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Energy performance evaluation and modeling for an indoor farming facility

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ABSTRACT

Indoor farming refers to a method of growing crops on vertically stacked layers in a soilless cultivation system (e.g., hydroponics) in a controlled indoor environment. In comparison with conventional open-field farms, indoor farming has advantages such as significantly improved productivity and water use efficiency, and reduction in food miles. However, indoor farming facilities are energy-intensive for maintaining favorable crop growing conditions.

In this study, we evaluated the energy performance of indoor farming operations using both measurements and simulation results. Key performance parameters were first analyzed based on utility bills and continuous measurements from an indoor farming facility. Several operational issues were identified for the mechanical system. An energy model for an indoor farming facility was created using building energy simulation software EnergyPlus and calibrated based on measurements. A novel modeling approach simulating the unique mechanical system—misting systems—for indoor farming was developed using one of the advanced features in EnergyPlus— energy management system (EMS). The energy model was used to evaluate the effectiveness of energy-saving strategies to improve the energy efficiency of facility operations. These include simultaneous heating and cooling, hardly met temperature setpoints and improperly controlled dampers. These energy efficiency measures include fixing motorized damper control, eliminating simultaneous heating and cooling, and having wider ranges of temperature setpoints. Up to 48.1% of reduction in annual natural gas consumption was predicted with energy-saving measures. In addition, the limitations of using building energy simulation software for indoor farming modeling were discussed.

Introduction

It is estimated that the world's population is expected to rise to nearly 9.1 billion and global food demand by 70% in 2050 [1]. Thus, feeding the world's population in the coming years will become a grand challenge. Indoor farms, such as plant factories, and shipping container farms [2], often employ a method of growing crops on vertically stacked layers in a soilless cultivation system (e.g., hydroponics) under a controlled indoor environment. Indoor farming has 10–20 times higher productivity per unit area than conventional farms [3,4]. As reported in a recent case study, the annual water use of hydroponic systems was about 8% of that from conventional farms per unit mass of lettuce [5]. Therefore, indoor farming can provide a possible solution to the grand challenge of food demands and reduce water demands in agriculture.

However, indoor farming is energy-intensive due to its use of grow lights, heating, ventilation, and air conditioning systems to maintain favorable growing conditions for crops, especially in harsh climates [5]. Energy is usually the second largest overhead cost in crop production, after labor cost [6] for indoor farming. It accounts for up to 25% of the operating costs of large indoor farms in the U.S. [7]. Reducing high energy demands for indoor farming facilities, while increasing crop yield, is identified as a key industry sustainable development goal [8].

EnergyPlus [9] — one of the most prestigious building modeling software — has been utilized to evaluate the energy performance of indoor farming facilities in recent studies. Harbick and Albright [10] compared annual energy consumption between plant factories and greenhouses with the same dimensions located in four ASHRAE climates (2B, 3A, 6A, and 6B) in the U.S using EnergyPlus. They found that given equal production, plant factories consume significantly more energy and have greater carbon emissions than traditional greenhouses for the range of climates in the continental US. Another study by Graamans et al. [11] compared the energy use per unit dry weight of crops between plant factories and greenhouses located in three different countries Netherlands (ASHRAE Climate Zone:5), United Arab Emirates (ASHRAE

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Climate Zone:1) and Sweden (ASHRAE Climate Zone:6). Greenhouses and plant factories were modeled using a greenhouse climate simulation model KASPRO [12] and EnergyPlus, respectively. In the study, crop transpiration based on an evapotranspiration (ET) model [13] was integrated with EnergyPlus, and lettuce production was predicted based on a growth model [14]. They found that the total energy per unit of dry matter in plant factories is lower than in greenhouses although the energy use per cultivation area in plant factories is greater. Furthermore, Graamans et al. [15] used EnergyPlus integrated with the ET model to facilitate façade design for reducing energy demands from plant factories in the three climates. Existing studies on energy performance analysis were from design perspectives based on theoretical indoor farming facilities instead of from real mechanical system operation perspectives in indoor farming facilities.

In this study, we evaluated the energy performance of indoor farming operations using both measurements and simulation results. Key performance parameters were first analyzed based on utility bills and continuous measurements from an indoor farming facility located in Jackson Hole, WY. Then, we identified several operational issues based on the performance data analysis. After that, an energy model for an indoor farming facility was created using building energy simulation software EnergyPlus and calibrated based on measurement data. The calibrated energy model was used to evaluate the effectiveness of energy-saving strategies for the facility. Limitations of using building energy simulation software for indoor farming modeling were also identified in this study.

This research represents one of few studies on energy evaluation for real indoor farming system operation. We identified operational issues of mechanical systems and quantified energy saving potentials through the implementation of several low-cost or no-cost control strategies. A novel modeling approach simulating the unique mechanical system—misting systems—for cooling and humidification of indoor farming spaces was developed using one of the advanced features in EnergyPlus—energy management system (EMS). This study can provide valuable operational experiences for energy-efficient operation of existing and future indoor farming facilities. The modeling methodology for misting systems can be adopted and applied for future simulations of indoor farming facilities with similar cooling and humidification systems.

Facility description

The indoor farming facility, located in Jackson, WY, was constructed in the year 2015. It is a three-story building with a gross area of 13,500 ft^2. The facility operates and grows fresh vegetables 365 days a year. The schematic diagram of mechanical heating and cooling systems of the indoor farming facility is shown in Fig. 1. Heating was supplied through an underfloor heating system as well as heating hot water pipes around the façade of the facility by a heating hot water system. Cooling was severed by a misting system on the first and second floor and mechanical ventilation throughout the building. Cross ventilation was achieved through motorized dampers installed on the north facade and exhaust fans installed on the south façade. The facility has seven growth compartments and a retail market. There is a carousel which automatically runs through the atrium of the three-story building for growing lettuces and microgreens. Also, there are carousels over the first and second stories next to the glazing facade. The compartments on the first and second floors are used for growing microgreens, while the two compartments on the third floor are exclusively for tomatoes.

Building construction

The north façade of the facility, connected to a parking garage, and the east and west walls of the stairwell are made of Kingspan Panel systems, which are composed of 10 cm (4 in.) mineral fiber fire-rated insulation and pre-painted steel panels on both sides. The south façade is made of 4 mm (0.158 in.) tempered glass. The thermal properties of the tempered glass and the Kingspan Panel are listed in Table 1.

Mechanical systems

The systems that maintain indoor environment conditions include a ventilation system composed of motorized dampers and exhaust fans, a heating hot water system composed of a boiler, underfloor heating on the first floor, a series of heating hot water pipes along the façade in various compartments, and a misting system for cooling and

Table 1
Thermal properties of building envelope materials for Vertical Harvest.

Material	Thickness (inch)	Specific Heat (Btu/lb °F)	R-Value (°F ft^2 hr/Btu)
4″ MF Fire-Rated Panel			
22 GA. Pre-Painted Steel	0.0299	0.12	0.61
Mineral Fiber Insulation	4	0.17	14.40
22 GA. Pre-Painted Steel	0.0299	0.12	0.61
TOTAL	4.06	0.41	15.62
Glass Panel Assembly (walls and roof)			
Tempered Exterior Glazing	0.158″	0.16	0.77

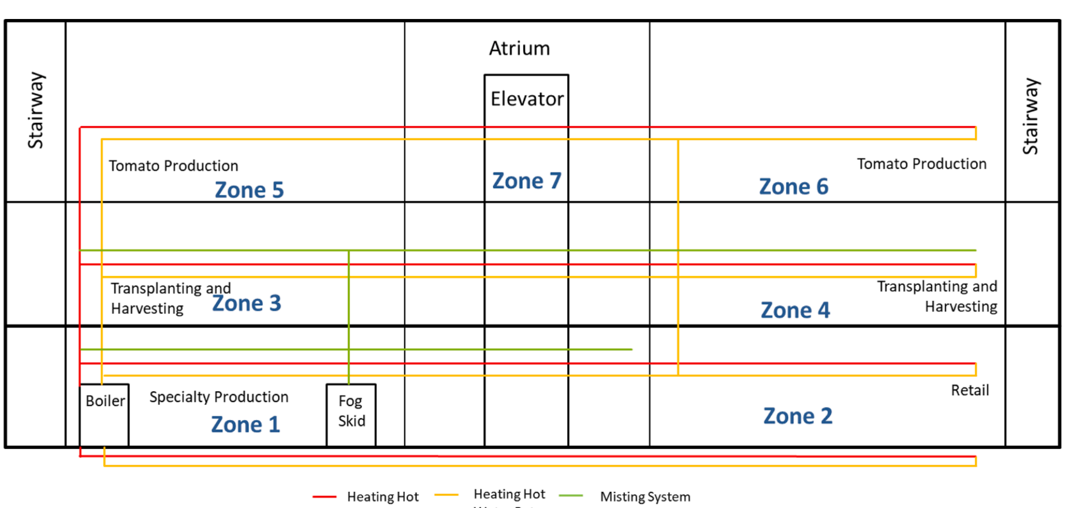

Fig. 1. Schematic diagram of mechanical heating and cooling systems.

humidification.

The required indoor temperature and CO_2 for each Compartment are listed in Table 2.

The heating system switches on when compartment indoor temperatures are below minimum indoor temperatures. Three minimum indoor temperature setpoints correspond to different periods throughout the day. They are 16 °C, 17 °C, and 16 °C for different periods between 3:27 and 10:55 (period 1), between 10:56 and 16:21 (period 2), and between 16:22 and 3:26 (period 3). Whenever the indoor temperature is below the minimum indoor temperature and the heating system has been turned off for at least half an hour, the heating system would come on. The heating system needs to be on for at least an hour. The natural gas boiler with a capacity of 450 kW supplies heating hot water to a series of heating hot water pipes. The supply heating hot water temperature ranges from 80 °C to 90 °C.

For ventilation controls, indoor air temperatures control the opening of the motorized dampers (24.5 in. × 24 in. each) on the south facade for ventilation. When the indoor temperatures are above 18 °C for periods 1 and 3 and 20 °C for period 2, the motorized damper for ventilation will open. There are 19 exhaust fans on the north façade of the facility in total. Each exhaust fan has a nominal flow rate of 6,560 m^3/h, an efficiency of 43.8%, and a pressure rise of 215 Pa.

The misting system with 0.008-inch diameter misting nozzles cools off the growth compartments on the first and second floors. The cooling temperature setpoints are 20 °C, 25 °C, 25 °C, and 20 °C for periods between 2:56 and 9:32, between 9:33 and 12:04, between 12:05 and16:38, and between 16:39 and 2:55, respectively. Both dead bands for cooling on and off are 5 °C. The maximum spray periods are 15 s, 15 s, 20 s, and 15 s for the four periods, respectively. The minimum spray periods are 5 s, 10 s, 10 s, and 5 s, respectively. The maximum pause periods are 4 min, 3 min, 3 min, and 4 min, respectively. The minimum pause time is 3 min, 2 min, 2 min, and 3 min, respectively.

Grow lights

There are several types of grow lights installed in the facility. These include high-pressure lights (HPS) and LED grow lights from Philips Horticulture, GE, and Thrive Agritech. The grow lights provide supplemental illumination to support plant growth. The number of grow lights and capacity are summarized in Table 3. LEDs are on 24/7, while HPS lights operate based on outside solar radiation.

Performance evaluation

Utility data analysis

Utility data were collected for the electricity and natural gas of the facility. This includes monthly data for natural gas and electricity (11/2015–08/2018), daily electricity data (11/2015–08/2018), and hourly electricity data (06/20/2017–09/30/2018). The electricity meter monitors the total electricity use for LED grow lights, carousels, pumps, and fans. The natural gas meter monitors the natural gas used by the boiler. We employed the inverse modeling approach [16] to analyze the utility data.

Table 2
Required Indoor Temperature and CO_2 Concentrations for each compartment.

	Temperature range (°C)	CO_2 (PPM)
Compartment 1	19–20	N/A
Compartment 2	18–25	N/A
Compartment 3	17–19	600–800
Compartment 4	17–19	400–500
Compartment 5	20–22	800–1000
Compartment 6	20–22	800–1000
Compartment 7	N/A	N/A

*N/A–Not Available (There was no setpoint for the parameters indicated).

Table 3
Grow lights for each compartment.

Compartment	Light type	Number	Capacity per unit
1	LED (Phillips)	24	105 W
	LED (GE)	175	36 W
2	LED (Phillips)	12	105 W
3	LED (Phillips)	24	105 W
	LED (GE)	45	36 W
	HPS	16	632 W
4	LED (Phillips)	12	105 W
	LED (GE)	48	36 W
	LED (Phillips)	144	32 W
5	HPS	30	632 W
6	HPS	30	632 W
	LED (Phillips)	36	32 W
7	LED (Thrive Agritech)	40	130 W

Energy use intensity (EUI)

EUIs were calculated for the year 2016, the year 2017, and the year 2018, respectively. The results are listed in Table 4. From the year 2017 to the year 2018, natural gas consumption was increased by 40%, and the total energy use intensity was increased by 17%.

Natural gas

Daily natural gas data was preprocessed by filling in missing data, removing data with zero readings, and neglecting the data for 11/2015–12/2015 during the commissioning stage. The daily natural gas consumption is plotted against daily outdoor air temperature in Fig. 2 for years 2016–2018. The points with red circle markers in the figure illustrate the daily natural gas consumption for the year 2016. The points with green diamond markers show the daily natural gas consumption for the year 2017. The points with blue triangle markers show the daily natural gas consumption for the year 2018. As shown in Fig. 2, daily natural gas consumptions decrease with the increase in outdoor air temperature and then fluctuates within a small range after the outdoor air temperature reaches a certain point ("change-point").

Daily natural gas consumption for the corresponding outdoor air temperature increases from 2016 to 2018. We used dashed contours to illustrate the trends of daily natural gas consumption every year. As observed in Fig. 2, daily natural gas consumptions in the year 2017 are slightly higher than those in the year 2016 although there are many overlapping points between the two years. Daily natural gas consumption in the year 2018 is much higher than those in the year 2016 and the year 2017.

To visualize the trends more clearly, we calculated monthly-averaged daily natural gas consumption for the years 2016–2018. We employ the 3-parameter (3P) change-point model [16] to describe the relationship between monthly-averaged daily natural gas consumption and monthly average outdoor air temperature.

The 3P change-point linear regression model can be formalized in Equation (1).

$$E = c1 + c2(c3 - T)^{+} \tag{1}$$

Where E is the estimated daily energy consumption (electricity or natural gas); *c1* is a constant in kWh/Day; *c2* is the slope of the linear

Table 4
Energy use intensity (site energy) for Vertical Harvest in years 2016–2018.

Year	Electricity	Natural Gas	Total
	kWh/ft²	*Therm/ft²*	*kBtu/ft²*
2016	30.00	1.71	272.93
2017	44.39	1.90	341.01
2018	38.27	2.65	395.58

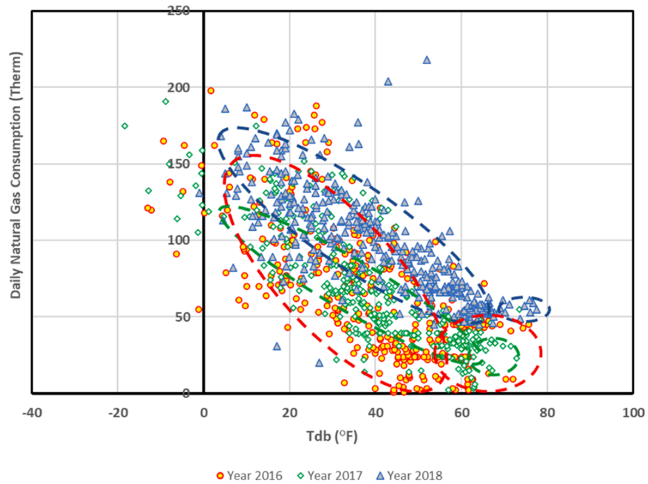

Fig. 2. Comparison of daily natural gas for years 2016–2018.

regression model; and *c3* is the change point temperature where the two lines intercept; *T* is the monthly average outside air dry-bulb temperature (independent variable); the superscript "+" indicates that only positive values of the bracketed quantity in the equation are taken into account, and the negative values of the bracketed quantity are considered as zeros. The change-point models were often used for building commissioning. When building systems are under normal operation, a change-point model can be developed as a baseline to estimate monthly-averaged daily energy use based on the utility data. It is a relatively simple data-driven (inverse) model and not for predicting hourly energy consumption. However, this type of model can provide the big picture by identifying changes in energy use profiles over time. The findings through comparing the models over time can help identify directions and efforts on where the potential system operation issues are. It is a useful tool to assess if there are abnormal changes in building energy performance over time.

The best-fitted models for years 2016–2018 based on monthly-averaged daily natural gas consumption are illustrated in Fig. 3. The goodness-of-fit for the 3P models can be judged based on the R-squared values. A value of 1.00 means a perfect fit, and values above 0.80 indicate a very good fit. The R-squared values for the 3P models of the year 2016, the year 2017, and the year 2018 are 0.82, 0.94, and 0.85, respectively. Fig. 3 indicates that the average daily natural gas consumption in the year 2018 is much higher than those in the years 2016–2017 for high outdoor air temperature. Through the analysis of change-point models over time, we know that there were operational issues related to increased natural gas consumption for heating.

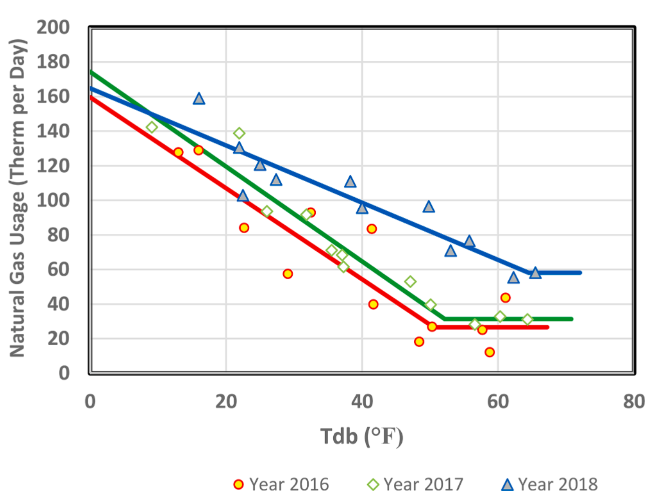

Fig. 3. Comparison of average daily natural gas for years 2016–2018.

Electricity

Average daily electricity consumption was calculated for each billing period. Fig. 4 illustrates the comparison of average daily electricity consumption for the years 2016–2018. With the increase of monthly-averaged outdoor air temperature, the average daily electricity consumption was slightly reduced. It is noted that this is different with most commercial building electricity use profiles because electricity use of grow lights instead of mechanical cooling dominates the electricity use profile in indoor farming facilities. Average daily electricity consumption in the year 2017 is higher than that for the years 2016 and 2018. This is probably because new LED grow lights have been installed in the facility in the year 2017 and many LED grow lights were broken in the year 2018 based on the maintenance log.

Trend data analysis

We reviewed the control sequences of the environmental control system for the facility and analyzed trend data for key environmental and control parameters. Similar to the building automation system, the environmental control system automates the operations of heating, cooling, ventilation, lighting, CO_2, and irrigation system for the facility. In this study, we focused on control strategies and the performance of heating, cooling, and ventilation systems.

Trend data (five-minute intervals) between January 2018 and December 2018 were collected. Indoor temperature data is compared with the desired setpoint for each compartment to determine how well the desired setpoint is being met. Indoor temperature and CO_2 concentrations were evaluated for each growth compartment. Table 5 summarizes the percentage of periods when the parameters were within the desired temperature range and CO_2 concentration range listed in Table 2 for each compartment.

We use compartment 3 as an example to illustrate the trend data analysis results. As presented in Fig. 5, the indoor temperature fluctuated from 14.79 °C to 33.38 °C. The indoor temperature for Compartment 3 reached the lowest point of 14.79 °C when the outdoor air temperature was −17.18 °C. This occurred at 3:15 on Jan 3, 2018. The highest indoor temperature 33.38 °C was recorded at 16:05 on August 9, 2018, while the outdoor air temperature was 30.4 °C. Only 21% of the time during the 12 months meets the required temperature range of 17–19 °C for Compartment 3. The CO_2 concentration ranged from 309 ppm to 1307 ppm. CO_2 concentrations were above the 600 ppm lower limit for only 9% of the time during the 12 months as presented in Fig. 6.

As shown in Fig. 7, boiler and air vents are simultaneously on for about 56.7% of the time throughout the monitoring period. Fig. 8

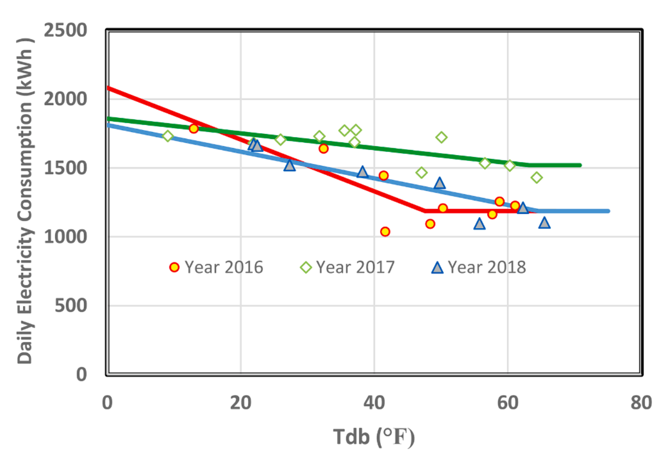

Fig. 4. Comparison of average daily electricity consumptions for years 2016–2018.

Table 5
Indoor environment analysis for each compartment.

	% within the desired temperature range	% within the desired CO_2 concentration range
Compartment 1	14	N/A
Compartment 2	72	N/A
Compartment 3	21	9
Compartment 4	26	74
Compartment 5	25	0
Compartment 6	18	0
Compartment 7	N/A	N/A

*N/A – Not Available (There was no setpoint for the parameters indicated).

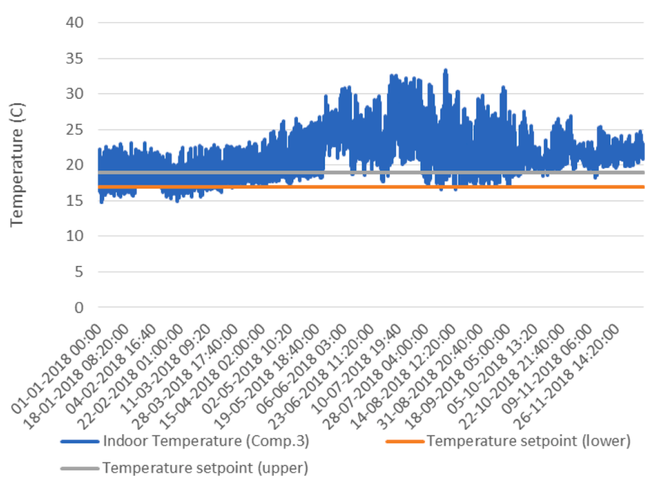

Fig. 5. Compartment 3 indoor temperature vs setpoints.

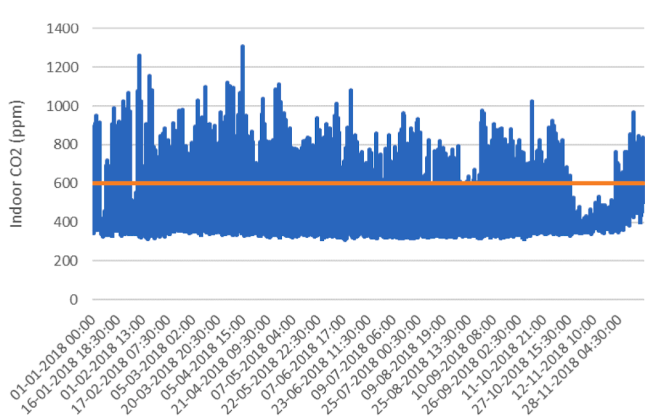

Fig. 6. Compartment 3 indoor CO_2 concentrations vs setpoint.

presents an enlarged section from Fig. 7 during March 17–18, 2018. The outdoor air damper for ventilation was continuously open (23–91%). The outdoor air temperature was in the range of −10.8 °C to 1.28 °C and the boiler was on for 74.3% of the time during this period.

Figure 9 showed the damper status, air temperature, and damper opening setpoints for compartment 3 between March 17–18, 2018. The motorized damper for each compartment should be controlled by indoor air temperature based on the control sequence as shown with the blue line in Fig. 9. When the indoor air temperature is above the damper opening setpoint ("blue line"), the motorized dampers in the compartment should open. Otherwise, the dampers should be closed. As we can see from Fig. 9, there are many mismatches between when the dampers are supposed to be opened and the actual opening status.

Based on the trend data analysis, several issues relating to operations have been identified. First, most of the time, the temperature, and CO_2 setpoints in growth compartments are hardly met. For optimal yield, crops require temperatures and CO_2 concentrations to be within the ideal range. Indoor temperatures in compartment 2 were well maintained in comparison with other compartments. The temperature setpoint for compartment 2 (retail) was met 72% of the time in 2018. However, for the other compartments, the period that the setpoint was met was only up to 26% of the time. The same applies to the CO_2 concentrations within the different compartments, with setpoints being met less than 10% of the time in compartments that require above 600 ppm.

The desired temperature ranges for compartments as listed in Table 2 are relatively narrow. Gray [17] identified an optimal temperature range (15–22 °C) for germination and emergence of lettuce varieties. Zan *et al.* [18] tested the effect of controlled air temperatures (16, 18, and 20 °C) on the growth, photosynthesis, yield, and quality of lettuce and found that 18 and 20 °C are the optimal temperatures for growing lettuce. Adams *et al.* [19] investigated the effect of temperature on tomato growth and development under various controlled temperatures 14, 18, 22, and 26 °C. The study showed that fruit sizes and yields under the temperature of 18 and 22 °C are higher than those under the temperature of 14 and 26 °C. The optimum temperature for tomatoes from 18.5 °C to 26.5 °C for fruit set was recommended [20]. Based on the given literature and original temperature setpoints, we can consider relatively wider ranges of temperature setpoints: 16 °C–22 °C for lettuces and microgreens in compartments 1–4 and 7 and 18–24 °C for tomatoes in compartments 5–6.

The second issue is simultaneous heating and ventilation with both the boiler and vent on. During the 2018 monitoring period this occurred frequently for compartments with ventilation as follows: 49.2% (compartment 1), 56.7% (compartment 3), 60.7% (compartment 4), 53.1% (compartment 5), and 30.5% (compartment 6). Open damper during cold weather substantially increased heating demands. The trend data analysis suggests that the simultaneous operation of the boiler and vent should be minimized. This could lead to substantial energy savings.

The third issue is related to the operation of motorized dampers. Motorized dampers on the south façade are not operating as expected based on our trend data analysis. There are many occasions throughout the year when actual damper positions and expected damper positions based on control sequences are mismatched.

The issue related to unmet temperature setpoints was mainly due to the narrow setpoint ranges and the operational issues identified for the growing compartments. Both second (simultaneous heating and ventilation) and third issues (incorrect operation of motorized dampers) identified are related to the control sequence of heating and mechanical ventilation systems. They can be fixed by modifying control sequences of heating and mechanical ventilation systems. Energy efficiency measures targeting individual operational issues identified here were evaluated using a calibrated energy simulation model.

Building energy modeling

We created a dynamic building energy model for the indoor farming facility using EnergyPlus [9]. Detailed information on components of mechanical systems such as exhaust fan, heating hot water pump, misting pump, irrigation pump, and misting nozzle as well as miscellaneous building loads was collected and used in model development. Baseboard water heating was used in the energy simulation model to represent heating pipes for each compartment. Motorized dampers and exhaust fans were simulated using the airflow network model in EnergyPlus. The exhaust fan system was set to operate in tandem with the motorized dampers, coming on whenever dampers were open for each

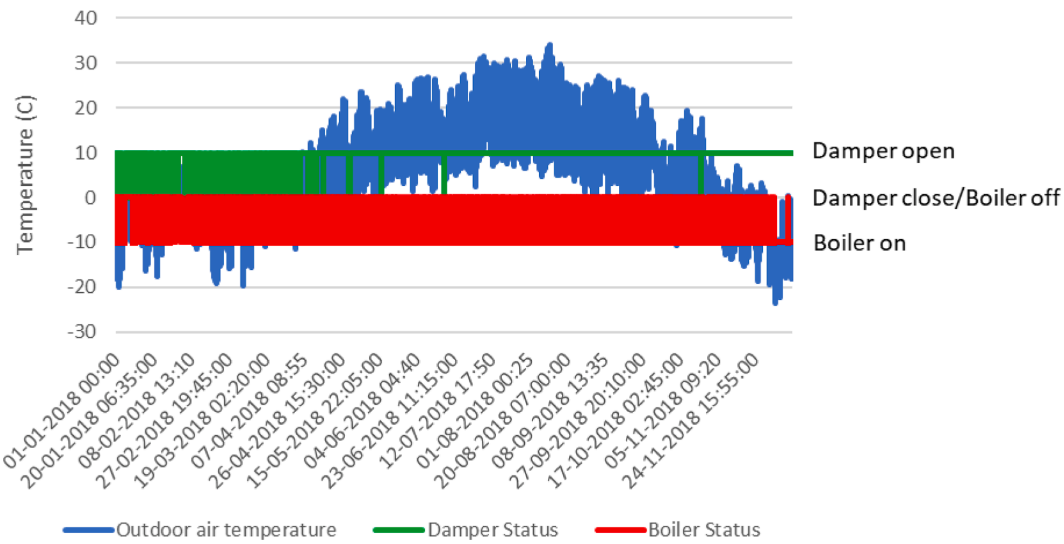

Fig. 7. Compartment 3 boiler and damper status.

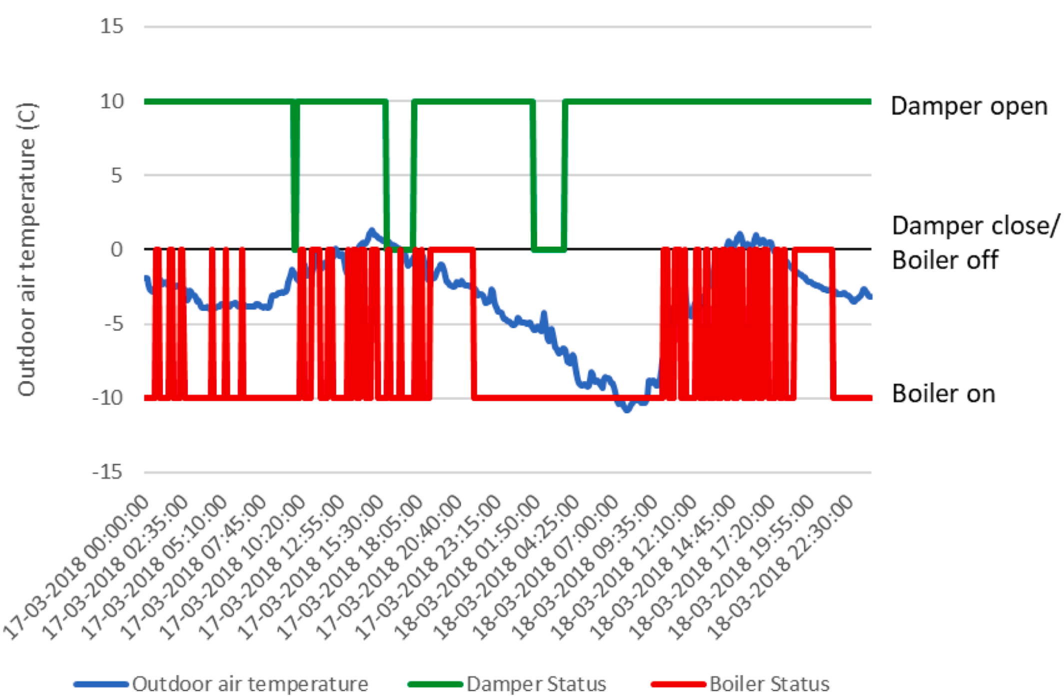

Fig. 8. Compartment 3 boiler and damper status.

compartment.

One challenge in modeling the indoor farming system is with modeling the misting system. The misting system, in compartments 3–7, sprays water through nozzles to add humidity to the environment and simultaneously cool off the temperature via vaporization. This is not an existing or common component in EnergyPlus. We employed the advanced—feature energy management system (EMS)— in EnergyPlus and calculated sensible and latent loads for compartments 3–7 through the misting system.

The algorithm for modeling the misting system is illustrated using a flow chart (Fig. 10). First misting mass flow rate $\dot{m}$ (kg/s) from each nozzle can be calculated based on misting system pressure and the nozzle diameter. Given the period of spray time t (s), we can calculate the humidity ratio W_m (kg H_2O/kg dry air) after misting.

$$W_m = W_z + \frac{\dot{m} \times t}{\rho \times V} \tag{2}$$

Where W_z (kg H_2O/kg dry air) is the zone air humidity ratio before misting, ρ (kg/m^3) is the dry air density, and V (m^3) is the volume of a thermal zone.

The humidity ratio W_m (kg H_2O/kg dry air) after misting is compared to the humidity ratio W_s of the saturated condition. If W_m is greater than W_s, the environment is in a saturated condition, the zone air temperature T_m after misting is equal to the zone wet-bulb temperature. Otherwise, the zone air temperature T_m can be calculated based on W_m and zone enthalpy h_z (kJ/kg dry air). The assumption is that zone air enthalpy before and after misting stays nearly constant for vaporization. We then define the enthalpy h_i (kJ/kg dry air) based on the calculated zone air temperature T_m and the zone air humidity ratio before misting

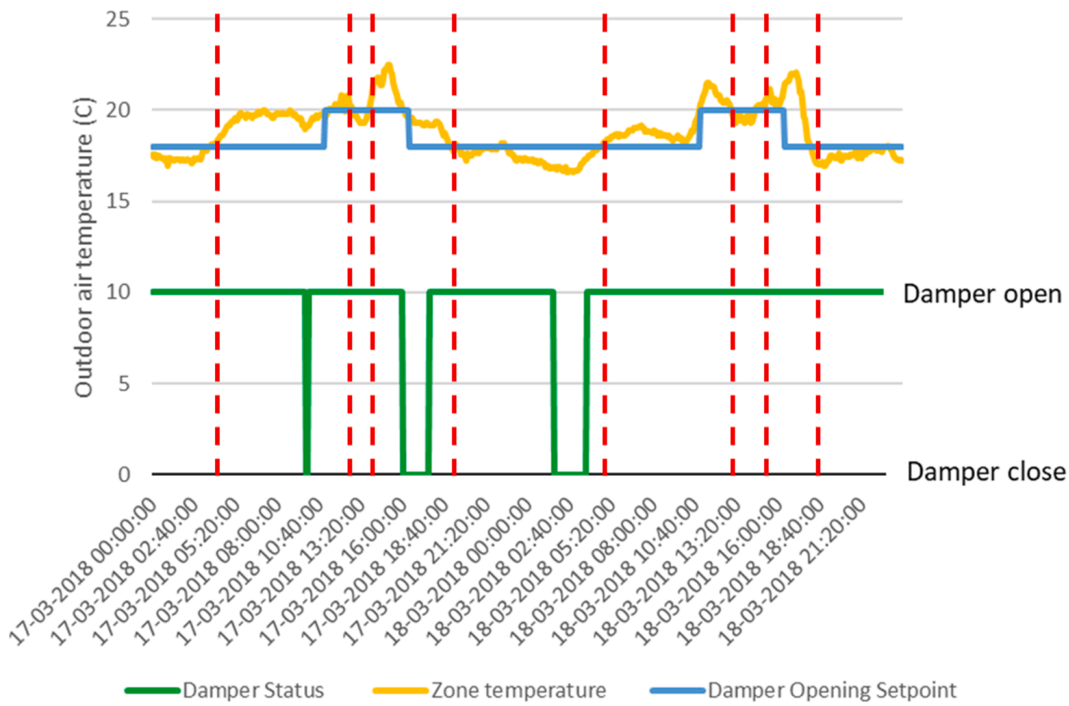

Fig. 9. Compartment 3 damper status and sequence mismatch.

W_z to decompose sensible and latent loads through the process. Therefore, sensible, and latent loads for each compartment from misting can be calculated with Equations ((3)–(4)). Through the misting process, space air was cooled while water vapor was added to the space, and the enthalpy of moist air stayed nearly constant as an evaporation process. The resultant sensible load through the misting process is negative representing the sensible cooling effect. The resultant latent load is positive representing the absolute humidity ratio of moist air was increased through the misting process.

$$\dot{Q}_s = \rho \times V \times (h_i - h_z) \tag{3}$$

$$\dot{Q}_l = \rho \times V \times (h_z - h_i) \tag{4}$$

Another challenge in this modeling effort is that the effect of crops on zone heat balance cannot be properly addressed using EnergyPlus alone. Models for crop growth and evapotranspiration (ET) need to be integrated with the building energy simulation model for a thorough understanding of thermal interactions within grow spaces [21]. Due to a variety of species growing at different stages within the facility, it is difficult to accurately model dynamic crop growth and ET for the entire facility. Therefore, crop growth and ET models are not included in this modeling effort. This limits the accuracy of our current model for the indoor farming facility.

Model calibration

Model calibration was performed using a full year of data collected from 07/01/2017 to 06/30/2018. The targeted key parameters in model calibration include electricity use, natural gas use, and compartment temperatures. We modified the weather file data for the calibration period by updating dry bulb temperature, wet bulb temperature, and relative humidity from National Climatic Data Center (NCDC) [22].

We manually calibrated the model based on the design information and trend data. During the calibration process, the operation hours of HPS lights and miscellaneous building loads were adjusted. Also, motorized damper opening positions were determined by trended damper positions from the control system for each compartment due to damper openings not conforming with compartment setpoints. With the adjustment of input parameters, we reviewed energy use and compartment temperatures for summer and winter seasons. ASHRAE Guideline 14 [16] provides calibration guidelines for energy models. The guideline requires a coefficient of variation of the root mean square error (CV-RMSE) of 30% and a net mean bias error (NMBE) of ±10% for hourly energy data and a CV-RMSE of 15% and an NMBE of ±5% for monthly energy data.

Energy use

The calibration results for hourly electricity use and monthly natural gas use are summarized in Table 6. The hourly metered electricity use was compared to the predicted electricity use from the model. The average absolute deviation between the model and the measurement for hourly electricity is 20% with a CV-RMSE of 25.9%, and an NMBE of −6.2%.

The comparison between measurement and prediction for monthly natural gas use resulted in a CV-RMSE of 15.2% and an NMBE of 0.6%. Monthly natural gas use predicted by the model differed from the measured value by 13.7% on average.

Temperatures

We also did a comparison for the hourly zone temperature of each compartment. Table 7 summarizes the average of absolute differences between measured and predicted zone temperatures for each compartment.

We use compartment 4 as an example to illustrate the comparison results. The model differs from measured hourly temperature by 12% on average after calibration in comparison with 71.3% before calibration. Figs. 11 and 12 compare the compartment temperatures for the summer and winter seasons, respectively. In summer, the predicted compartment temperature fluctuated more than the measured temperature. In winter, the predicted compartment temperature is always higher than the measured temperature. The absence of plant ET data for the compartments contributes to the disparity between the measured and predicted temperature values.

The absence of the effects of the plants in terms of energy exchanges

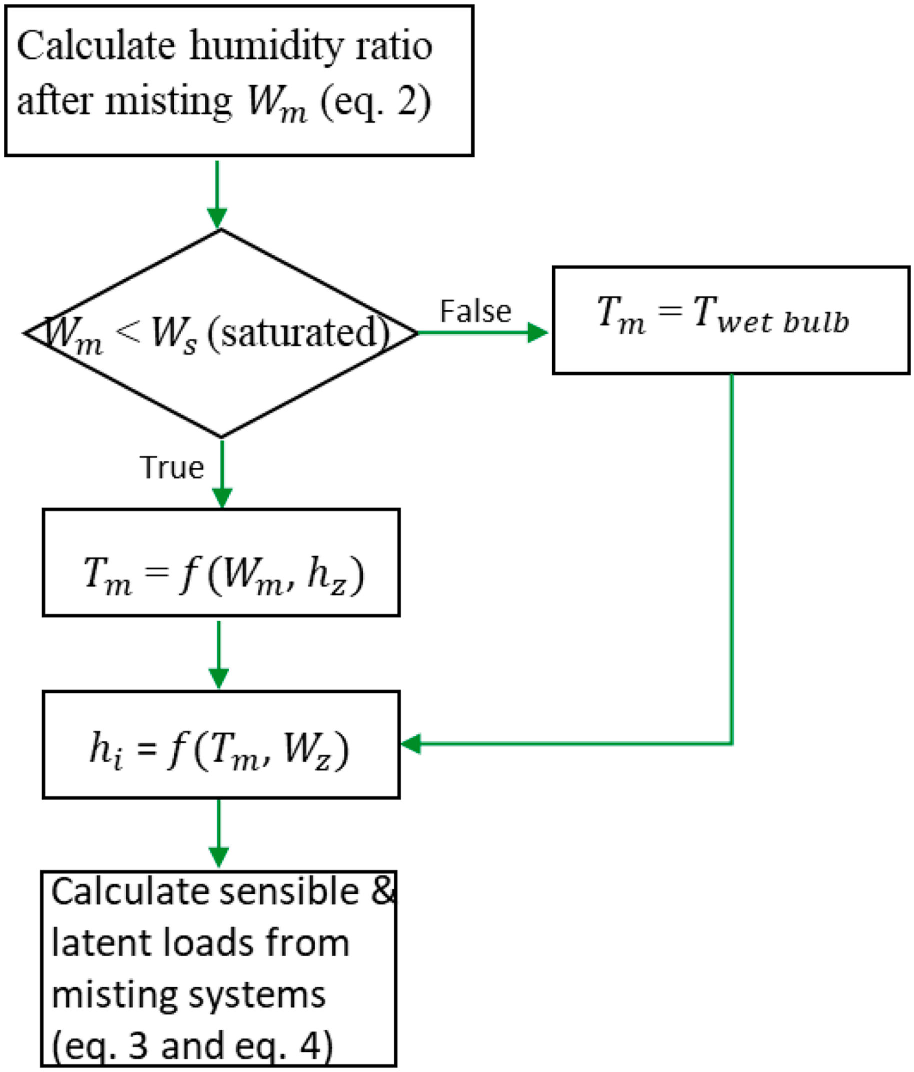

Fig. 10. Misting system model flowchart.

Table 6
Calibration Results for Energy Use.

Variable	CV-RMSE (%)	NMBE (%)	CV-RMSE (%)	NMBE (%)
	After Calibration		Before Calibration	
Electricity use	25.9	−6.2	35.5	31.8
Natural gas use	15.2	0.6	62.4	53.1

Table 7
Calibration Results for Compartment Temperatures.

S/N	Parameter	% Difference	
		After calibration	Before calibration
1	Compartment 1 Temperatures	10.4	64.4
2	Compartment 2 Temperatures	12.0	73.3
3	Compartment 3 Temperatures	13.4	72.7
4	Compartment 4 Temperatures	12.0	71.3
5	Compartment 5 Temperatures	12.1	64.9
6	Compartment 6 Temperatures	13.7	63.5
7	Compartment 7 Temperatures	12.8	50.8

due to ET plays a key role in energy use and zone temperature. However, even with this limitation, the calibration results still show some promise. The comparison between predictions and measurements for electricity and natural gas is within the required threshold from ASHRAE Guideline 14.

Evaluation of energy efficiency measures (EEMs)

Based on trend data analysis, we identified a few issues related to HVAC system operation. These include simultaneous heating and cooling, ventilation control, and temperature setpoints hardly met. These issues highlighted lead to inefficiencies and higher energy use. We proposed and evaluated three energy efficiency measures (EEMs) using the calibrated model for the facility.

1) Properly control damper and exhaust fan based on temperature setpoints. – EEM 1.
2) Eliminate simultaneous heating and cooling sequence. – EEM 2.
3) Have wider ranges of temperature setpoints: 16–22 °C for lettuces and microgreens in compartments 1–4 and 7, and 18–24 °C for tomatoes in compartments 5–6. – EEM 3.
4) Combination of all three EEMs.

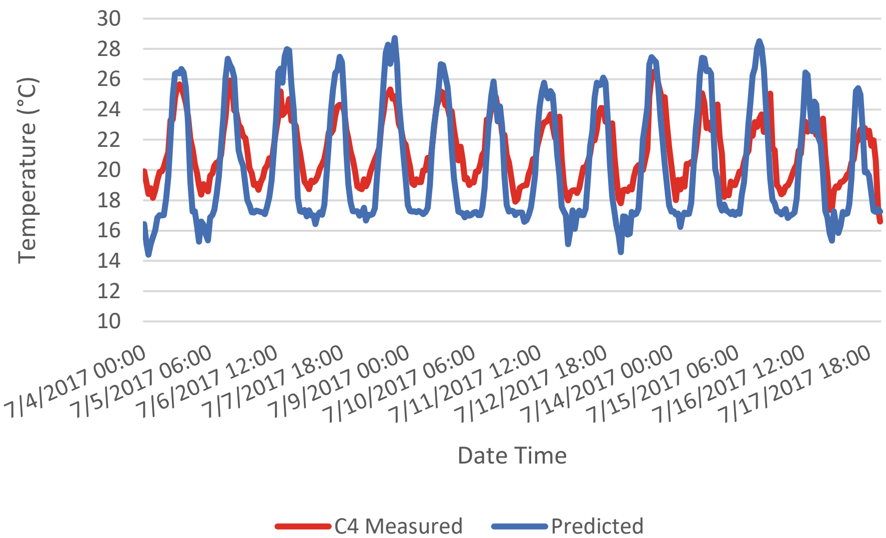

Fig. 11. Compartment 4 temperatures (Summer).

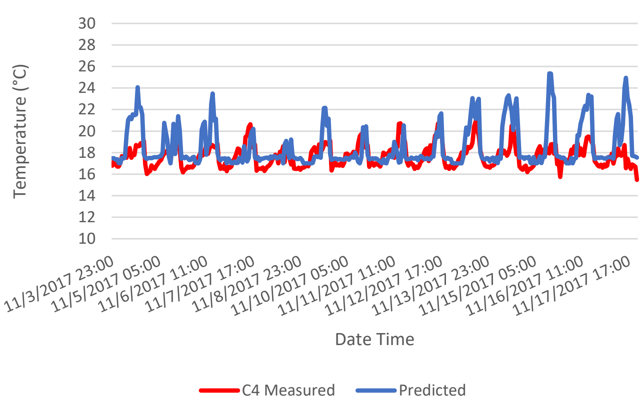

Fig. 12. Compartment 4 temperatures (Winter).

Electricity use

Figure 13 compared all 4 EEM scenarios with the calibrated model values. The "Combined" scenario which combines all three EEMs gives the best result with a 4.7% reduction in electricity use compared to the calibrated prediction model (baseline).

Since most of the electricity use is due to grow lights which do not change amongst EEM scenarios, there are little savings in terms of electricity use. Most of the changes here are due to exhaust fan and vent operation as well as heating hot water pumps.

Natural gas use

Figure 14 compared natural gas use for all EEM scenarios with measured and calibrated model values (baseline). Again, the best performer is the combination of all three EEMs. This leads to a 48.1% reduction in natural gas use compared to the calibrated model.

Table 8 summarizes the results for the EEM scenarios and their impact on electricity and natural gas use. EEM2— elimination of simultaneous heating and cooling— has the most influential impact on

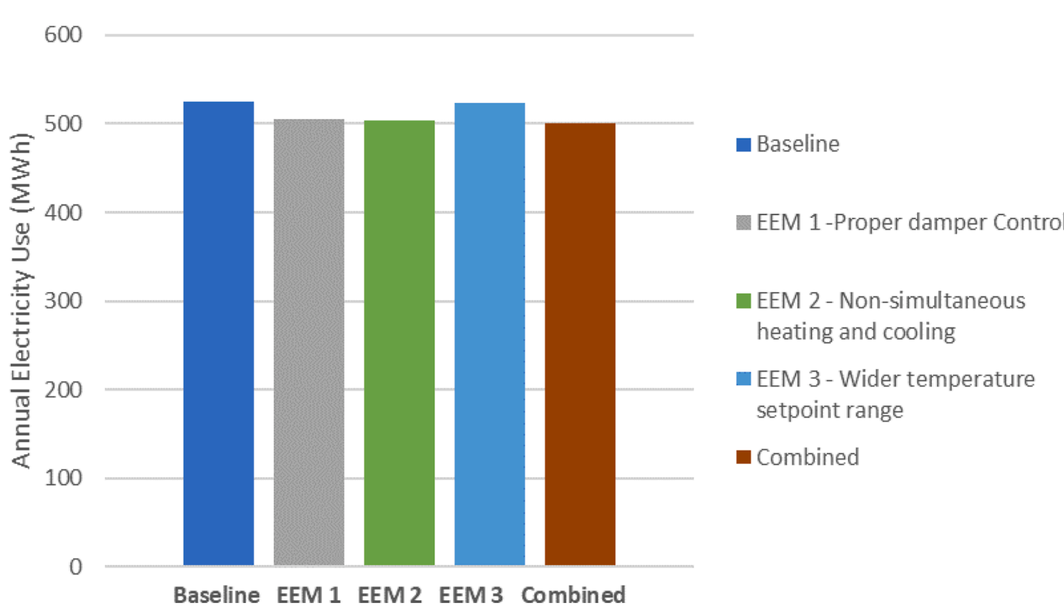

Fig. 13. EEMs - Electricity use comparisons.

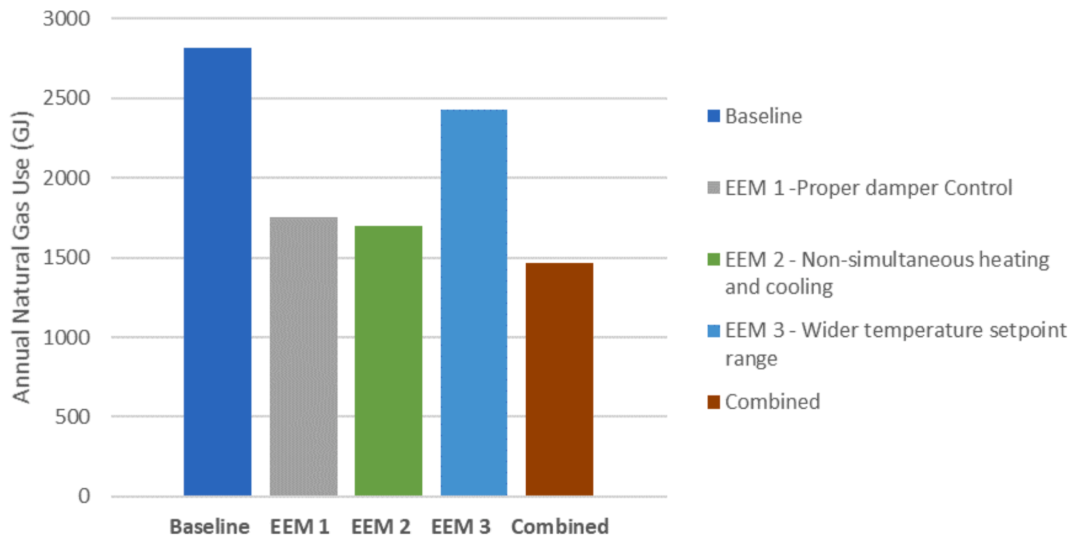

Fig. 14. EEMs - Natural gas use comparisons.

Table 8
EEMs - Utility and energy savings.

S/N	Scenario	Electricity (%)	Natural gas use (%)
1.	EEM 1	3.8	37.8
2.	EEM 2	4.1	39.8
3.	EEM 3	0.3	14.0
4.	Combined	4.7	48.1

reducing energy use. EEM2 reduces annual natural gas use by 39.8% and annual electricity use by 4.1% in comparison to the baseline. Having a wider temperature setpoint range (EEM3) can result in a reduction of natural gas use by 14%. We also noticed that the energy savings from combined EEMs are less than the sum of the energy savings from individual EEMs. This is because of the interaction among different measures. For example, fixing incorrect ventilation damper control would reduce damper open frequency, especially during unfavorable weather conditions, and thus reduce wasted energy from simultaneous heating and cooling. By enlarging the temperature setpoint range, heating and cooling demands are reduced and the opportunities of having simultaneous heating and cooling can potentially be reduced as well. The three energy efficiency measures are considered as low-cost/no-cost measures and can be easily implemented through modification of control sequences for heating and ventilation systems of the indoor farming facility.

Conclusion

This study set out to investigate areas for energy efficiency in an indoor farming facility. The first stage looked at utility and trend data to identify areas of inefficiency. From the utility and trend data analysis and energy model, three main issues were identified. These include improper damper operation, simultaneous heating, and cooling, and setpoints hardly met. Energy efficiency measure studies were performed to implement appropriate EEMs to address these issues and quantify the amount of savings that could be realized. These EEMs include fixing motorized damper control, eliminating simultaneous heating and cooling, and having wider ranges of temperature setpoints. It was found that implementing all three EEMs could cut down natural gas usage by nearly half.

We explored the use of building energy simulation for the indoor farming facility. A misting system was modeled through EMS of EnergyPlus. Calibrated modeling results have shown that the model can help predict conditions within the compartments and energy use for the facility, albeit, the model prediction could be further improved with a more complete information set such as internal loads and plant ET. Additional information on the contribution of the plants would also assist in understanding the energy cost of crop production. This would play an important role in decision-making as regards crop selection as well as production techniques.

In future studies, we would like to explore how design decisions on indoor farming facilities impact energy use in various climates. Also, integration of plant growth model, ET model, and building energy model would be the key for accurate performance prediction of indoor farming facilities. This would require cross-disciplinary research between building science and agricultural engineering.

CRediT authorship contribution statement

Liping Wang: Conceptualization, Methodology, Writing – original draft. **Emmanuel Iddio:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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