Comparing the energy performance of different controlled environment agriculture spaces using TRNSYS

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Abstract

Controlled Environment Agriculture (CEA) offers many advantages, including high crop productivity and the ability to produce all year-round. The control of the indoor environment – temperature, humidity, carbon dioxide concentration (CO_2), lighting intensity (spectrum, and duration) – leads to higher yield than agriculture in fields. However, these advantages are often offset by high energy use. In this paper, the overall performance (i.e., the energy consumption, the peak electricity demand, and the greenhouse gas (GHG) emissions) of two different CEA spaces, a greenhouse and a container farm, having the same production surface area were compared. The spaces and the heating, ventilation and air conditioning (HVAC) systems were modelled in TRNSYS, where a crop growth model was integrated. The overall performance of the container farm was shown to be better in terms of energy consumption, peak electricity demand and GHG emissions with ratios of 0.284 $kWhe \cdot m^{-2} \cdot kg^{-1}$, 0.083 $kW \cdot m^{-2} \cdot kg^{-1}$ and 0.010 $gCO_2eq \cdot m^{-2} \cdot kg^{-1}$ compared to ratios of 0.453-0.604 $kWhe \cdot m^{-2} \cdot kg^{-1}$, 0.020-0.391 $kW \cdot m^{-2} \cdot kg^{-1}$, and 0.016-0.153 $gCO_2eq \cdot m^{-2} \cdot kg^{-1}$ for the greenhouse scenarios.

Introduction

There is a rising interest in developing solutions to address increased local food demand. In cities, land availability is sparse and small-scale "urban agriculture" can be viewed as a viable solution (Goldstein et al., 2016). Small-scale urban agriculture can take several forms; however, for year-round production at every location, even in northern cities, controlled environment agriculture (CEA) solutions offer many advantages, including high crop productivity (McCartney and Lefsrud, 2018). Small-scale greenhouses and container farms are CEA solutions that can be more easily integrated into the urban environment.

Few studies have evaluated the energy use of greenhouses and container farms or vertical farms under different climatic conditions. Harbick and Albrigth (2016) used building energy simulations to compare the annual energy consumption of a plant factory to a traditional greenhouse located in four different US cities (Atlanta GA, Helena MT, Minneapolis MN, Phoenix AZ). Their results showed that the energy use for plant factories with a single layer of plants was higher than for greenhouses when standard HVAC systems were used. However, in plant factories or container farms, vertical stacking often occurs, which could have an influence on the energy use. A different metric was proposed by Grammans et al. (2018) to compare the energy required to produce 1 kg (dry weight) of lettuce. They reported energy consumption of 247 kWhe in a plant factory compared to 70, 111, and 211 kWhe in greenhouses in the Netherlands, United Arab Emirates, and Sweden, respectively for a footprint of 10,000 m^2. It was also concluded by Weidner, Yang, and Hamm (2021) that the energy consumption in vertical farms was higher than for high-tech ventilated greenhouses in most regions. They used the energy consumption per unit fresh weight produced ($kWhe \cdot kg^{-1}$) as a comparison metric for different floors and growing surface areas with simplified assumptions for the type of crops being grown. As highlighted by Dorr et al. (2021), different metrics are often used to compare the energy performance of CEA spaces, making it challenging to draw conclusions for specific climatic conditions.

In this paper, the overall performance of two different CEA spaces, a greenhouse and a container farm, having approximately the same cultivated area are compared. The spaces and heating, ventilation and air conditioning (HVAC) systems are modelled in TRNSYS, where a crop growth model is integrated. Three different metrics are used to complete a yearly comparison: (1) the energy consumption, (2) the peak electricity demand, and (3) the associated greenhouse gas (GHG) emissions normalized per cultivated area and fresh weight produced ($m^{-2} \cdot kg^{-1}$). Different greenhouse scenarios (without and with artificial lighting) for two different sources of energy for heating (natural gas and electricity) are compared to a container farm having standard HVAC systems.

Methods

To compare the overall performance of the greenhouse to a container farm, both spaces are modelled in TRNSYS (Klein & al., 2017). A crop (lettuce) growth model is integrated to the space models to consider the crop-environment interactions and estimate the yields for different scenarios considered in both CEA spaces located in Montreal, CA. Table 1 summarizes the relevant geometrical parameters of these two spaces. It is important to specify that the orientation (33° to the northeast) as well as the cultivated area ($A_{cultivated}$) are identical.

Table 1: Geometrical parameters of the two CEA spaces.

Parameter	Greenhouse (GH)	Container farm (CF)
Dimensions (LxWxH), m	15.2 x 7.6 x 3.7	12.2 x 2.4 x 2.9
Footprint, m^2	116.1	29.7
Cultivated space, %	0.55	0.72
Growing layers	1	3
Cultivated area ($A_{cultivated}$), m^2	63.9	64.2
Crop density, lettuces·m^{-2}	18	18

Different scenarios are compared as specified in Table 2. In these scenarios, the energy source, the type of lighting (Table 3), and the daily light integral (DLI), which describes the number of photosynthetically active photons (individual particles of light in the 400-700 nm range) that are delivered to a specific area, the photosynthetic photon flux density (PPFD), over a 24-hour period for crop growth, are varied.

Table 2: CEA scenarios.

Scenario	Energy source	Lighting	DLI, $mol \cdot m^{-2} \cdot d^{-1}$
GH-1	Natural gas	Natural only	N/A
GH-2	Natural gas	HPS	10
GH-3	Natural gas	DEL	10
GH-4	Natural gas	HPS	14
GH-5	Natural gas	DEL	14
GH-6	Electricity	DEL	14
CF-1	Electricity	DEL	14

Table 3: Characteristics of the lighting.

Parameters	HPS	LED
Electric power input, $W \cdot m^{-2}_{cultivated}$	350	167
PPFD, $\mu mol \cdot s^{-1} \cdot m^{-2}_{cultivated}$	458.5	434
Efficacy, $\mu mol \cdot J^{-1}$	1.31	2.6
Heat fractions, $f_{conv}/f_{LW}/f_{SW}$	0.28/0.46/0.26	0.37/0.11/0.52

Crop growth model

To model the crops, a TRNSYS component has been created. The component estimates the crop heat gains/losses using a single energy balance between the crops and its environment as illustrated in Figure 1 (Talbot and Monfet, 2020). It is expressed at the canopy scale as an energy flux per unit surface cultivated area ($W \cdot m^{-2}_{cultivated}$), where the cultivated area ($A_{cultivated}$) is the sum of all the horizontal areas of the growing beds.

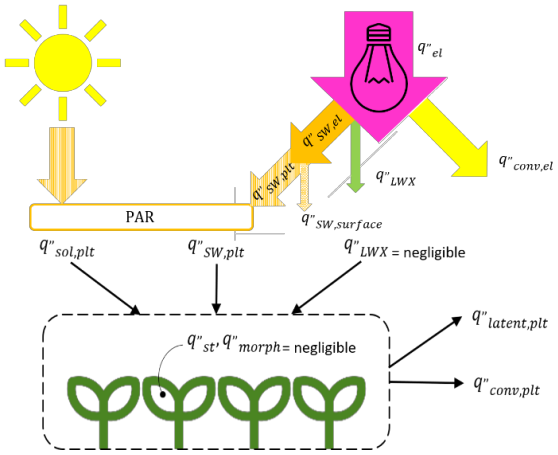

Figure 1: Crop-environment energy balance.

where,

$q"_{el}$ is the installed electric power density;

$q"_{SW,el} = f_{SW} \cdot q"_{el}$ is the short-wave radiation flux;

$q"_{conv,el} = f_{conv} \cdot q"_{el}$ is the convective part of electrical lighting heat gains;

$q"_{LWX}$ is the net long-wave radiation flux exchange between surfaces;

$q"_{SW,surface}$ is the short-wave radiation flux not absorbed by the crops from lights;

$q"_{SW,plt}$ is the short-wave radiation flux absorbed by the crops from lights;

$q"_{sol,plt}$ is the short-wave radiation flux absorbed by the crops from the sun;

$q"_{st}$ and $q"_{morph}$ are the fluxes stored within the leaves, stems and fruits or used for the photosynthesis, respectively;

$q"_{latent,plt}$ is the latent exchange flux with indoor air;

$q"_{conv,plt}$ is the convective exchange flux with indoor air.

The energy balance proposed by Graamans, van den Dobbelsteen, Meinen, et Stanghellini (2017) is modified to consider the impact of crop growth since it has a significant impact on the crop heat gains/losses and the CEA space energy demand (Talbot & Monfet, 2021). As the crops grow, the leaves intercept more Photosynthetically Active Radiation (PAR), which influences the heat balance of the

space as well as the crops heat gains/losses. To consider this phenomenon, a crop (lettuce) growth model is added to the existing component according to the equations proposed by Van Henten (1994) to estimate the total (shoot and root) dry weight of a lettuce head (DW_{total}). Then, the leaf area per lettuce head (LA) and the Leaf Area Index (LAI) are estimated as illustrated in Figure 2. The growth model estimates these variables according to equations proposed by Both, 2002; Schwartz, Anderson & Timmons, 2019; and Tei, Scaife & Aikman, 1996.

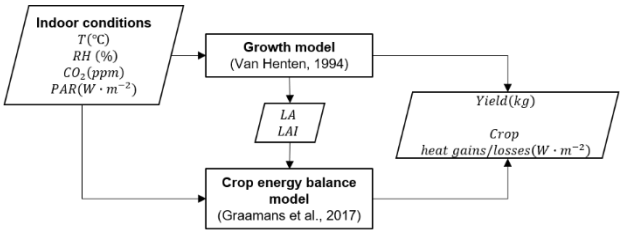

Figure 2: Adaptation of a TRNSYS component to model crop growth as well as crops-environment interactions.

Thus, the developed component dynamically estimates the yield and crop heat gains/losses ($q''_{latent,plt}$ and $q''_{conv,plt}$) based on the dry weight and leaf area calculated at each time step according to the indoor growing conditions (temperature, humidity and CO_2) as well as the PAR. In the modelled greenhouse, the PAR can be from the sun ($q''_{sol,plt}$) and/or supplemented by artificial lighting ($q''_{SW,el}$), while it is solely from artificial lighting in the modelled container farm.

Greenhouse model

The modelled greenhouse is a gothic arch greenhouse (Figure 3) covered mainly with an inflated double layer of polyethylene with 4 mm thick polycarbonate panels for the front and back facades. The structure is made of rectangular steel braces.

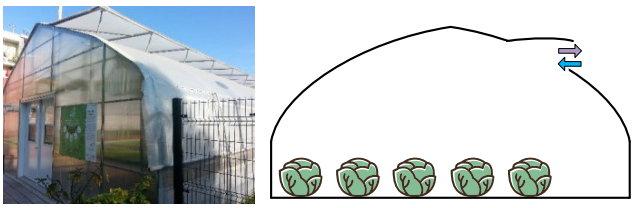

Figure 3: Modelled greenhouse.

The indoor conditions are set to 21°C and 18°C during the daytime and night-time respectively, and maintained using a natural gas unit heater having a capacity of 48.93 kW, a thermal efficiency of 93% and an air flowrate of 1425 $L \cdot s^{-1}$. The motor power of the unit heater fan is 745 kW. Natural ventilation is also used to cool down the greenhouse when the indoor air temperature is higher than 24°C through a 7.5 m^2 roof vent opening and two 15 m^2 side vents that are manually operated. Four 50 W horizontal circulation fans are also used continuously inside the greenhouse to maintain well-mixed air conditions. The power consumption of the 37 W blower used continuously to inflate the greenhouse double-layer polyethylene cover is also considered in the greenhouse electricity consumption. The air infiltration rate in the existing greenhouse is not known. In the model, it is set to 0.6 Air Change per Hour (ACH) as recommended by ASHRAE (2015) for greenhouses covered with plastic film. The detailed description of the model and its calibration was completed by Lalonde, Monfet and Haillot (2022).

For scenarios GH-2 to GH-6 (Table 2), artificial lighting is controlled using the simulated daylight availability inside the greenhouse. Artificial lighting schedule begins at 8:00 and is only turned on if the PPFD falls below 200 $\mu mol \cdot s^{-1} \cdot m^{-2}_{cultivated}$. It remains available until the DLI reaches the specified setpoint.

Container farm model

The modelled container farm is a maritime container that is assumed to have been refurbished to have the envelope characteristics described in Table 4. The infiltration rate is estimated at 0.6 ACH.

Table 4: Envelope characteristics of the container farm.

Building envelope component	Overall U-value, $W \cdot m^{-2} \cdot K^{-1}$
Roof and walls	0.20
Floor	0.25

The container farm is dedicated to the hydroponic culture of lettuce heads stacked in multi-tier growing beds. The production system can grow 18 $lettuces \cdot m^{-2}_{cultivated}$ and covers approximately 72% of the floor area. The indoor conditions and growing parameters are summarized in Table 5, where the VPD is the vapour pressure deficit. VPD is the difference between the vapour pressure inside the leaf to the vapour pressure of the air, which is often used by growers to maintain the indoor air conditions instead of controlling the temperature and the humidity independently.

Table 5: Indoor growing conditions of the container farm.

Parameters	Photoperiod 8:00 to 17:00	Dark period 17:00 to 8:00
Temperature, °C	21	18
Humidity, %	70	74
VPD, kPa	0.75	0.54
CO_2, ppm	1000	1000

The modelled HVAC systems have the same configuration as the existing container farm used in Liebman-Pelaez et al. (2021), i.e., a mini-split air conditioning system and a stand-alone three stages dehumidifier installed within the container farm. A humidification system is required to maintain the relative humidity setpoint most of the time (~8500 hours). To minimize simultaneous use of the dehumidification and humidification equipment, humidification is only available when the dehumidifier is off or operating at the first stage. Three circulation fans are also modelled and used continuously inside the container farm to ensure well-mixed air conditions. Table 6

summarizes the characteristics of the HVAC systems. Ventilation is not provided to the container farm to avoid CO_2 dilution.

Table 6: HVAC system characteristics of the container farm.

Equipment type	TRNSYS Type	Capacity / Electric power
Mini-split AC	Type 56 Type 2280	19.4 kW / 5.3 kW
Stand-alone dehumidifier	Type 688 Type 1503	Stage 1: 2.85 kW / 1.2 kW Stage 2: 5.7 kW / 2.3 kW Stage 3:14.25 kW / 5.7 kW
Electric heater	Type 56	3.5 kW / 3.5 kW
Electric humidifier	Type 56	3 kW / 3 kW
Circulation fans	N/A	N/A / 50 W (with η= 0.4)

Results

The results are compared for the scenarios described in Table 2. The yearly yield, based on production starting on the first day of January, are detailed for all scenarios in Table 7. It is assumed that harvest occurs when the fresh weight of the lettuce reaches a value of 240 g. For the greenhouse scenarios, the yield is only influenced by the DLI, while the type of lighting has limited impact. In terms of yield per cultivated area, it is 56% higher in the container farm than in the greenhouse. However, for the same footprint, the production is six times higher in the container farm compared to the greenhouse. In the container farm, the growth cycle is short, 26 days on average, because optimal indoor conditions are maintained. For the greenhouse scenarios, the growth cycle is between 40 days (GH-5 & GH-6) and 52 days (GH-1).

Table 7: Estimated yearly yield for the CEA scenarios.

Scenario	Yield per footprint, $kg \cdot m^{-2}$	Yield per cultivated area, $kg \cdot m^{-2}$	Average duration of the growth cycle, days
GH-1	17	30	52
GH-2	19	34	44
GH-3	19	35	46
GH-4	21	39	41
GH-5	21	39	40
GH-6	21	39	40
CF-1	131	61	26

Energy consumption

The energy consumption of the different scenarios is described in Table 8 and illustrated in Figure 4, where a calorific value of 37.89 $MJ \cdot m^{-3}$ is used for natural gas. The use of HPS versus LED lighting as an impact on the electricity consumption since they require more energy to operate. However, the heating requirements of the scenarios with HPS (GH-2 & GH-4) are slightly higher than the scenarios with LED (GH-3 & GH-4) even though HPS lighting releases more heat to the space than LED. This is explained by the type of HPS specified in this study, which gave off slightly more PPFD than the LED (458.5 $\mu mol \cdot s^{-1} \cdot m^{-2}_{cultivated}$ vs. 434 $\mu mol \cdot s^{-1} \cdot m^{-2}_{cultivated}$), thus the crops under HPS lighting transpire more and get cooler.

Table 8: Estimated yearly energy use of the CEA scenarios.

Scenario	Natural gas, m^3	Electricity, kWh	
		Lighting	HVAC
GH-1	6 615	–	5 240
GH-2	6 157	7 910	5 020
GH-3	6 150	3 962	5 017
GH-4	5 975	16 543	4 933
GH-5	5 959	8 300	4 925
GH-6	–	8 300	63 750
CF-1	–	35 049	32 141

As expected, the energy consumption varies monthly according to the outdoor conditions for the greenhouse scenarios while being relatively constant for the container farm (Figure 4). There is also an increase in energy consumption when artificial lighting is used in the winter months for the greenhouse scenarios.

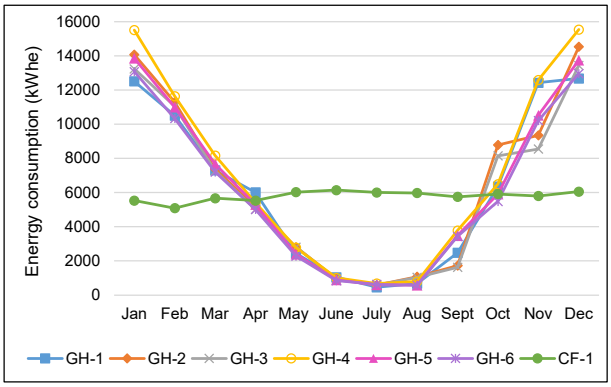

Figure 4: Energy consumption of the CEA scenarios.

The energy consumption per fresh weight produced ($kWhe \cdot kg^{-1}$) often used to compare the energy performance of CEA scenarios is presented in Table 9. Using this metric, the container farm is the most efficient.

Table 9: Estimated yearly energy consumption per fresh weight produced for the CEA scenarios.

Scenario	Energy consumption per fresh weight produced, $kWhe \cdot kg^{-1}$
GH-1	39
GH-2	35
GH-3	33
GH-4	34
GH-5	31
GH-6	29
CF-1	18

Figure 5 illustrates the energy intensity per yield normalized per cultivated area and per footprint. The energy intensity calculated with the footprint is considerably higher for the

container farm. This is expected since CEA spaces like container farms and plant factories are well known for having a high energy consumption (e.g., Avgoustaki and Xydis (2020)) mostly due to lighting, cooling and dehumidification. However, calculating the energy intensity of a container farm using the footprint might not be appropriate for comparison purposes with other CEA spaces such as greenhouses. The cultivated area is more analogous to the conditioned surface area in buildings than the footprint. In fact, for the same conditions, the yield and the energy use are proportional to the cultivated area, rather than only being limited by the floor area. Moreover, the space organization of container farms or plant factories can vary significantly in terms of floor-plan layout and growing bed orientation (horizontal or vertical stacking). As such, if an additional growing bed is added, the energy intensity per footprint will be higher than the one presented for the CF-1 scenario (green ×) in Figure 5 since the energy consumed for the same footprint area would be higher. Thus, the use of the cultivated area as a reference metric seems more reasonable to compare different CEA spaces and was selected in this study to complete the proposed comparison.

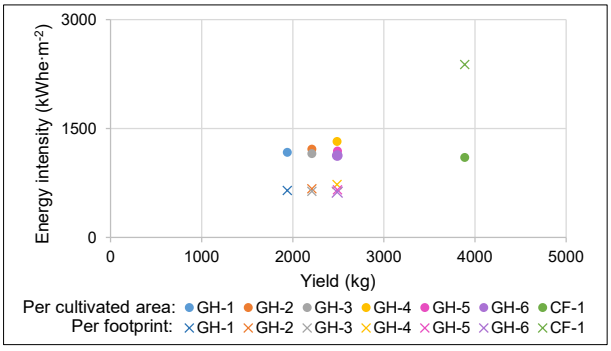

Figure 5: Energy intensity per yield of the CEA scenarios.

In terms of the energy consumption ratio (kWhe·m^{-2}·kg^{-1}), the greenhouse scenarios perform better in the summer months while having a lower performance in the winter months compared to the container farm (Figure 6).

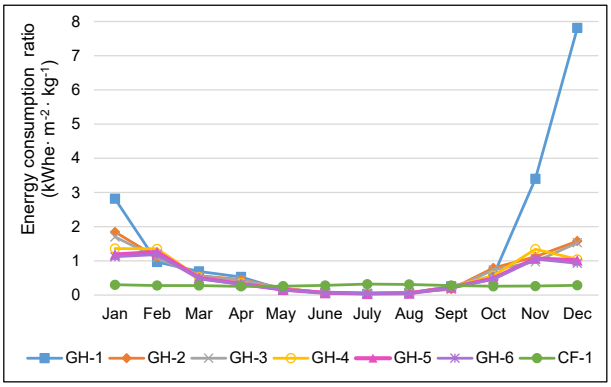

Figure 6: Energy consumption ratio of the CEA scenarios.

It is also noted that when there is no supplemental lighting provided in the winter months (January, November and December), the energy consumption ratio degrades significantly (scenario GH-1). This is explained by lower yield caused by limited natural lighting availability in those months. Thus, from October to March, the container farm outperformed the greenhouse scenarios in terms of energy consumption ratio.

Peak electricity demand

For the greenhouse scenarios with natural gas heating, the peak electricity demand is relatively constant throughout the months (Figure 7). However, when HPS lighting is used with a DLI of 14 mol·m^{-2}·d^{-1} (GH-4), the peak electricity demand is slightly higher than for the container farm even with natural gas heating since artificial lighting is used to reach the specified DLI throughout the year. Also, for the greenhouse heated using electricity and with LED artificial lighting (GH-6), the peak electricity demand is higher or similar than for the container farm.

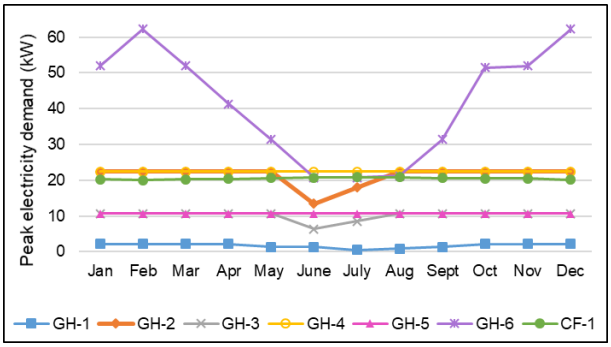

Figure 7: Peak electricity demand of the CEA scenarios.

The peak electricity demand intensity per yield (Figure 8) illustrates that the container farm has a similar intensity in terms of cultivated area to most of the greenhouse scenarios. The yield is however higher. This leads to peak electricity demand ratio being higher for the greenhouse scenarios where HPS lighting (GH-2 & GH-4) or electric heating (GH-6) is used compared to the container farm (Figure 9).

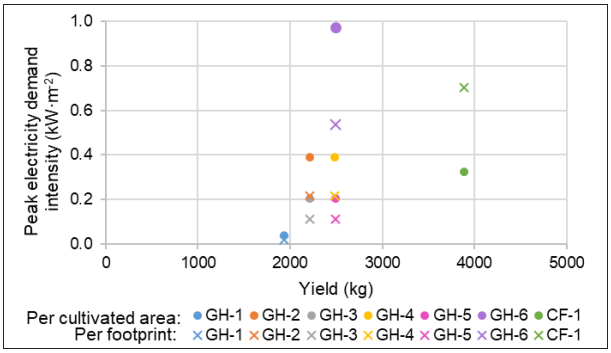

Figure 8: Peak electricity demand intensity per yield of the CEA scenarios.

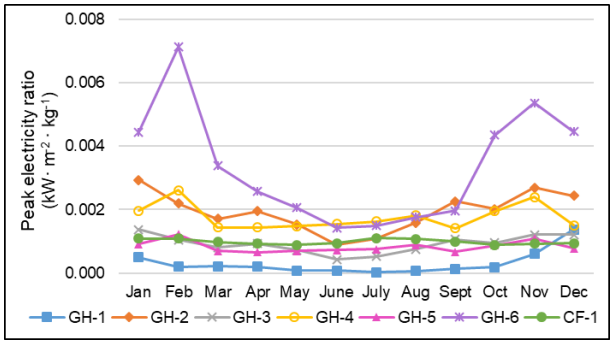

Figure 9: Peak electricity demand ratio of the CEA scenarios.

Associated greenhouse gas (GHG) emissions

The associated GHG emissions (Figure 10) are estimated using a factor of 270 $gCO_2eq \cdot kWhe^{-1}$ (CIRAIG, 2020) for natural gas and of 34.5 $gCO_2eq \cdot kWhe^{-1}$ for electricity (Levasseur et al., 2021). Since the GHG factor is much lower for electricity in Quebec, the electric heated greenhouse and the container farm scenarios have lower impacts both in terms of cultivated areas or footprints. However, the greenhouse with electric heating and artificial lighting has lower impacts than the container farm. It is important to keep in mind that the ratios obtained for the electric heated greenhouse and the container farm are largely influenced by the Quebec energy context. In most regions of the world, those scenarios would have a higher GHG emissions ratio.

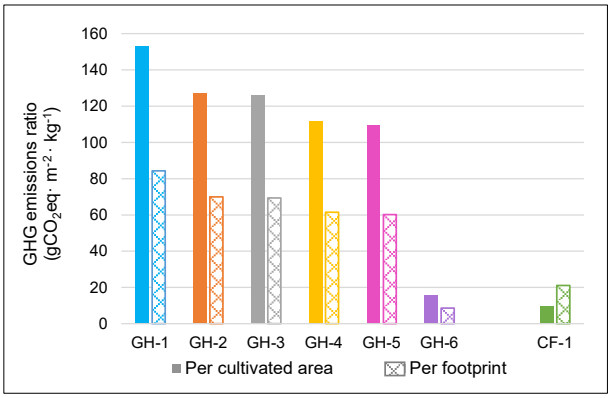

Figure 10: Estimated GHG of the CEA scenarios.

Yearly results

An overview of the yearly energy consumption ratio, peak electricity demand ratio and GHG emissions ratio are presented in Table 10. On a yearly basis, the container farm outperformed all of the greenhouse scenarios in terms of energy consumption ratio and has a lower peak electricity demand ratio compared to most of the greenhouse scenarios where artificial lighting is used.

The GHG emissions ratio is much lower when the energy source is solely electric (scenarios GH-6 and CF-1). Also, when artificial lighting is used, the yield is increased leading to an improved GHG emissions ratio for the greenhouse scenarios (GH-2 to GH-6).

Table 10: Yearly ratio of the CEA scenarios.

Scenario	Energy consumption, $kWhe \cdot m^{-2}_{cultivated} \cdot kg^{-1}$	Peak electricity demand, $kW \cdot m^{-2}_{cultivated} \cdot kg^{-1}$	GHG emissions, $gCO2eq \cdot m^{-2}_{cultivated} \cdot kg^{-1}$
GH-1	0.604	0.020	0.153
GH-2	0.551	0.177	0.127
GH-3	0.522	0.093	0.126
GH-4	0.531	0.157	0.112
GH-5	0.477	0.082	0.109
GH-6	0.453	0.391	0.016
CF-1	0.284	0.083	0.010

Discussion

The yield per cultivated area ($kg_{dry} \cdot m^{-2}$) and the energy consumption per dry weight produced ($kWhe \cdot kg_{dry}^{-1}$) are compared to the results reported by Grammans et al. (2018) for a similar greenhouse without artificial lighting (scenario GH-1) and a container farm (scenario CF-1) located in Sweden, which is a similar climate to the one in this study, i.e., ASHRAE Zone 7, as reported in Table 11.

Table 11: Comparison with Grammans et al. (2018) results.

Space type	Scenario	Yield per cultivated area, $kg_{dry} \cdot m^{-2}$	Energy consumption over yield , $kWhe \cdot kg_{dry}^{-1}$
GH	GH-1	1.43	819
	Grammans et al. (2018)	~2.00	~210
CF	CF-1	2.86	386
	Grammans et al. (2018)	~5.00	~247

For the compared greenhouse scenario without artificial light (GH-1), the estimated yield per cultivated area is 29% lower even though a higher temperature setpoint was maintained in the studied greenhouse (GH-1) – 21°C/18°C vs. 12°C/9°C – and the annual solar radiation was higher – 13 117 $MJ \cdot m^{-2}$ vs. 5 187 $MJ \cdot m^{-2}$. This difference may be explained by how yield was estimated by the growth model. In the proposed growth model, yield is influenced by both the maintained growing conditions, the crop size at transplant, the harvest size and the dry matter content, with several of those parameters not being specified or based on different assumptions in Grammans et al. (2018). As an example, the dry matter content was set to 4.3%, while being set to 7% in Grammans et al. (2018), which are two values proposed in the literature. This difference in assumption leads to significant deviation in terms of yield. In terms of energy consumption per fresh weight produced, it is about 4 times higher, which is explained by (1) the higher temperature setpoint in scenario GH-1 which increases the heating consumption and (2) the higher

envelope area over the floor area ratio which is 2.06$m^2 \cdot m^{-2}$ in GH-1 compared to 1.24$m^2 \cdot m^{-2}$ in Grammans et al. (2018), leading to more important heat losses.

For the container farm scenario (CF-1), the yield per cultivated area is 43% lower compared to the value reported by Grammans et al. (2018). This is explained by difference in DLI, which was set to 14 $mol \cdot m^{-2} \cdot d^{-1}$ for CF-1 compared to 28.8 $mol \cdot m^{-2} \cdot d^{-1}$. Here again, the results are also influenced by the assumptions made for the dry matter content. The energy consumption per dry weight is 43% higher for CF-1, which can be explained by a combination of factors, such as lower electricity consumption for lighting, but higher consumption for cooling and dehumidification for scenario CF-1. These differences are explained by the different temperature and relative humidity setpoints used, 21°C/18°C and 70%/74% for CF-1 vs. 30°C/30°C and from 65% to 90%, respectively in Grammans et al. (2018). The sensible cooling system and dehumidification COP of CF-1 were also set to lower values.

When comparing the greenhouse scenarios (GH-1 to GH-6) with the CF-1 scenario, the energy consumption ratio ($kWhe \cdot m^{-2} \cdot kg^{-1}$), calculated over the cultivated area, is higher during the winter months while being lower during the summer months. However, when there is no supplemental lighting provided in the winter months (January, November and December), the energy consumption ratio degrades significantly (scenario GH-1). This analysis could be considered to optimize the use of greenhouses and container farms when their impacts are minimal. As such, the concept of "cold" greenhouse, where the maintained indoor temperature is below optimal, might need to be further explored as well as potential synergies that could be established between the two types of CEA spaces.

In terms of peak electricity demand ratio ($kW \cdot m^{-2} \cdot kg^{-1}$), the use of electric heating as well as HPS lighting led to higher values compared to the container farm. Different operating strategies could be considered to minimize or shift peak electricity demand in greenhouses such as modulating lights by lowering the power demand while extending the photoperiod in order to reach the same DLI or even lowering the heating setpoints.

As expected, and due to the low impact of the electricity grid in Quebec, the GHG emissions ratio ($gCO_2 \cdot m^{-2} \cdot kg^{-1}$) is much lower for the greenhouse with electric heating and for the container farm. For a more complete approach, a life cycle analysis (LCA) should be completed that would consider not only the GHG emissions associated with the operation phase.

The container farms and plant factories are often identified as spaces with high energy intensity. However, metrics that include the cultivated area and yield to assess CEA spaces performance have illustrated that container farms are not outperformed by greenhouses in terms of energy consumption, peak electricity demand and GHG emissions in Quebec. Moreover, for the same cultivated area, container farms have a much smaller footprint and thus, are easier to implement in the urban environment. On the other hand, greenhouse implementation can be limited by their larger footprint and possible shading from surrounding buildings.

Conclusion

In this paper, the overall performance of two different CEA spaces, a greenhouse and a container farm, having approximately the same cultivated area were compared. TRNSYS was used to model the spaces, crops and HVAC systems with a transient approach to estimate the energy use and crop yield for the different scenarios. A growth model was added to an existing crop model to consider crop growth in the estimation of crops heat gains/losses, which has not previously been done. The model used for the greenhouse scenarios was a calibrated model.

The addition of an integrated growth model to the CEA space model enhanced the estimation of three different metrics to support a more comprehensive comparison of the performance of different CEA spaces using: (1) the energy consumption, (2) the peak electricity demand, and (3) the associated greenhouse gas (GHG) emissions normalized per cultivated area and fresh weight produced ($m^{-2} \cdot kg^{-1}$). The use of the cultivated area as opposed to the footprint seemed more appropriate to assess the performance of CEA spaces since there is an important variability in terms of space organization amongst CEA spaces.

Finally, determining the most promising scenario was challenging as it is influenced by the time of year when the space was expected to be in operation as well as by the assumptions used to estimate yield, which directly affects the performance's ratios. To conclude on the best small-scale CEA solutions to be easily integrated to the urban environment, the implementation of additional constraints is required and the comparison should be supplemented by a LCA and financial analysis.

Nomenclature

f_{conv}	convective heat fraction of lights [-]
f_{LW}	long-wave radiative heat fraction of lights [-]
f_{SW}	short-wave radiative heat fraction of lights [-]
HPS	high-pressure sodium
LAI	leaf area index [m^2leaves$\cdot m^{-2}$cultivated]
LED	light-emitting diode
PAR	Photosynthetically Active Radiation
PPFD	photosynthetic photon flux density [$\mu mol \cdot s^{-1} \cdot m^{-2}_{cultivated}$]

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