The Impacts of Plants on HVAC System Performances: A Parametric Study

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Abstract

In this paper, the TRNSYS simulation results of a building integrated agricultural space (BIAs), where a lettuce model estimated the latent and sensible heat transfers between the plants and the environment, were presented. The energy performance of two heating, ventilation and air conditioning (HVAC) systems was assessed for different cultivated densities. The results showed that the use of an economizer system reduced the total energy use of the HVAC system for high-density BIAs. It demonstrated that considering the sensible heat transfer between the plants (the cooling effect of the plants) and the environment was of crucial importance for adequate sizing of the heating equipment. The high latent heat transfer of the plants by evapotranspiration allowed adequate sizing of the dehumidification system, which is of prime importance in cold climates due to the risk of condensation in the building envelope.

Introduction

The loss of cultivable lands around large cities due to urban development and the densification of the urban population will decrease food security in cities in the foreseeable future (Al-Kodmany, 2018). Consequently, moving agriculture inside buildings is gaining momentum. In insular regions, like Japan, cultivable land is scarce and controlled environment agriculture is already being implanted (Despommier, 2013). For cold climate regions, moving agriculture indoor would allow yearlong production of many crops. Furthermore, local production would decrease food miles, effectively reducing transport costs and related CO₂ emissions. Previous studies stated also that controlled environment agriculture is more water-efficient and has little need of pesticide use (Kozai, Niu & Takagaki, 2015; Van Ginkel, Igou & Chen, 2017). It is also noteworthy to mention that some effects of climate change could cause loss of cultivable lands in multiple areas around the globe due to drought, recurrent wildfires and floods.

The downside of controlled environment agriculture is the high energy costs required to maintain the indoor environmental conditions in the optimal range for crop growth. In BIAs, energy is used primarily for electrical lighting, then, in order of importance, cooling, dehumidification, and heating and humidification of the air (Graamans et al. 2018). In order to develop strategies to reduce these costs and to make BIAs a viable

alternative to conventional agriculture, the simulation of the energy performance of BIAs is of utmost importance. This simulation should include the latent and sensible heat transfers between the plants and the environment since several studies show its significant impact on the thermal loads (Talbot & Monfet, 2018; Ward et al. 2015). In fact, including a crop model is of paramount importance to estimate the humidity levels inside the space for BIAs operating in cold climate, since the building envelop integrity can be adversely affected by condensation inside the external walls during the winter months. Adequate prediction of the humidity levels attributable to plants would help minimizing this risk.

In this study, the energy performance of two HVAC systems is assessed by considering the sensible and latent heat transfers between the plants and the environment for different cultivated densities. This is completed by detailed modelling, using TRNSYS, of the BIAs to assess its energy performance and predicting the risk of condensation in order to support the design of various HVAC system equipment and configurations. The simulation results also deepen the understanding of the energy fluxes inside BIAs by growers and allow researchers to work toward optimization of HVAC systems to meet the indoor environmental conditions requirements of these particular spaces.

Overall approach

In this paper, a BIAs located inside a revamped industrial building in Montreal was modeled to assess the energy performance of two HVAC systems. TRNSYS, a transient simulation software, was used to complete the analysis. The BIAs model was coupled to a crop (lettuce) model based on the algorithm proposed by Graamans, van den Dobbelsteen, Meinen & Stanghellini (2017) and implemented as a TRNSYS component.

To evaluate different HVAC system equipment and configurations and the impact of different cultivated density, the following steps were completed:

1. Modeling the existing building in TRNSYS;
2. Sizing the HVAC equipment and systems according to best practices: two HVAC systems are proposed;
3. Modeling the HVAC systems;
4. Inserting the crop (lettuce) model component to the TRNSYS model;
5. Conducting a parametric study for different cultivated densities.

Each step is described in more details.

Modeling the existing building in TRNSYS

The revamped industrial building, located in Montreal (Canada), included a BIAs surrounded by various spaces maintained at 21°C as illustrated in Figure 1.

Figure 1: Building spaces configuration.

The BIAs was considered as an interior zone with a floor area of 110.56 m² and a ceiling height of 5.3 m. The external losses or gains due to infiltration and conduction were considered minimal since air and thermal exchanges with the outside were limited. The interior walls of the BIAs were assumed to be covered with water repellent material to ensure the integrity of the envelope. Since it is a very humid space, the coating retained water vapor in the space and minimized the risk of its migration through the envelope. The thermal resistance of the roof, slab and interior walls were set respectively to 5.43, 0.18 and 0.39 m²K/W as defined in ASHRAE 90.1-2010 for a medium office in the 6A climate zone (ASHRAE, 2010). The gains of five occupants doing light work on a typical workday schedule in the BIAs were considered.

Different temperature and relative humidity (RH) setpoints were selected for the photoperiod and the dark period to enhance crop growth as detailed in Table 1. BIAs is a critical space and tight dead bands are recommended by ASHRAE (2010). They are often selected in controlled environment agriculture applications because it allows for better control of the setpoints while preventing simultaneous operation.

Table 1: Photoperiod and dark period setpoints.

	Photoperiod	Dark period
Schedule	6:00 - 22:00	22:00 - 6:00
Plants activity	Photosynthesis	Respiration
Lamps state	On	Off
Temperature setpoints [°C] (dead band)	21.5 (1)	19.5 (1)
RH setpoints [%] (dead band)	70 (5)	80 (5)

The electrical lighting was set to horticultural LED lamps with an input electrical power of 168 W/m²_{cultivated} and an efficiency of 52% (Royal Philips, 2018). This converted to a photosynthetic photon flux density of 437 μmol/m².

Sizing the HVAC equipment and systems according to best practices

Two HVAC systems were sized according to best practices and modeled to maintain the indoor conditions of the BIAs. They were modeled to be completely independent of the HVAC systems that served the other

spaces of the building. The first one is referred to as the airtight system as illustrated in Figure 2. It consisted of a variable air volume (VAV) recirculation unit with terminal cooling and heating.

Figure 2: Airtight system.

Since the BIAs was considered to be airtight, a CO₂ enrichment system was used to maintain the CO₂ concentration between 700 ppm and 1000 ppm. Studies show that infiltration and/or ventilation air flow higher than 0.1 ACH causes losses of the injected CO₂ to the outside (Ohyama & Kozai, 1998). Therefore, the infiltration was estimated to 0.02 ACH as recommended by Kozai et al. (2015) to avoid the dilution of CO₂. The cooling coils and electric heating coils were sized to meet the user design loads, which are the design loads multiplied by a service factor of 1.25. The heat transfer between the plants and the environment was not included in the load calculations. The capacity of the dehumidification system was selected heuristically according to industry practice. It was done iteratively by adjusting the dehumidification capacity until the relative humidity setpoint was met.

The second system is referred to as the economizer system and is illustrated in Figure 3. An economizer was added to provide free cooling and dehumidification when outdoor conditions were suitable. A with an electric preheating coil.

Figure 3: Economizer system.

In this case, the space was still considered airtight with an infiltration rate estimated at 0.02 ACH. However, in order to maintain the CO₂ concentration around the atmospheric concentration estimated at 400 ppm, a minimal outdoor air flowrate had to be specified. According to ASHRAE's recommendation for winter ventilation of a greenhouse (ASHRAE, 2011), an outdoor air flowrate of 10 to 15 L/s per square meter of floor area is required to maintain the CO₂ concentration depending of the cultivated density.

Modeling the HVAC systems

The HVAC systems were modelled using the TRNSYS components detailed in Table 3, which are either available in the TRNSYS original library or in the TESS library.

The air flowrates through all the fans, which varied with the cultivated density, were determined to ensure that the indoor environmental conditions were maintained. The fans static pressure head was estimated to 375 Pa and accounted for pressure drops through the filters and the coils in the system, while the pumps pressure head was estimated at 60 kPa to account for fluid pressure drop through the cooling and dehumidification coils.

The humidifier used was the ideal humidifier included in TRNBuild and it was set to maintain the humidity setpoint at all time with an electrical energy use efficiency of 97%, which is commonly seen for steam humidifiers.

A design choice was also made to split the loads: the sensible cooling was used to size the HVAC system and the latent cooling load was handled by the dehumidification system. The cooling coils used in the HVAC and dehumidification loops were slightly different. The *Type 508b* used in the HVAC loop allowed the control of the outlet air temperature by bypassing excess cooling fluid; it was set to maintain a constant supply air temperature of 16.5°C, just above the dew point temperature. Moreover, the coil fluid inlet temperature was set to 6.67°C and the temperature differential through the coil was set to remain under 7°C when in operation. The cooling capacity was then determined using the indoor air conditions, the cooling coil air outlet conditions and the user design load. The *Type 508c* used in the dehumidification loop was selected since it can control the cooling fluid outlet temperature to remain under 13.5°C, which cooled the air to low temperature in order to extract the moisture while maintaining a reasonable temperature range between entering and leaving cooling fluid temperatures. The dehumidification system reheat coil was set to only supply sufficient heat so that the supply air temperature matched the BIAs setpoint temperatures, thus not altering the sensible cooling load to be handled by the HVAC loop. The heating coil capacity was set to the user design heating load. The economizer was set to reduce the outdoor air flowrate to its minimal value when the outside air temperature was lower than 12°C and higher than 16°C.

Table 3: TRNSYS components used to model the two HVAC and dehumidification systems.

TRNSYS component	Airtight system		Economizer system	
	HVAC	Dehumidification	HVAC	Dehumidification
<i>Type 662</i> - Variable-speed fan	X	X	X	X
<i>Type 655</i> - Air-cooled chiller	X	X	X	X
<i>Type 741</i> - Variable-speed pump	X	X	X	X
<i>Type 508b,c</i> - Cooling coil	X (b)	X (c)	X (b)	X (c)
<i>Type 930</i> - Electric heating coil	X	X	X	X
<i>Type 684a</i> - Enthalpy economizer	N/A	N/A	X	N/A
<i>Type 760</i> - Heat recovery device	N/A	X	N/A	X
<i>Type 23</i> - PID controllers	X	X	X	X
TRNBuild integrated - Ideal humidifier	X	N/A	X	N/A

The controllers used for cooling, dehumidification and heating were PID controllers due to their ability to closely monitor and regulate the coils capacity in function of the room temperature and humidity. For cooling controls, the PID controller modulated the fluid flowrate of the cooling coil, while maintaining a minimal flowrate to avoid dirt accumulation.

Inserting the crop (lettuce) model component to the TRNSYS model

The crop (lettuce) model was connected to other components of the TRNSYS model, which is based on a specific set of user-defined parameters. At each time step the lettuce model exchanged inputs and outputs with the building model. Parameters, inputs and outputs of the lettuce model are presented in Table 2, with a description of each of the parameters following the introduction of Table 2.

Table 2: Parameters, inputs and outputs required by the crop (lettuce) model

Parameters	Cultivated density (CD), Cultivated area (A_{BIAs}), Leaf Area Index (LAI), Cultivated area cover (CAC), Lamps efficiency, Properties of moist air, Leaf reflectivity
Inputs	Lamps input electric power, BIAs temperature, BIAs relative humidity
Outputs	Crop latent heat gain, Crop sensible heat gain, Vegetation temperature

The cultivated density (CD) is the ratio of the cultivated area ($A_{cultivated}$) over the floor area (A_{BIAs}) (equation 1). This value is fixed by the grower and varies between a minimal and a maximal value.

$$CD = \frac{A_{cultivated}}{A_{BIAs}} \quad (1)$$

A minimal CD value of 0.6 was assumed acceptable since it provided sufficient space for pathways and equipment. For the maximal value, a vertical distance between tiers of 30 cm was considered: it maximized BIAs productivity since the typical distance between tiers is 30-100 cm (Kozai et al., 2015). Considering the space requirement of the growing beds, a maximum of 10 tiers can be stacked vertically in the BIAs under study, which corresponded to a CD value of 6.

The Leaf Area Index (LAI) is the ratio of the mean leaf area per unit of cultivated area. The LAI was set to the average value of 2.1 to represent a steady state operation with lettuces growing at all development stages simultaneously (Graamans et al., 2018).

The cultivated area cover (CAC) represents the fraction of the cultivated area covered with plants and varies with the LAI. The CAC was set to 80%, which was obtained from the linear relationship between LAI and CAC for lettuces (Tei, Scaife & Aikman, 1996). This simplification meant that 20% of the PAR light emitted from the electrical lighting did not reach any leaves and was absorbed by the floor. Furthermore, 5% of the PAR light that reached the leaves was considered to be reflected.

Also, the crop (lettuce) model included some simplifications and assumptions:

- The radiative heat transfer from plants to the environment was neglected.
- The heat storage in the hydroponic solution was neglected.
- The impact of the CO₂ concentration on the thermal behaviour of lettuces was neglected (Graamans et al., 2017). The model considered that the plants behaviour depended mostly on the photosynthetic photon flux density and indoor air conditions (temperature and humidity).
- The aerodynamic boundary layer resistance of the plant was considered constant at 100 s/m, as per Graamans et al. (2017) recommendation with forced air circulation on.
- Since HVAC system maintained the space conditions, the air thermodynamic properties were considered constant in the model.

Conducting a parametric study for different cultivated densities

To assess the impact of different cultivated density on the systems performance, a parametric study was conducted with a time step of 0.01 hour. Table 4 presents the parametric study parameters used for each system. A simulation was run for a typical meteorological year in Montreal for three cultivated densities: low (CD = 0.6), medium (CD = 3) and high-density (CD = 6). While the number of tiers increased, the total lamps electric power input increased proportionally to make sure that each growing bed had optimal lightning conditions. The heating design load for the airtight system was set to a fixed value, regardless of the CD. However, for the economizer system, the load varied since the outdoor air flowrate increased with higher CD. The sensible cooling load always increased with higher CD since the additional heat gains from the electrical lighting needed to be accounted for. The latent cooling design load, used to size the dehumidification system, as stated previously, was determined iteratively.

Table 4 : Parametric study parameters.

		BIAs cultivated density		
		Low	Medium	High
CD [-]		0.6	3	6
Tiers [-]		1	5	10
Total lamps electric power [kW]		11	56	111
Airtight system	HVAC heating capacity [kW]	12.9		
	HVAC sensible cooling capacity [kW]	7	26.7	53.4
	Dehumidification latent cooling capacity [kW]	6.7	31.9	63.6
	Ventilation air flowrate [L/s/m ² _{floor}]	0		
Economizer system	HVAC heating capacity [kW]	73.5	85.7	104
	HVAC sensible cooling capacity [kW]	23.2	53.2	91.6
	Dehumidification latent cooling capacity [kW]	33.9	80.7	130
	Ventilation air flowrate [L/s/m ² _{floor}]	10	12	15

Results

The global performance of the systems was assessed based on the following:

1. The HVAC annual energy consumption and BIAs peak demand per end use;
2. The heating system peak load and capacity;
3. The total annual energy consumption.

HVAC annual energy consumption and BIAs peak load per end use

One of the main concerns for BIAs is their high energy costs. Thus, it is of vital interest to evaluate the energy consumption profile of this particular space. In colder climates, the option of using free-cooling can be considered to reduce cooling energy consumption. However, since the outdoor air flowrate required to maintain the CO₂ concentration is important, it leads to higher heating energy consumption during the winter. Figure 4 presents the energy consumption of the airtight system per end use. It illustrates the energy consumption of the heating, cooling, fans, humidification and dehumidification systems. The airtight system had little need of humidification, since the evapotranspiration of the plants influenced the humidity level in the space. The low infiltration rate of 0.02 ACH had a limited impact on the humidity level of the BIAs, which lead to important need for dehumidification as the humidity built up. The energy consumption of the dehumidification system for a BIAs airtight system operating in cold climate was by far the most important. This was expected since the dehumidification system must cool an important volume of air at low temperatures to extract moisture, which then

needed to be reheated to reach the supply air temperature setpoint.

Figure 4: Energy consumption distribution of the airtight system for different CD.

The heating energy consumption of the HVAC system remained relatively stable, with a slight increase observable for high-density BIAs due to the impact of heat transfer between the plants (cooling effect of the plants) and the environment. It was observed also that the energy consumption for cooling varied with the cultivated density. This was expected since the electrical lighting heat gains were significant and increased with CD. One notable advantage of this system was that it greatly reduced the introduction of outside airborne contaminants and pathogens into the BIAs and allowed for CO₂ enrichment.

Figure 5 presents the annual energy consumption of the economizer system, where free-cooling was possible with the use of an enthalpy economizer with temperature-based control. The energy consumption of the dehumidification system was lower for the economizer system since a significant part was handled by the increase in outdoor air.

Figure 5: Energy consumption distribution of the economizer system for different CD.

On the other hand, the heating and cooling energy consumption were higher since this additional outdoor air required to maintain the CO₂ concentration must be conditioned during colder and warmer months. The difference in heating energy consumption between the medium and high-density BIAs can be explained by the higher outdoor air flowrate required as well as by the

impact of plants on the BIAs load. The higher energy consumption required for the heating of a low-density BIAs was explained by the fact that the lighting heat gains were not sufficient to offset the required heat for conditioning the outdoor air. Similarly, the cooling energy consumption for low-density BIAs was lower since the number of hours where cooling was required was reduced by the use of the economizer during summer. However, as the CD increased, the electrical lighting heat gain increased, leading to higher cooling energy consumption. Since the humidity level was higher in the BIAs than the outside air humidity level for most of the year, the energy consumption of the humidification system was important and compensated for the humidity losses due to the high outdoor air flowrates required to maintain the CO₂ concentration. This requirement was lower for higher CD since plants also raised the humidity level of the air.

Figure 6 presents the BIAs peak demand per end use of the airtight and the economizer systems for different CD. The power demand was calculated over an integration period of 15 minutes, as calculated by the electricity provider in Quebec.

Figure 6: BIAs peak demand distribution for different CD.

For the airtight system, the peak demand increased with the electrical lighting heat gains that was proportional to the CD. For the economizer system, the different peak demand distribution was explained by the use of free-cooling. While the electrical lighting heat gains still increased with CD, the use of the free-cooling reduced the cooling load and increased the heating load requirements caused by the high outdoor air flow requirement of this system. Finally, the peak demand for medium and high-density are similar for both systems while for low-density, it is much lower for the airtight system.

Heating system load and capacity

The performance of the installed heating system was investigated by comparing the heating system peak load to capacity ratio (*hcr*) as defined by Equation 2.

$$hcr = \frac{\text{Peak load}}{\text{Capacity}} \cdot 100\% \quad (2)$$

Figure 7 illustrates the heating system peak load to capacity ratio for each system. The results showed that the installed heating system capacity was sufficient to maintain the indoor air temperature for any CD for both systems.

Figure 7 : Heating system peak load to capacity ratio for different CD.

However, for the airtight system, as the CD increased, the heating system capacity, which corresponds to the use of a 1.25 oversizing factor, was barely sufficient to maintain the indoor air temperature when a typical meteorological year in Montreal (Canada) was used. This can be explained by the sensible heat transferred between the plants (cooling effect of the plants) and the environment when the CD was increased. This could be problematic under extreme weather conditions, which could occur in real-life, as the installed heating system capacity would probably not be sufficient to maintain the indoor air temperature, leading to potential condensation in the exterior walls. Similar results were noted by Talbot & Monfet (2018): the installed heating system capacity, sized according to best practices, could not maintain the indoor temperature setpoint in dark period during the winter months when the heat transfer between the plants and the environment was considered.

Total energy consumption

Table 5 presents a comparison between the total HVAC energy consumption and the electrical lighting energy consumption over the total energy consumption of both systems for different CD, while Figure 8 illustrates the total HVAC energy consumption of both systems for different CD. Results showed that while the electrical lighting accounted for most of the energy consumption, the HVAC systems contributed significantly to the energy

consumption and peak demand (Figure 6). For the airtight system, Graamans et al. (2018) have shown similar results for different locations with electrical lightning accounting for about 57% of the total energy consumption. This highlights the need to implement measures to improve HVAC system efficiency to increase BIAs viability.

The results showed that the system that had lower energy consumption changed from lower to higher density BIAs (Figure 8).

Figure 8: Energy consumption for different CD.

For lower density BIAs, when the economizer system was used, the outdoor air flowrate losses during the winter was more important in comparison to the lighting heat gains, leading to an important sensible and latent heating energy consumption for that period of the year. This explained why the energy consumption of the economizer system was higher for a CD of 0.6 compared to a CD of 3: the installed lighting power was proportional to the number of tiers leading to additional lighting heat gain for higher CD. However, the use of cold outdoor air to cool the space provided reduction in the energy consumption for cooling. For both cases, when the CD increased, the energy consumption of the dehumidification system intensified. On the other hand, the condensate from the dehumidification of the air could be reused to water the crops or for humidification in the case of the economizer system, which would be important in the design of BIAs located in area where water use efficiency is a priority as well.

Discussion

The results showed that the lettuces thermal interactions with the environment inside a BIAs have a significant impact on HVAC system performance. While Graamans et al. (2018) results did not show any need for heating, this study shows that even for an airtight system, some heating is required for a BIAs located in cold climate during dark periods in winter months.

Table 5: Percentage of the HVAC and electrical lighting energy consumption for both BIAs systems and different CD.

System	CD = 0.6			CD = 3			CD = 6		
	HVAC [%]	Electrical lighting [%]	Total energy consumption [MWh]	HVAC [%]	Electrical lighting [%]	Total energy consumption [MWh]	HVAC [%]	Electrical lighting [%]	Total energy consumption [MWh]
Airtight system	48	52	124	36	64	507	37	63	1041
Economizer system	78	22	302	40	60	539	35	65	999

However, this study has its limits and further development is required to scale adequately the outdoor air input required to maintain CO₂ concentration before it is possible to state that one of the two systems studied is more suitable for application in a BIAs context in cold climate.

The implemented control strategy of the economizer system could be improved. Such improvement could include the use of a recirculating system, such as the airtight system in colder and hotter months, to reduce the heating and cooling energy consumption. Under these operating conditions, an auxiliary CO₂ enrichment system would be required to maintain the CO₂ concentration during those periods, which would lead to higher crop yields. In fact, Wang, Tong, Yang & Xin (2016) experimentally used this strategy to ensure a minimal CO₂ concentration when outdoor air was not needed for cooling. It has shown to reduce the energy consumption for cooling in Beijing. Moreover, since some peak demands occurs when the lights are turned on or turned off, a lightning strategy could lower the BIAs peak demand for both systems. For high-density BIAs, those improvements of the control strategy have the potential to benefits the economizer system.

A disadvantage of the economizer system is that the high outdoor air flowrate requirement does not allow for CO₂ enrichment of the air to higher values than 400 ppm. Since higher CO₂ concentration (700-1000 ppm) are reported for the production of certain lettuce crops (Knight & Mitchell, 1988), this lower CO₂ concentration could generate lower crop yield. However, according to Wang, Tong, Yang & Xin (2016), the use of outdoor air for cooling does not have a significant impact on lettuce growth.

Furthermore, synergies between the HVAC system and efficient use of other resources like the water balance needs to be considered.

Three main difficulties were noted when completing the simulations. First, there seems to be no humidifier with a variable moisture addition flowrate available in the TRNSYS and TESS standard components library. As a consequence, the humidifier power requirement may stray from real life energy consumption. However, since both studied systems relied on the use of the same TRNSYS component, the comparison between both systems is still possible and provides adequate approximation of the energy consumption distribution of the BIAs HVAC systems. Obviously, the introduction of real-life data from manufacturers to size the system components would improve the precision of the simulation results.

The second difficulty is of most important and requires further investigation from the scientific community. In this simulation, the ventilation air flowrate used were based on the ASHRAE recommendation for winter ventilation of a greenhouse. However, there is no indication whether or not this value is suitable to maintain CO₂ concentration for high cultivated densities, such as those encountered in BIAs. It is possible that this value has thus been under or overestimated when simulating the

economizer system. Furthermore, a better characterization of the gaseous exchanges between plants and their environment as function of their stage of growth and the ambient conditions would facilitate the selection of outdoor air flowrate required to maintain atmospheric CO₂ concentration in BIAs when an economizer system is installed.

The third difficulty relates to the lettuce model used. It has been noted that under high temperature and relative humidity, the model output values were aberrant with respect to their impact on sensible and latent heat gains. This means that additional verifications of the lettuce model outputs must be completed before using it to evaluate the performance of different BIAs HVAC systems. This limitation could be further investigated in order to create an error message when the model strays from its validity range.

Finally, since the interaction of plants with the environment depends significantly on the crop type, it would be of great interest to create a library of models for crops that could be grown in controlled environment. A list of potential crops as defined by Kozai et al. (2015) could be used to create a database of models or tables to be used for simulations. For other indoor applications, such as indoor plant wall that is currently gaining in popularity, and is not as stringent as controlled environment agriculture, a simplified model could be developed. This is of particular interest in cities like Montreal, where many public buildings have mould control issues and are less inclined to the introduction of plants inside buildings.

Conclusion

The use of a lettuce model inside a BIAs showed to have a great impact on HVAC system design and performance. Using simulations, it was demonstrated that although a typical airtight system was the system of choice in the controlled environment agriculture industry, energy savings can be realized through the use of a system completed with an economizer while still maintaining the required indoor environmental conditions of a BIAs. However, further development of the model is required to better characterize gaseous exchanges between crops and their environment in a BIAs. This would help design systems that are capable of maintaining a steady CO₂ concentration using outdoor air. The use of crop models allows for better HVAC system design and analysis leading to reduced risks of condensation in the building envelope in cold climate while also allowing future research to study cost-efficiency for different HVAC systems configurations. This step is critical in order to demonstrate the economic viability of large-scale indoor agriculture facilities. It has previously been noted by Graamans et al. (2018) that there are few locations on the globe that would justify the use of controlled environment over traditional agriculture, but through research, HVAC and electrical lighting system optimization, water use efficiency, higher crop yield and lower transport costs might well someday turn this vision into a reality.

Finally, the possibility to increase of BIAs energy efficiency and reduce condensation risks in the building envelop made this modelling approach an inestimable tool to increase BIAs' viability in cold climate.

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