integrated Agriculture (BIA) In Urban Contexts: Testing A Simulation-Based Decision Support Workflow 10.

Both, A.J., 1998. Coordinated management of daily PAR integral and carbon dioxide for hydropnic lettuce production. Crop Models Prot. Cultiv.

Both, A.-J., 1995. Dynamic simulation of supplemental lighting for greenhouse hydroponic lettuce production (Dissertation). Cornell University, Ithaca, New York.

Both, A.-J., Bugbee, B., Kubota, C., Lopez, R.G., Mitchell, C., Runkle, E.S., Wallace, C., 2017. Proposed Product Label for Electric Lamps Used in the Plant Sciences. HortTechnology 27, 544–549. https://doi.org/10.21273/HORTTECH03648-16

Campbell, G.S., Norman, J.M., 1998. Introduction to environmental biophysics, 2nd ed. ed. Springer, New York.

Despommier, D., 2011. The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. J. Für Verbraucherschutz Leb. 6, 233–236. https://doi.org/10.1007/s00003-010-0654-3

DLC Horticultural Lighting Database, D., 2021. DLC Horticultural Lighting Database.

Eaton, M., Harbick, K., Shelford, T., Mattson, N., 2021. Modeling Natural Light Availability in Skyscraper Farms. Agronomy 13.

Emissions and Generation Resource Integrated Database (eGRID). [WWW Document], 2022. URL https://www.epa.gov/egrid

Engler, N., Krarti, M., 2021. Review of energy efficiency in controlled environment agriculture. Renew. Sustain. Energy Rev. 141, 110786. https://doi.org/10.1016/j.rser.2021.110786

Fujiwara, K., Kozai, T., Runkle, E.S. (Eds.), 2016. LED Lighting for Urban Agriculture, 1st ed. 2016. ed. Springer Singapore : Imprint: Springer, Singapore. https://doi.org/10.1007/978-981-10-1848-0

Gent, M.P.N., 2014. Effect of Daily Light Integral on Composition of Hydroponic Lettuce. HortScience 49, 173–179. https://doi.org/10.21273/HORTSCI.49.2.173

Gómez, C., Currey, C.J., Dickson, R.W., Kim, H.-J., Hernández, R., Sabeh, N.C., Raudales, R.E., Brumfield, R.G., Laury-Shaw, A., Wilke, A.K., Lopez, R.G., Burnett, S.E., 2019. Controlled Environment Food Production for Urban Agriculture. HortScience 54, 1448–1458. https://doi.org/10.21273/HORTSCI14073-19

Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I., Stanghellini, C., 2018. Plant factories versus greenhouses: Comparison of resource use efficiency. Agric. Syst. 160, 31–43. https://doi.org/10.1016/j.agsy.2017.11.003

Graamans, L., Tenpierik, M., van den Dobbelsteen, A., Stanghellini, C., 2020. Plant factories: Reducing energy demand at high internal heat loads through façade design. Appl. Energy 262, 114544. https://doi.org/10.1016/j.apenergy.2020.114544

Graamans, L., van den Dobbelsteen, A., Meinen, E., Stanghellini, C., 2017. Plant factories; crop transpiration and energy balance. Agric. Syst. 153, 138–147. https://doi.org/10.1016/j.agsy.2017.01.003

Harbick, K., Albright, L.D., 2016. Comparison of energy consumption: greenhouses and plant factories. Acta Hortic. 285–292. https://doi.org/10.17660/ActaHortic.2016.1134.38

Iddio, E., Wang, L., Thomas, Y., McMorrow, G., Denzer, A., 2020. Energy efficient operation and modeling for greenhouses: A literature review. Renew. Sustain. Energy Rev. 117, 109480. https://doi.org/10.1016/j.rser.2019.109480

Katzin, D., van Henten, E.J., van Mourik, S., 2022. Process-based greenhouse climate models: Genealogy, current status, and future directions. Agric. Syst. 198, 103388. https://doi.org/10.1016/j.agsy.2022.103388
Koudela, M., Petříková, K., 2008. Nutrients content and yield in selected cultivars of leaf lettuce (*Lactuca sativa* L. var. *crispa*). Hortic. Sci. 35, 99–106. https://doi.org/10.17221/3/2008-HORTSCI
Kozai, T., 2013. Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proc. Jpn. Acad. Ser. B 89, 447–461. https://doi.org/10.2183/pjab.89.447
Kozai, T., Niu, G., 2016. Plant Factory -An indoor vertical farming system for efficient quality food production, 1st ed.
L. D. Albright, A.-J. Both, A. J. Chiu, 2000. Controlling greenhouse light to a consistent daily integral. Trans. ASAE 43, 421–431. https://doi.org/10.13031/2013.2721
Lamalice, A., Haillot, D., Lamontagne, M.-A., Herrmann, T.M., Gibout, S., Blangy, S., Martin, J.-L., Coxam, V., Arsenault, J., Munro, L., Courchesne, F., 2018. Building food security in the Canadian Arctic through the development of sustainable community greenhouses and gardening. Écoscience 25, 325–341. https://doi.org/10.1080/11956860.2018.1493260
Li, L., Li, X., Chong, C., Wang, C.-H., Wang, X., 2020. A decision support framework for the design and operation of sustainable urban farming systems. J. Clean. Prod. 268, 121928. https://doi.org/10.1016/j.jclepro.2020.121928
Liebman-Pelaez, M., Kongoletos, J., Norford, L.K., Reinhart, C., 2021. Validation of a building energy model of a hydroponic container farm and its application in urban design. Energy Build. 250, 111192. https://doi.org/10.1016/j.enbuild.2021.111192
Lubna, F.A., Lewus, D.C., Shelford, T.J., Both, A.-J., 2022. What You May Not Realize about Vertical Farming. Horticulturae 8, 322. https://doi.org/10.3390/horticulturae8040322
MarketsandMarkets, 2021. Vertical Farming Market with COVID-19 Impact Analysis - Global Forecast to 2026. MarketsandMarkets.
McCree, K.J., 1971. The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agric. Meteorol. 9, 191–216. https://doi.org/10.1016/0002-1571(71)90022-7
Monteith, J.L., 1965. Evaporation and Environment. Symp. Soc. Exp. Biol. 19, 205–234.
Monteith, J.L., Unsworth, M.H., 2013. Principles of environmental physics: plants, animals, and the atmosphere, 4th ed. ed. Elsevier/Academic Press, Amsterdam ; Boston.
Nicholson, C.F., Harbick, K., Gómez, M.I., Mattson, N.S., 2020. An Economic and Environmental Comparison of Conventional and Controlled Environment Agriculture (CEA) Supply Chains for Leaf Lettuce to US Cities, in: Aktas, E., Bourlakis, M. (Eds.), Food Supply Chains in Cities. Springer International Publishing, Cham, pp. 33–68. https://doi.org/10.1007/978-3-030-34065-0_2
Rodríguez, F., Berenguel, M., Guzmán, J.L., Ramírez-Arias, A., 2015. Modeling and Control of Greenhouse Crop Growth, Advances in Industrial Control. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-11134-6
Shelford, T.J., Both, A.-J., 2021. On the Technical Performance Characteristics of Horticultural Lamps. AgriEngineering 3, 716–727. https://doi.org/10.3390/agriengineering3040046
Stanghellini, C., 1987. Transpiration of greenhouse crops an aid to climate management.
United Nations, U.N., 2019. World Urbanization Prospects: The 2018 Revision. UN.
Van Henten, E.J., 1994. Validation of a dynamic lettuce growth model for greenhouse climate control. Agric. Syst. 45, 55–72. https://doi.org/10.1016/S0308-521X(94)90280-1
Vanthoor, B. H. E., de Visser, P.H.B., Stanghellini, C., van Henten, E.J., 2011. A methodology for model-based greenhouse design: Part 2, description and validation of a tomato yield model. Biosyst. Eng. 110, 378–395. https://doi.org/10.1016/j.biosystemseng.2011.08.005

Vanthoor, B.H.E., Stanghellini, C., van Henten, E.J., de Visser, P.H.B., 2011. A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. Biosyst. Eng. 110, 363–377. https://doi.org/10.1016/j.biosystemseng.2011.06.001

Vanthoor, B.H.E., Stigter, J.D., van Henten, E.J., Stanghellini, C., de Visser, P.H.B., Hemming, S., 2012. A methodology for model-based greenhouse design: Part 5, greenhouse design optimisation for southern-Spanish and Dutch conditions. Biosyst. Eng. 111, 350–368. https://doi.org/10.1016/j.biosystemseng.2012.01.005

Wang, L., Iddio, E., 2022. Energy performance evaluation and modeling for an indoor farming facility. Sustain. Energy Technol. Assess. 52, 102240. https://doi.org/10.1016/j.seta.2022.102240

Weidner, T., Yang, A., Hamm, M.W., 2021. Energy optimisation of plant factories and greenhouses for different climatic conditions. Energy Convers. Manag. 243, 114336. https://doi.org/10.1016/j.enconman.2021.114336

Wilcox, S., Marion, W., 2008. Users manual for tmy3 data sets (revised). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Wood, J., Wong, C., Paturi, S., 2020. Vertical Farming: An Assessment of Singapore City. ETropic Electron. J. Stud. Trop. 19, 228–248. https://doi.org/10.25120/etropic.19.2.2020.3745

Zhang, Y., Kacira, M., 2020. Comparison of energy use efficiency of greenhouse and indoor plant factory system. Eur. J. Hortic. Sci. 85. https://doi.org/10.17660/eJHS.2020/85.5.2

Zwart, H.F. de, 1996. Analyzing energy-saving options in greenhouse cultivation using a simulation model. Wageningen.

Table 1: General model input parameters. Curly brackets "{}" indicate a set or range of values for different scenarios.

Category	Parameter	Value	Units
Facility Information	Building footprint	4,095	m^2
	Building Height	8	m
	Space Utilization	50%	%
	Layers	10	#
	U-Value (Walls/Roof)	0.28 / 0.21	$W\ m^{-2}\ K^{-1}$
Environmental Control	HVAC System type	Packaged CAV unit	-
	Nominal Cooling COP	4.0	-
	Heating Efficiency	80%	%
	Heating/Cooling Setpoint	19 / 24	ºC
	Min/Max Humidity Setpoint	50 / 85	%
	Dehumidifier efficiency	3.42	$kWh\ L^{-1}$
Crop Parameters	Crop type	Lettuce	-
	Evapotranspiration rate	{37-57}	$ml\ head^{-1}\ day^{-1}$
	Crop Area Coverage	90%	%
	Leaf Area Index	2.1	-
Lighting Systems	Lighting Fixture Type	LED	-
	Daily Light Integral	{17,14}	$mol\ m^{-2}\ day^{-1}$
	PAR Lighting Efficacy	{2.0, 2.5, 3.0}	$\mu mol\ J^{-1}$
	Photoperiod	24	hours
	PPFD	{196.8, 162}	$\mu mol\ s^{-1}\ m^{-2}$
	Installed Lighting Capacity	{55-98.6}	$W\ m^{-2}$

Table 2: Scenario details with values of varied parameters.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Lighting Efficacy	2.0	2.0	2.0	2.0
CO_2 level	ambient	ambient	839	839
Economizer	No	Yes	No	Yes

	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Lighting Efficacy	2.5	2.5	2.5	2.5
CO_2 level	ambient	ambient	839	839
Economizer	No	Yes	No	Yes

	Scenario 9	Scenario 10	Scenario 11	Scenario 12
Lighting Efficacy	3.0	3.0	3.0	3.0
CO_2 level	ambient	ambient	839	839
Economizer	No	Yes	No	Yes

Table 3: Modeled PF sites with parameter details.

Location	Abbreviation	CO_2e Emissions Factor (kg/MWh)	ASHRAE Climate Zone
Atlanta, GA	ATL	400.4	3A
Los Angeles, CA	LA	176.0	3B
New York, NY	NYC	171.9	4A
Seattle, WA	SEA	136.0	4C
Chicago, IL	CHI	329.9	5A

*(Color Figure)

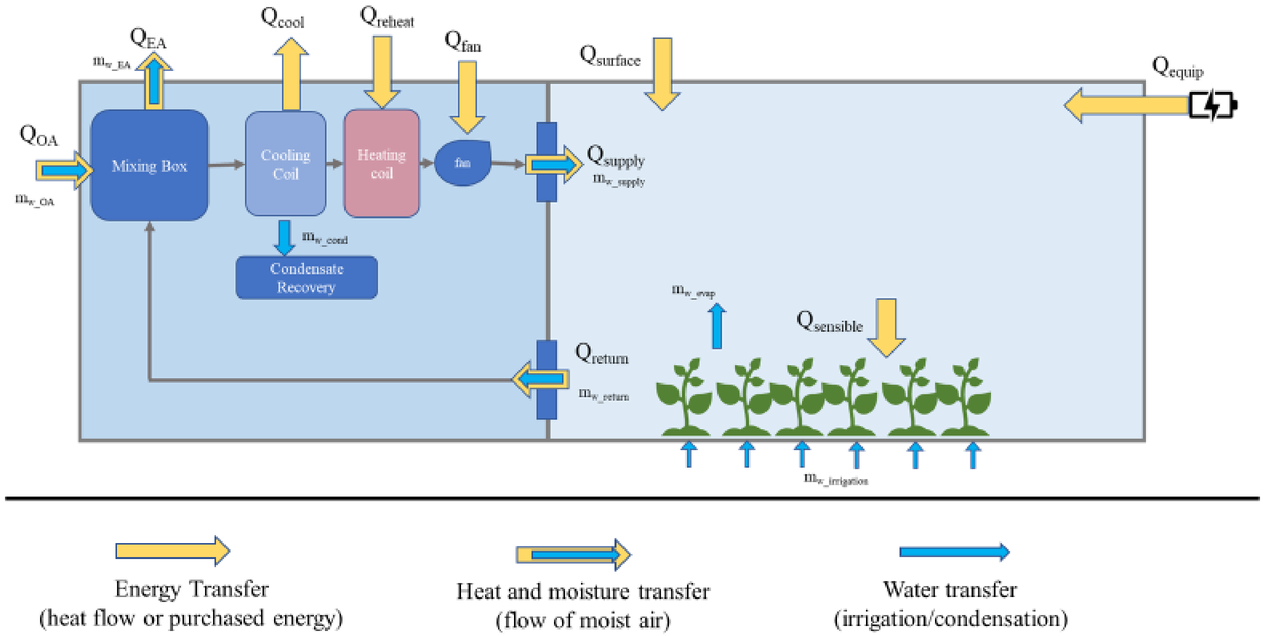

Figure 1. Energy and water flow diagram of PF system.

*(Color Figure)

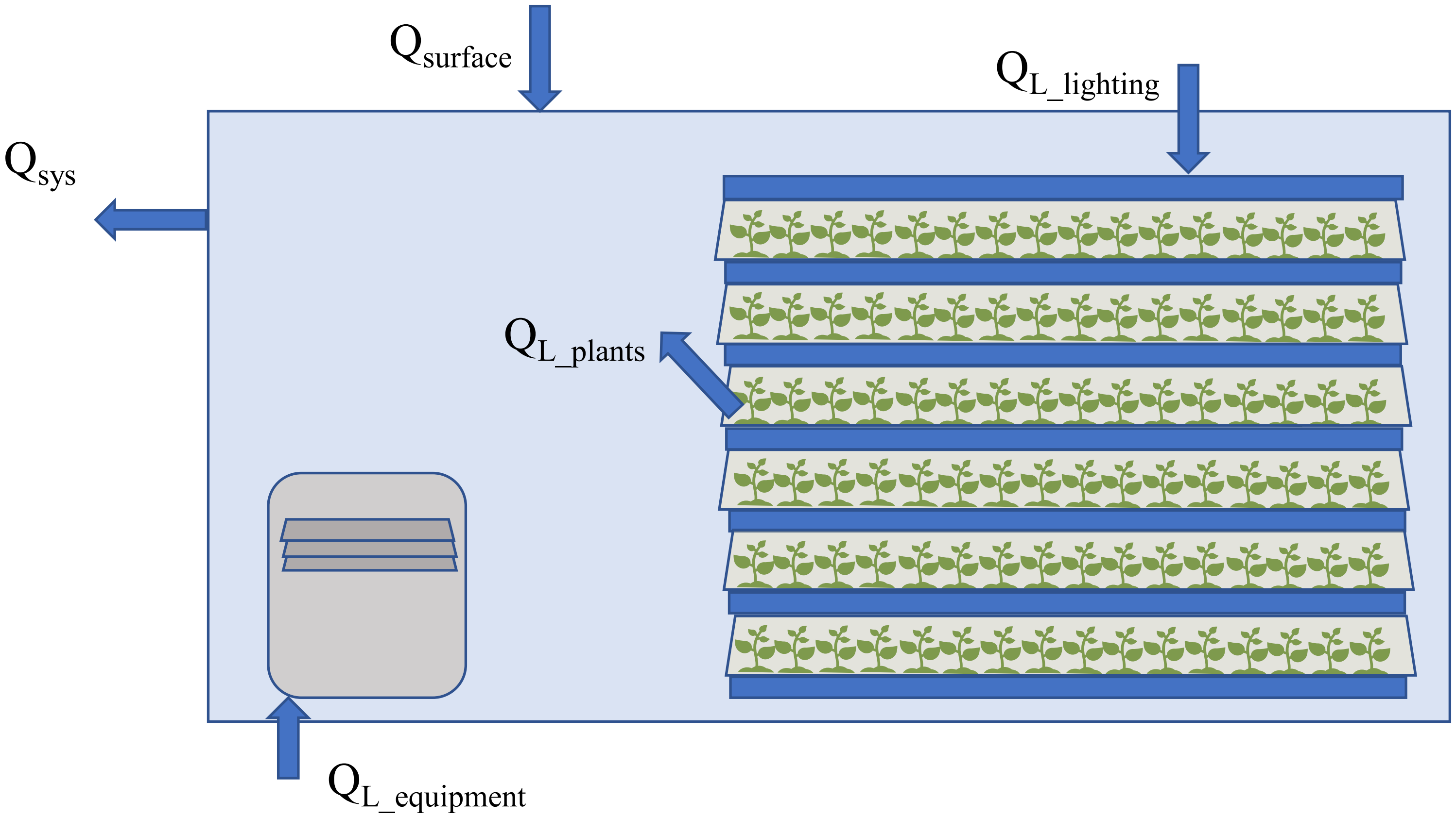

Figure 1. Energy flow diagram of PF system.

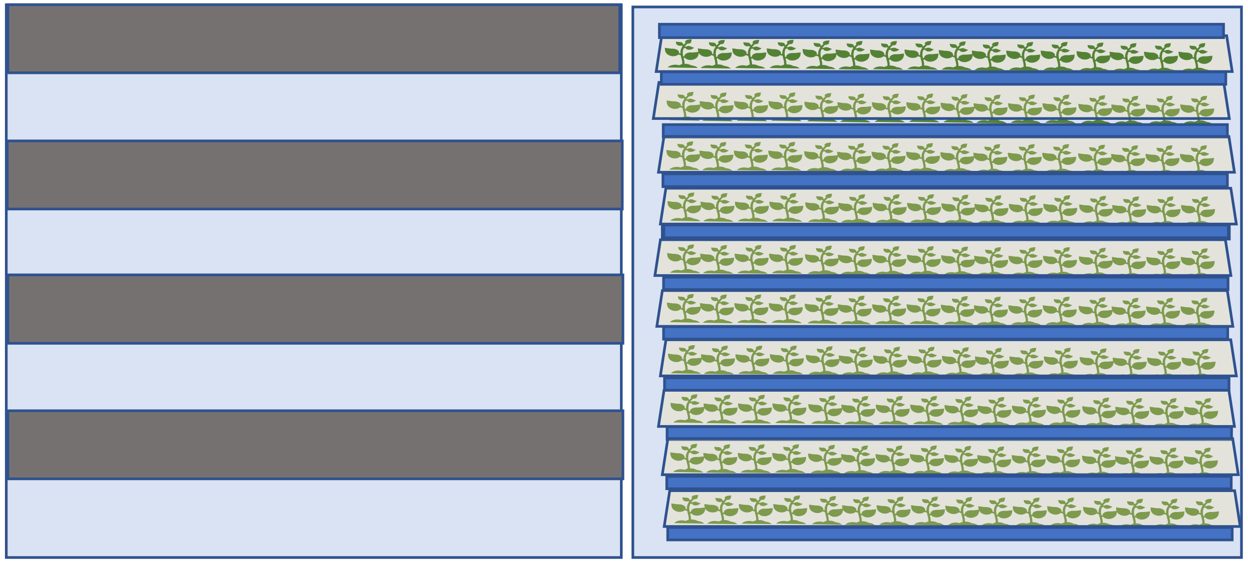

Figure 1. (a) Top view and (b) side view of PF system layout with tiered growing shelves in aisles

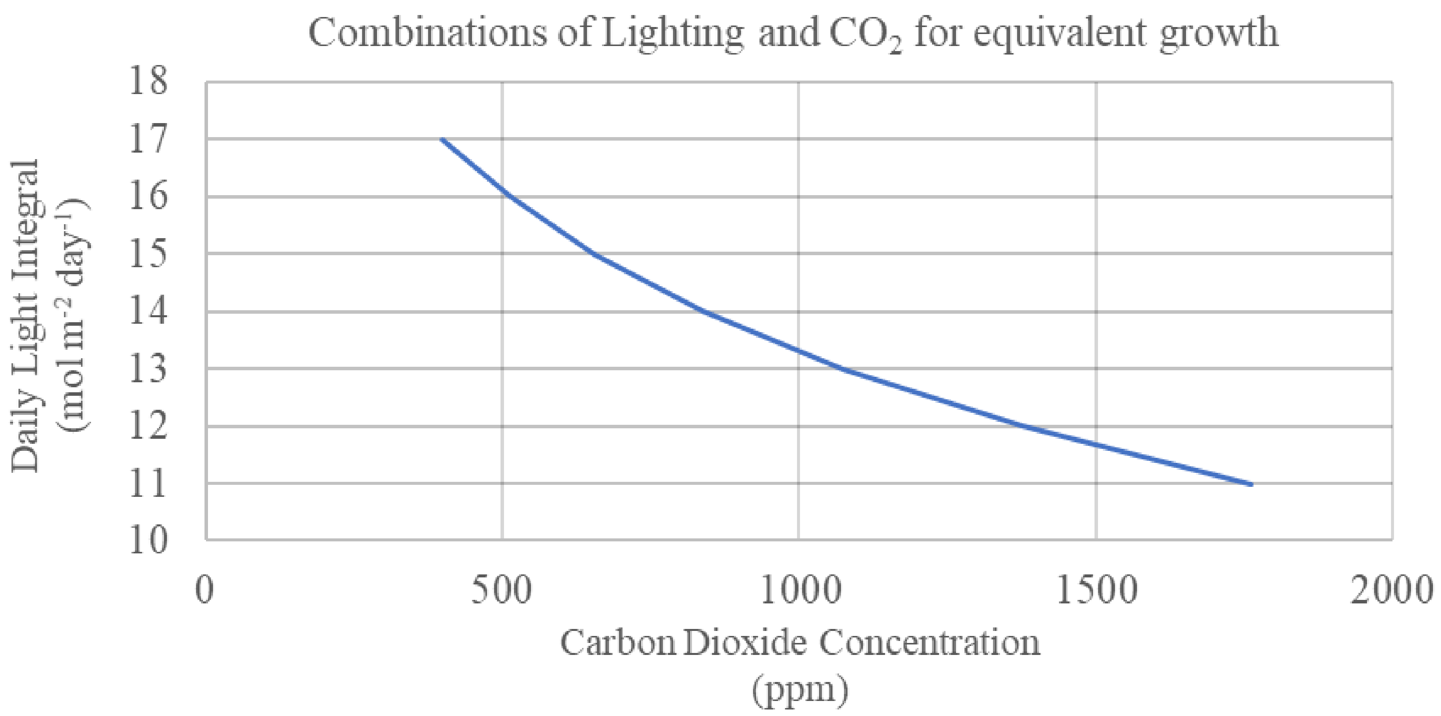

Figure 2. Relationship between delivered DLI (mol day^{-1}) and CO_2 concentration (ppm), holding growth rate constant.

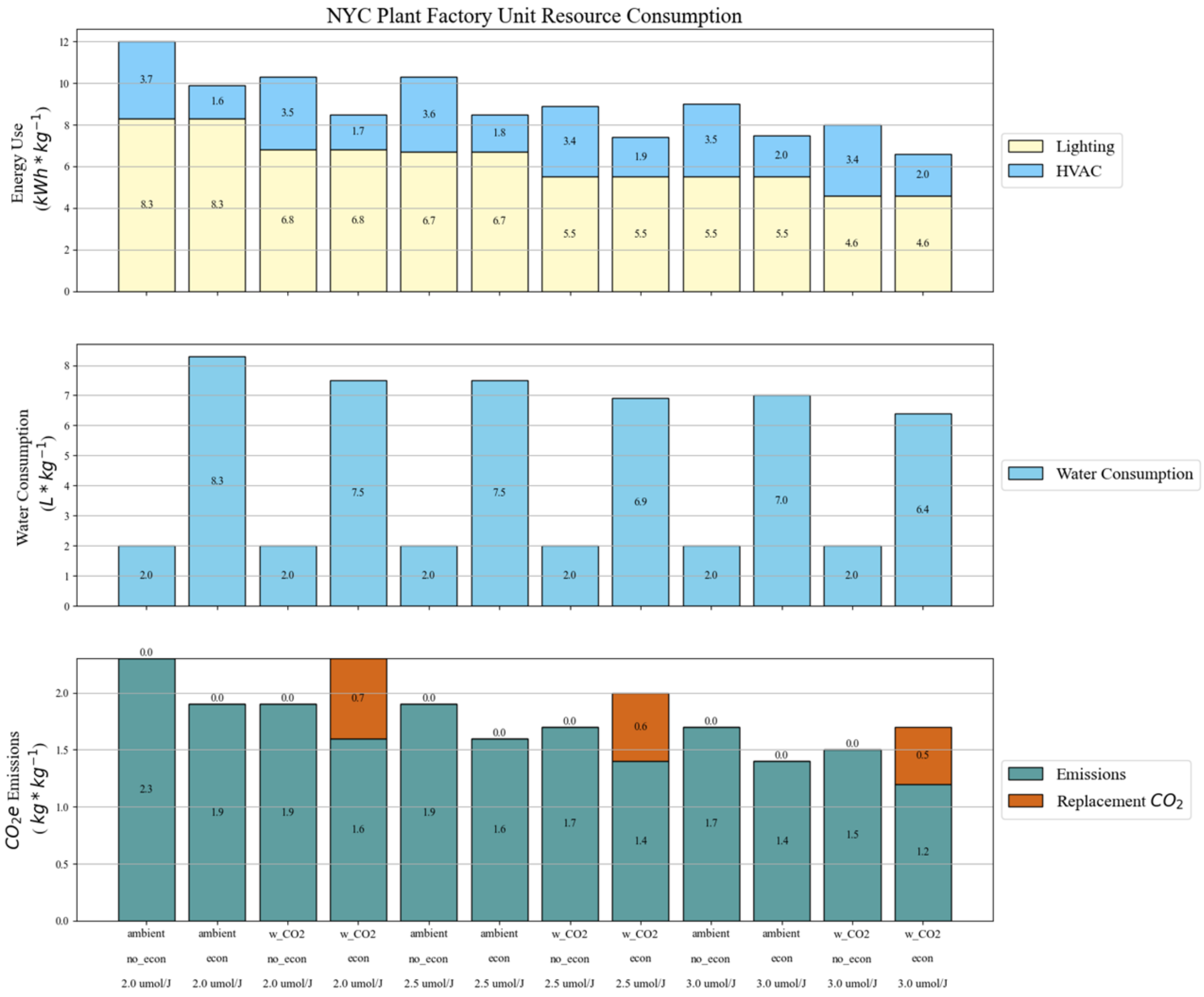

Figure 3: Unit resource consumption for PF production of lettuce in energy, water, and CO_2 equivalent emissions. kWh kg^{-1} lettuce (FW).

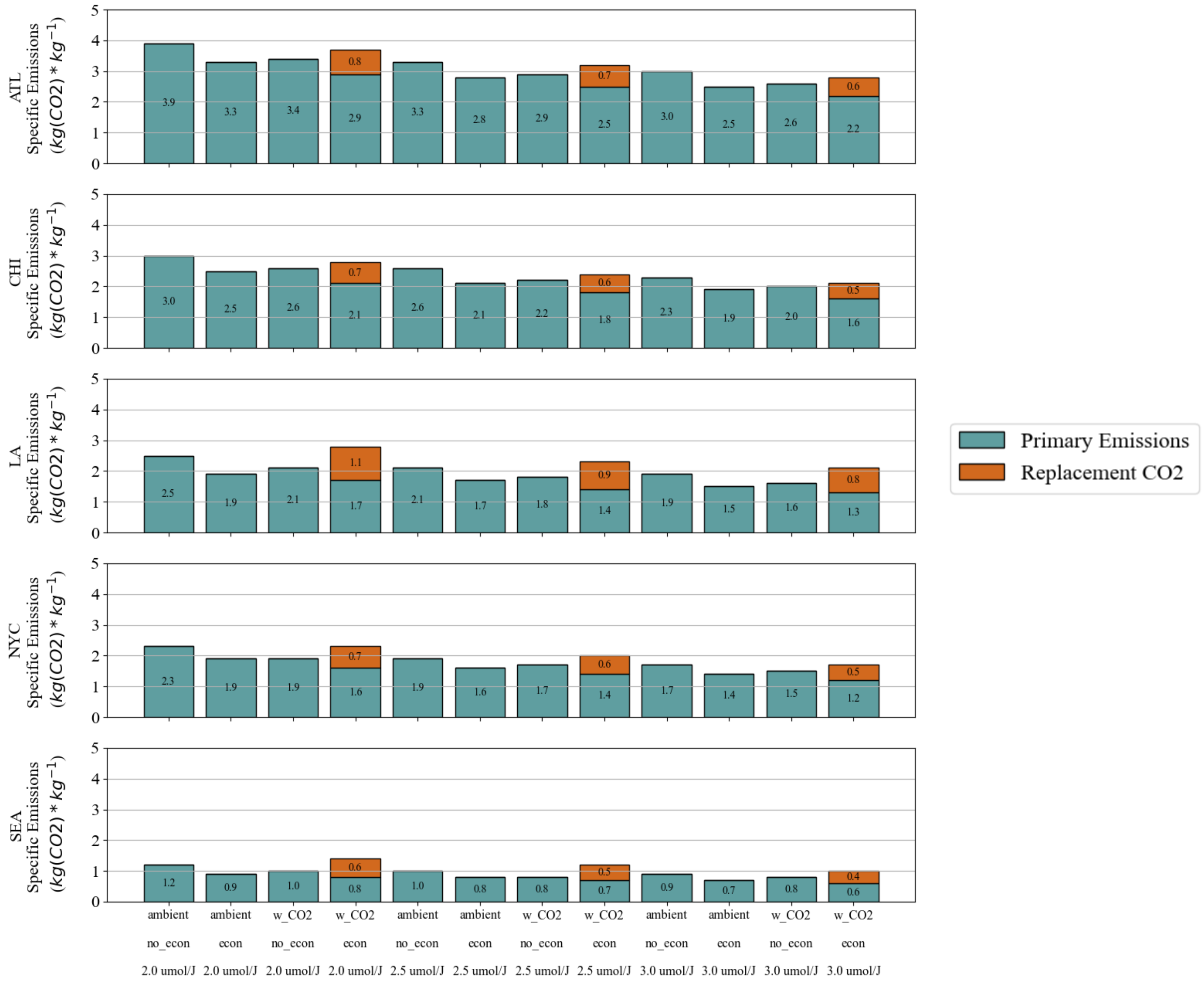

Figure 4: Annual CO_{2e} emissions (kg kg^{-1} canopy) for PF lettuce production across 5 locations, and 12 scenarios.

Location impact on emissions of production