Evaluating and optimizing the performance of energy-saving dehumidification in Ontario year-round greenhouse production

Greenhouse Competitiveness and Innovation Initiative (GCII)

Technical Report

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Executive Summary

Energy costs are rising rapidly for the Ontario greenhouse industry which relies heavily on natural gas (NG) for heating. Opportunities for decreasing fossil fuel consumption are needed to improve both economic and environmental sustainability in the greenhouse sector.

In conventional practice, greenhouses are vented to remove the excess humidity caused by plant transpiration in order to avoid conditions that are conducive to plant disease. In cold conditions, this means substantial heat is lost that must be replaced to maintain optimal greenhouse conditions for crop production. Dehumidification systems that reduce humidity without associated heat loss are one potential way of improving energy use efficiency.

Four dehumidification/energy saving technologies (Heat Recovery Ventilation (HRV), Mechanical Refrigeration Dehumidifier (MRD), Liquid Desiccant Dehumidifier (LDD), Nortek Energy Recovery Ventilator (ERV)) were installed at three commercial greenhouses and monitored. The current project objectives were to 1) evaluate energy savings and the reduction of fossil fuel use, 2) assess the reduction of condensation occurrences which increase heat loss and reduce light transmittance, 3) assess impacts on air quality, and 4) explore optimized control strategies for the dehumidification systems.

An HRV system exchanges warm humid inside air with drier outside air thereby reducing the humidity in the greenhouse and in the process recovers some of the heat lost as the inside air is exhausted to the outside. Generally, the lowest outside relative humidity (RH) conditions occur in the winter, but in the current study, the heat recovery was not sufficient to warm the incoming air sufficiently so as to not damage the sensitive greenhouse crops. This resulted in the necessity to sometimes override the HRV controls, thus reducing its performance. During the On/Off trials, the system was able to realize a cost reduction in January, April and November, but the RH conditions were improved compared to traditional ventilation only during April and November. Overall, the energy savings and dehumidification performance were quite variable. The HRV system might be more cost effective if used for crops grown under colder conditions.

An MRD system reduces humidity by condensation on a cold coil surface. It uses only electrical power and releases latent heat back into the greenhouse reducing the demand on the greenhouse heating system. In the 2022 On/Off trials, the MRD unit was shown to provide better humidity control compared to traditional ventilation. Using both the 2019 (GRET) and 2021 (GCII) data, the overall energy requirement of the MRD unit was less compared to traditional ventilation to achieve the same level of dehumidification. If, as suggested by the research literature, there is an additional heat loss due to increased transpiration resulting from temperature fluctuations during venting, the gap between energy requirement of the MRD system and traditional ventilation becomes wider, making the MRD more economical. The MRD uses only electrical energy to operate, and the relative price of electrical and natural gas will dictate the cost effectiveness of the MRD system.

The LDD system reduces humidity by passing moist air through a liquid desiccant and releasing warm dry air. The LDD unit itself produces latent heat, resulting in a reduced requirement from the greenhouse heating system. However, the LDD unit also requires extra heat from the greenhouse system to regenerate the liquid desiccant. Since both electrical and heat energy are required for the unit to operate, the relative cost of these two energy sources at any point in time will alter the potential cost

savings achieved by the units. One unit was installed in one section at the flower greenhouse and four units were installed in one zone at an herb greenhouse in the Niagara area. The overall energy requirement of the LDD unit was generally slightly lower in 2019 at the flower greenhouse but slightly higher in 2021 at both the flower and herb greenhouses compared to traditional ventilation during the winter and shoulder months. However, if additional heat loss due to additional transpiration resulting from temperature fluctuations during venting is considered, the gap between energy requirement of the LDD system and traditional ventilation widens, making the LDD more economical.

The ERV State Point Liquid Desiccant System (SPLDS) is a novel combination of HRV and LDD technologies, designed to maximize potential energy savings in all seasons. It exchanges greenhouse and outside air, and recovers heat energy in the process. An ERV pilot system was installed at an organic tomato operation in the Leamington area. The moisture removed by the ERV unit operating in HRV mode (dry mode) was mainly affected by the outdoor air conditions, and had the highest moisture removal rate at low outdoor temperatures. Condensation, resulting from the temperature and moisture differentials between the greenhouse and external conditions, increases temperature loss and reduces light transmittance, thus reducing energy use efficiency. Condensation on leaves is conducive to disease development in the crop. Peak condensation was shown to occur just after sunset and sunrise. The ERV unit in HRV mode was shown to reduce the condensation in the greenhouse. Due to crop failure and changes at the greenhouse, it was not possible to collect additional supportive data on the LDD mode (wet mode) operation of the ERV. However, the prototype ERV dehumidification system has the potential to save both energy and operating cost, and was shown to be useful for humidity control.

In general, the systems were most effective at saving energy compared to traditional ventilation during the winter and shoulder seasons. During the summer, greenhouses usually vent to remove heat from the greenhouse and so there are no net energy savings. For operations where cooling systems are used to control high indoor temperatures, energy savings would likely extend to the summer months.

In order to assess the impacts of the systems on microbial air quality, air entering and leaving the MRD and LDD units was monitored using the 3M Petrifilm method. The results indicated that the process of air passing through the liquid desiccant of the LDD system was better to some extent than the MRD system at minimizing the risk of recirculating air-borne pathogens through the greenhouse. However, neither system reduced the overall load of air-born fungal propagules.

Overall, the dehumidification technologies:

1. were effective at improving humidity control in the greenhouses,
2. generally reduced energy use during the shoulder and winter seasons, and therefore have potential to achieve cost savings, which will increase as energy costs increase,
3. the relative cost of electricity and natural gas will dictate the cost-effectiveness of each system
4. need to be integrated properly into the greenhouse control system logic to achieve optimum energy and cost savings, and
5. need to be sized properly to meet the greenhouse dehumidification requirements in order to achieve adequate humidity control and cost savings.

This project was supported through the Greenhouse Competitiveness and Innovation Initiative (GCII), a cost share program funded by the Ontario Ministry of Agriculture, Food and Rural Affairs, and delivered by the Agricultural Adaptation Council.

Project Scope

This project was designed to continue to monitor four different dehumidification/energy saving technologies (HRV, MRD, LDD, Nortek ERV) at floriculture, herb and vegetable greenhouses to demonstrate their capabilities of saving energy and reducing fossil fuel use. By using commercially available leaf wetness sensors (LWSs) at the vegetable greenhouse, we assessed the reduction of condensation occurrences on the greenhouse cover surfaces resulting in increased light transmittance/minimized heat loss.

The main objectives were:

1) to evaluate energy savings and the reduction of fossil fuel use by adding a dehumidification system,
2) to assess the reduction of condensation occurrences on the greenhouse cover surfaces and increased light transmittance/minimized heat loss,
3) to assess the impacts on plant health, air quality, and yield due to energy recovery dehumidification, and
4) to explore optimized control strategies for the dehumidification systems.

Background

The greenhouse sector in Ontario depends heavily on marketable natural gas (NG) for heating. The 80% federal rebate on fossil fuels under the Greenhouse Gas Pollution Pricing Act is insufficient as the price of carbon increases, putting an additional cost burden for using NG. At the current price of carbon (\$50/tCO_2e), a floriculture greenhouse pays ~\$3,000 per acre per year after the rebate, and a vegetable greenhouse pays approximately double per acre due to the intensive growing conditions required for food production. By 2030, with the price of carbon set at \$170/tCO_2e, the cost to an average floriculture greenhouse rises to ~\$10,000/acre/year, and over \$24,000/ac/y to a vegetable greenhouse – the cumulative cost to the greenhouse sector is anticipated to be nearly \$400M, making operation of the greenhouses effectively unsustainable.

While the sector would like to move towards a more renewable and environmentally sustainable heating source, the reality is that NG is the only available and practical solution for at least the next decade. Therefore, the sector is searching for opportunities to decrease their fossil fuel consumption while investigating feasible options for alternative heating. Energy-efficient thermal curtains and high efficiency boilers are the two widely adopted technologies to limit fossil fuel consumption; the concept of a closed greenhouse preventing heat loss is a far more novel idea that has implications on the growing environment in temperate climates. Closing a greenhouse results in spikes of relative humidity through transpiration from the growing plants, and this moisture must be removed to avoid disease issues with the crops. Typically, greenhouses open their vents to release the humidity, but this solution results in a loss of warm air, requiring additional heating and thus, additional fossil fuel consumption. Dehumidification technologies for greenhouses are not widely adopted in Canada but represent a viable solution for maintaining the dry air required for healthy growth, while minimizing the heat loss through vent opening.

In a previous FCO-led project (GRET#11, Greenhouse Renewable Energy Technologies Research Initiative), the main objective was to evaluate energy recovery dehumidification technologies that largely circumvent greenhouse ventilation and associated heat losses and substantially reduce fossil fuel consumption in the greenhouse sector. Four different dehumidification/energy saving technologies (heat recovery ventilation system – HRV, mechanical refrigeration dehumidifier – MRD, chemical liquid desiccant dehumidifier – LDD, and a prototype state point liquid desiccant system more simply called 'energy recovery ventilation' - ERV) were installed and tested at flower, herb and vegetable greenhouses to demonstrate their capabilities in different environments. For a description of the technologies, refer to Appendix 1. The current project (GCII) continued the evaluation of these technologies for their capacity for managing relative humidity, effectiveness at reducing energy consumption for the greenhouse, and overall crop health management as measured by leaf wetness and microbial air quality.

Methods & Results

1.0 Heat Recovery Ventilation (HRV)

To evaluate the relative benefits of the HRV unit, the dehumidification performance and the total energy consumption while the system was operating were compared with the traditional ventilation option for managing relative humidity or 'RH' (for system specifications and installation details refer to Appendix 2). The parameters considered included the overall energy consumption of the HRV system, the energy required to heat the zone, the estimation of the operation cost (which is based on the prices for electricity and natural gas from the farms), and the potential energy consumption and heat loss through ventilation under similar conditions. Calculations were based on representative data for each month the dehumidification unit was in operation. Note that because supplemental light energy, CO_2 burner energy consumption, and power consumption of other production equipment are the same whether or not the dehumidification units are running, their energy requirements are not considered in the following evaluations.

In the absence of a proper control zone, the method used to evaluate the energy/cost savings performance of the units were based on "on/off trials" during which the units were manually turned off for a week at a time (contiguous with weeks where the unit was on) to provide a better comparison of ventilation and dehumidification system performance under similar environmental conditions. During "On" days, the units were controlled automatically via the greenhouse computer control system and included periods where the units did not run based on the greenhouse set points. When the units were manually turned off, these constituted "off" days for the trial. The "On" periods ranged from one to two weeks (e.g., Jan-April 2 weeks, 1 week Oct-Nov), while "off" periods typically lasted for one week. The data were averaged to per week values for each calendar month.

The HRV system depends solely on electricity, and functioned without any maintenance issues throughout the project, as well as during the previous GRET project. However, due to the cold weather conditions, the unit mostly ran at very low air flow exchange rates.

In Table 1-1, savings in heat energy are noted in the "% Heat Reduction" column and converted to total heating cost impacts based on 2021/2022 energy rates (natural gas rate $7.70/GJ, electricity price for Class A program $0.07/kWh). Positive values indicate a savings by using the HRV.

Table 1-1 Energy comparison between the HRV unit (on and off) in Section 5 at the flower greenhouse from January to November 2022.

Month	Unit status	Out Temp (°C)	Unit running time (hrs/day)	Heat energy (kWh/wk)	Unit power (kWh/wk)	Heat reduction (%)	Total heating cost ($/wk)	Total unit operation cost ($/wk)	Total heating cost reduction ($/wk)
Jan	ON	-5.5	17.4	40715	58	**9.8**	1128	4.1	**122**
	OFF	-5.8	0.0	45131	0		1250	0.0	
Feb	ON	-2.2	19.6	38870	59	**-0.5**	1077	4.1	**-6**
	OFF	-3.9	0.0	38667	0		1071	0.0	
Mar	ON	3.2	19.2	32216	80	**-0.8**	892	5.6	**-7**
	OFF	0.5	0.0	31949	0		885	0.0	
Apr	ON	6.9	16.5	26500	75	**15.1**	734	5.2	**131**
	OFF	4.9	0.0	31228	0		865	0.0	
May	ON	15.9	5.8	21498	25	**-5.1**	595	1.8	**-29**
	OFF	10.9	0.0	20459	0		567	0.0	
Oct	ON	11.0	11.0	25825	49	**-45.6**	715	3.4	**-224**
	OFF	11.0	0.0	17735	0		491	0.0	
Nov	ON	8.4	17.9	18584	68	**13.4**	515	4.8	**80**
	OFF	7.8	0.0	21461	0		594	0.0	

Results Summary:

- January, April and November runs realized an energy (and cost) savings by running the HRV compared to other months.
- In October, the outside air is more humid, and the outside air humidity ratio is greater than January-April and November.
- Not effective when outside air temp is higher than 10°C and humid, especially in through May to October.
- When outdoor temp is lower than 0°C, the unit runs at a very low speed, meaning it is not exchanging air at a sufficient rate to manage the relative humidity. The system is more effective when the outside air is not too cold.

How good is the unit at managing relative humidity? Figure 1-1 illustrates the percentage of time the zone had a RH value over 85% and 90% for each month in 2022, comparing back-to-back weeks when the unit was on versus off.

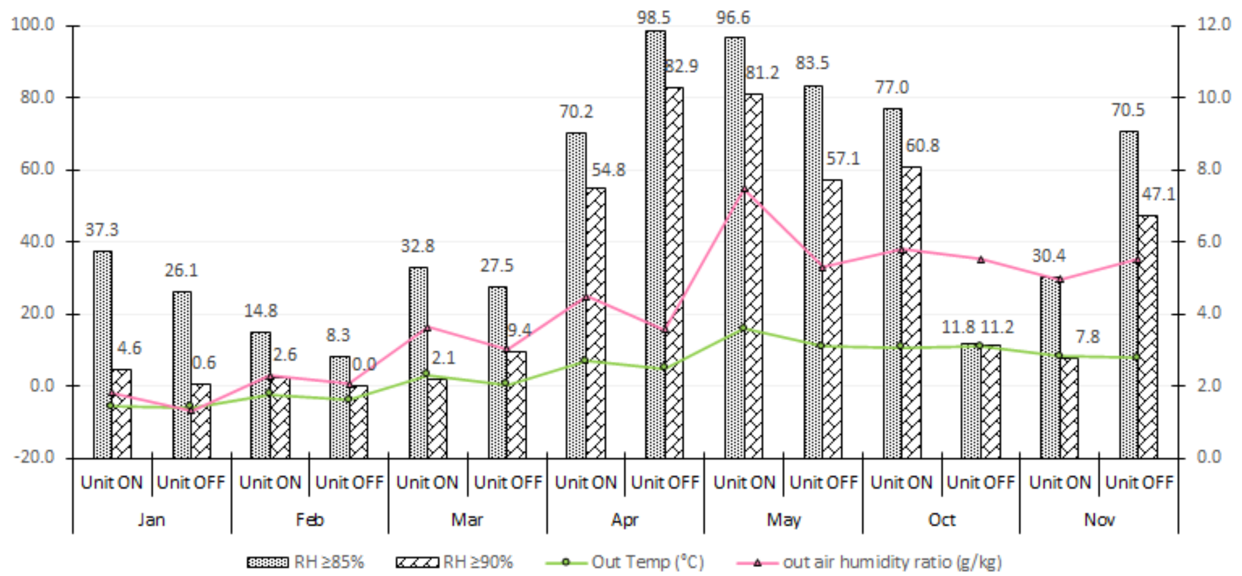


Figure 1-1 Indoor RH percentages over 85% and 90% when HRV unit is on versus off. The scale on the left is % of time RH is over the set points, and the right scale is the outdoor air humidity ratio.

Results Summary:

- Only in April and November were the RH conditions improved by running the HRV unit (where the % of time the RH is over 85% or 90% is higher when the HRV is off).
- From the table, we can see that the units ran about 17h-19h per day in the winter and shoulder months. In February and March, the units didn't really cost much more to run than the traditional ventilation operation of the greenhouse, but the HRV was not able to manage the RH as well.

Additional Observations:

- 3M Petrifilm testing was completed for on/off trials but illustrate minimal colony-forming units (CFUs). Refer to Chapter 5 for details of the results. The HRV system is not treating the recycled air withing the greenhouse - it's using fresh air from outside the greenhouse. Note that the HRV air quality results are not normalized for flow rates due to the lack of CFU's observed.
- The zone was less humid (less transpiration occurring) compared to other zones due to crop maturity, and extra outside wall.
- The HRV system did not appear to run when RH>75%, and it is possible that the internal HRV set points were not aligned with the greenhouse control system (Argus).
- The facility had the ability to turn the units off if the temperatures in the greenhouse zone were too cold, overriding the programmed set points.

Overall (HRV):

- Energy savings were quite variable – the system appears to have value if the outdoor temperatures are not too cold and the air is dry, so good air exchange is possible without over-cooling the greenhouse
- Not generally recommended for Southern Ontario climate and greenhouses growing crops at warmer temperatures, however, there may be value for cold-growing crops

2.0 Mechanical Refrigeration Dehumidification (MRD)

The dehumidification performance and the total energy consumption while the MRD system was operating were compared with the traditional ventilation option for managing relative humidity or 'RH' (for system specifications and installation details refer to Appendix 2). Two methods were used to evaluate the energy/cost savings performance:

A. 2019/2021: comparison of the data when the units were running under the greenhouse control system logic (i.e., turned off when ventilation required for temperature/excessive humidity control). To provide year over year comparisons, 2019 data from the GRET project was also reevaluated using this method.

B. 2022: in the absence of a proper control zone(s), trials were conducted in which the units were manually turned on and then off for contiguous weeks to provide a better comparison of ventilation and dehumidification system performance under similar environmental conditions. During "On" days, the units were controlled automatically via the greenhouse computer control system and included periods where the units did not run based on the greenhouse set points. When the units were manually turned off, these constituted "off" days for the trial. The "On" periods ranged from one to two weeks (e.g., Jan-April 2 weeks, 1 week Oct-Nov), while "off" periods typically lasted for one week. The data were averaged to per week values for each calendar month.

The MRD depends solely on electricity, and functioned without any maintenance issues throughout the project, as well as during the previous GRET project. However, after the GRET project it was determined that the unit was undersized for the specific requirements in Section 3 of the flower greenhouse. Note that while MRD units were originally installed in the herb greenhouse, they were not re-installed after the facility moved locations during the GRET project, and there is no data available for the GCII project.

MRD Compared to Traditional Ventilation in 2019 and 2021

The data collected for the MRD system included the average operation time per day of the MRD, the overall energy consumption of the system, the moisture removal (the amount of water that was removed from the air), and the total heat energy released by the operation of the units. The indoor and outdoor temperatures and relative humidity (RH) were also monitored throughout both GRET and GCII projects. Tables 2-1 and 2-2 provide the average monthly MRD performance in 2019 and 2021, respectively, in the Section 3 zone. The greenhouse RH set point was 80%. Figure 2-1 illustrates the average monthly greenhouse conditions for the zone.

Table 2-1 Monthly MRD performance and environmental conditions in the flower greenhouse in 2019.

Month	Average MRD unit running time (hrs/day)	Total MRD unit power consumption (kWh/mo)	Total air moisture removal (L/mo)	Total heat released by MRD (latent + motor) (kWh/mo)	Average of Indoor Temperature (°C)	Average of Indoor RH (%)	Average of Outdoor Temperature (°C)	Average of Outdoor RH (%)
Jan	23.0	7135	22236	-21539	22.1	84.9	-4.8	75.0
Feb	22.2	6224	19702	-18996	22.1	86.9	-2.8	76.8
Mar	14.9	4646	14557	-14078	22.1	82.8	-1.2	72.3
Apr	12.1	3713	12217	-11639	23.2	87.9	4.6	80.7
May	10.4	3327	11988	-11129	24.0	88.2	9.7	85.8
Jun	6.5	1986	7884	-7137	24.1	87.9	15.0	82.6
Jul	1.1	338	439	-602	24.4	91.4	20.7	86.4
Aug	2.7	840	3475	-3113	24.3	92.4	19.1	82.5
Sep	7.1	2181	9129	-8157	24.1	90.2	16.8	81.0
Oct	17.5	5680	20662	-19143	23.3	90.2	10.6	80.3
Nov	23.5	7215	22725	-21940	22.3	87.9	2.0	75.3
Dec	22.6	7145	22721	-21872	22.5	88.6	0.5	77.5

Table 2-2 Monthly MRD performance and environmental conditions in the flower greenhouse in 2021.

Month	Average MRD unit running time (hrs/day)	Total MRD unit power consumption (kWh/mo)	Total air moisture removal (L/mo)	Total heat released by MRD (latent + motor) (kWh/mo)	Average of Indoor Temperature (°C)	Average of Indoor RH (%)	Average of Outdoor Temperature (°C)	Average of Outdoor RH (%)
Jan	23.4	7332	23521	-22573	23.27	85.31	-0.70	73.50
Feb	20.8	5860	19066	-18224	23.33	83.03	-3.44	69.79
Mar	16.1	5086	15296	-14960	23.92	81.97	4.09	60.88
Apr	16.2	5002	16224	-15509	24.29	79.65	6.63	71.81
May	11.9	3850	12167	-11718	24.49	79.90	12.83	65.43
Jun	3.7	1149	3801	-3611	25.13	87.56	20.49	70.09
Jul	5.8	1919	1594	-5813	24.89	88.74	20.76	78.53
Aug	0	0	0	0	25.78	87.50	23.21	75.46
Sep	5.5	1672	1822	-5066	24.65	83.94	18.33	74.07
Oct	12.3	3827	10015	-10240	24.19	86.23	14.57	81.77
Nov	14.6	4601	16836	-15559	24.77	83.71	5.49	71.18
Dec	17.1	5388	18301	-17267	24.24	86.56	4.24	70.39

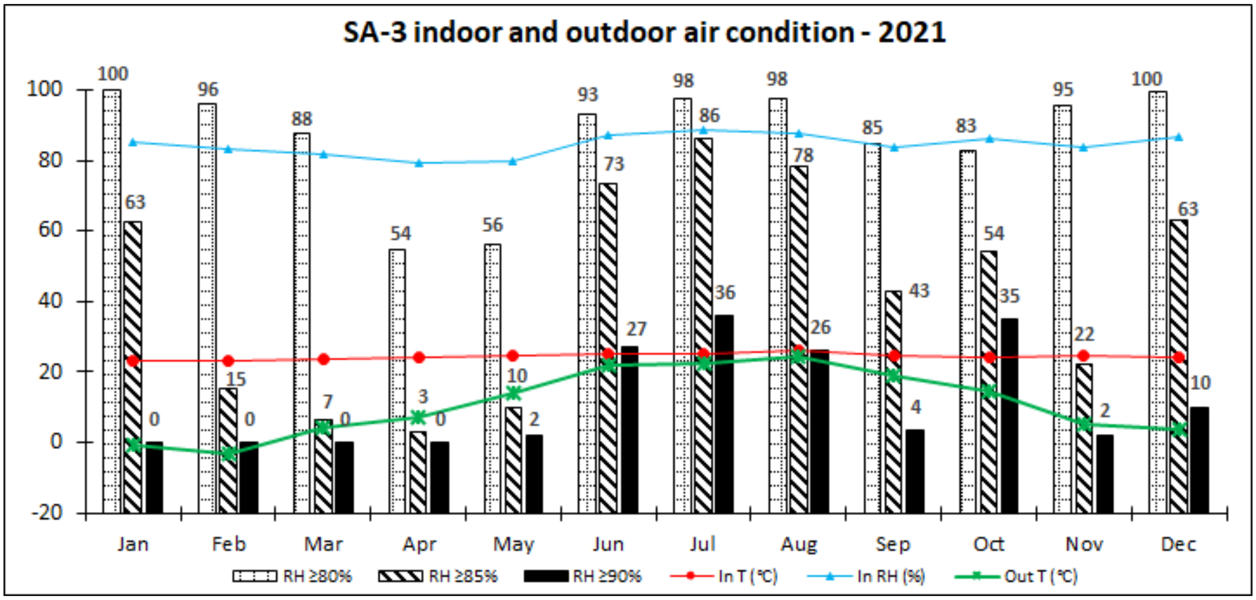


Figure 2-1 Indoor and outdoor conditions at the MRD section (SA-3) of the flower greenhouse in 2021.

Results Summary:

- Since the MRD unit produces energy in the form of heat (negative value in column 5 of each table), there is a decrease in the energy inputs into the Section 3 zone when the unit is running
- For both years of collected data, the unit ran nearly 24h/day during the winter months, and very few hours during the summer months
- The unit was not run in August of 2021, so there was no MRD performance data
- The data presented was averaged over each month, as the unit was left on continuously through these periods
- RH was not maintained at the 80% set point, it frequently exceeded the 80, 85 and 90% levels as seen in Figure 2-1.

To compare the MRD performance to traditional ventilation, the energy inputs were metered for the MRD, and the net energy consumption when the MRD units were running was calculated. To determine the estimated heat loss due to ventilation, the ventilation rate was calculated based on the humidity ratio difference between indoor and outdoor conditions, which then is used in the heat loss calculation. These results are summarized in Tables 2-3 (2019) and 2-4 (2021). The third and fourth columns carry down the MRD performance measurements from Tables 2-1 and 2-2, with the fifth column (green highlighted) summing the average monthly net energy requirement for MRD operation. The total monthly energy requirement for the zone if vented traditionally was calculated and provided in the remaining columns (yellow highlighted).

Variable transpiration rates should be considered when calculating the heat loss through ventilation if venting is used to remove the same amount of the moisture from the greenhouse as the dehumidification unit does. When vents are opened and additional heat is pumped into the greenhouse (bottom supply) to compensate for the drop in indoor temperature, this fluctuation in temperature (specifically, the difference in convective heat flux) induces increased water consumption by the plants (externally induced transpiration), resulting in further humidification of the greenhouse air (Assaf & Zieslin, 1996). These researchers observed an increase in night water loss of up to 57%, requiring even further management of RH through venting. To reflect the potential for increased energy consumption when there is a higher difference in convective heat flux, the savings were calculated with 20 and 40% additional heat energy input as conservative estimates compared to the 57% observed in the research study. The additional energy required as the percentage increases from 0 to 40% (Tables 2-3 and 2-4) is found in the yellow-orange highlighted columns at the right of the tables.

Table 2-3 Monthly energy consumption at the flower greenhouse when using MRD compared with traditional ventilation method in 2019.

Month	Total heating supply to GH when MRD is on[1] (kWh/mo)	Total MRD unit power consumption[2] (kWh/mo)	Total heat released by MRD (latent + motor)[3] (kWh/mo)	Total energy requirement when MRD is on[4] (kWh/mo)	If heat loss from ventilation does not induce increased transpiration		If ventilation results in 20% more heat loss due to increased transpiration		If ventilation results in 40% more heat loss due to increased transpiration	
					Estimated heat loss through ventilation[5] (kWh/mo)	Estimated total energy requirement[6] (kWh/mo)	Estimated heat loss through ventilation[7] (kWh/mo)	Estimated total energy requirement[6] (kWh/mo)	Estimated heat loss through ventilation[8] (kWh/mo)	Estimated total energy requirement[6] (kWh/mo)
Jan	94355	7135	-21539	101490	29372	145266	47894	163788	164633	280527
Feb	81639	6224	-18996	87863	25163	125798	40024	140659	104352	204987
Mar	81577	4646	-14078	86223	18712	114367	29917	125572	79208	174863
Apr	72015	3713	-11639	75728	14219	97873	21435	105089	43884	127538
May	67483	3327	-11129	70810	13360	91972	19697	98309	37687	116299
Jun	57463	1986	-7137	59449	8254	72854	11848	76448	21166	85766
Jul	60812	338	-602	61150	382	61796	522	61936	834	62248
Aug	65810	840	-3113	66650	3294	72217	4544	73467	7385	76308
Sep	55457	2181	-8157	57638	9037	72651	12673	76287	21319	84933
Oct	32861	5680	-19143	38541	21859	73863	31522	83526	56922	108926
Nov	72727	7215	-21940	79942	27731	122398	42119	136786	88969	183636
Dec	82198	7145	-21872	89343	28358	132428	43612	147682	95834	199904

Table Notes:

1. Measured from hot water pipes (note – accounts for the latent/motor heat generated by the unit that adds to overall section heat)
2. Measured with a current sensor
3. Calculated as the sum of latent heat released by MRD + 90% of MRD power consumption (90% of the electrical energy consumption is converted to heat released into the greenhouse (ASHRAE, 2009)).
4. Total energy requirement when MRD is on = Total heating supply when MRD is on (includes the total heat released by MRD (latent heat + motor heat)) + MRD power consumption
5. Calculated as if the same amount of water condensed by MRD is removed by traditional ventilation, assuming that there is no extra transpiration
6. Estimated total energy requirement when using traditional ventilation method = Total heating supply when MRD is on (1) - Total heat released by MRD (3) + Heat loss through ventilation (5)
7. Calculated as if the same amount of water condensed by MRD is removed through traditional ventilation system, assuming that 20% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).
8. Calculated as if the same amount of water condensed by MRD is removed through traditional ventilation system, assuming that 40% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).

Table 2-4 Monthly energy consumption at the flower greenhouse when using MRD compared with traditional ventilation method in 2021.

Month	Total heating supply to GH when MRD is on[1] (kWh/mo)	Total MRD unit power consumption[2] (kWh/mo)	Total heat released by MRD (latent + motor)[3] (kWh/mo)	Total energy requirement when MRD is on[4] (kWh/mo)	If heat loss from ventilation does not induce increased transpiration		If ventilation results in 20% more heat loss due to increased transpiration		If ventilation results in 40% more heat loss due to increased transpiration	
					Estimated heat loss through ventilation[5] (kWh/mo)	Estimated total energy requirement[6] (kWh/mo)	Estimated heat loss through ventilation[7] (kWh/mo)	Estimated total energy requirement[6] (kWh/mo)	Estimated heat loss through ventilation[8] (kWh/mo)	Estimated total energy requirement[6] (kWh/mo)
Jan	100226	7332	-22573	107558	29496	152296	40989	163788	84356	207156
Feb	88863	5860	-18224	94723	24574	131660	35323	142410	84231	191318
Mar	88726	5086	-14960	93812	18438	122125	25867	129553	52104	155790
Apr	69487	5002	-15509	74489	19277	104274	26544	111540	50693	135690
May	69907	3850	-11718	73757	13455	95080	18011	99636	31592	113217
Jun	64718	1149	-3611	65868	3871	72201	5003	73333	7621	75951
Jul	29344	1919	-5813	31263	1677	36834	2143	37300	3233	38390
Aug	n/a									
Sep	74456	1672	-5066	76128	1977	81499	2681	82203	4498	84020
Oct	85460	3827	-10240	89287	10859	106560	15356	111056	29367	125067
Nov	79592	4601	-15559	84192	18917	114067	27101	122252	54049	149199
Dec	106512	5388	-17267	111899	10685	134464	15356	139135	31390	155169

Table Notes:

1. Measured from hot water pipes (note – accounts for the latent/motor heat generated by the unit that adds to overall section heat)
2. Measured with a current sensor
3. Calculated as the sum of latent heat released by MRD + 90% of MRD power consumption (90% of the electrical energy consumption is converted to heat released into the greenhouse (ASHRAE, 2009)).
4. Total energy requirement when MRD is on = Total heating supply when MRD is on (includes the total heat released by MRD (latent heat + motor heat)) + MRD power consumption
5. Calculated as if the same amount of water condensed by MRD is removed by traditional ventilation, assuming that there is no extra transpiration
6. Estimated total energy requirement when using traditional ventilation method = Total heating supply when MRD is on (1) - Total heat released by MRD (3) + Heat loss through ventilation (5)
7. Calculated as if the same amount of water condensed by MRD is removed through traditional ventilation system, assuming that 20% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).
8. Calculated as if the same amount of water condensed by MRD is removed through traditional ventilation system, assuming that 40% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).

Results Summary:

- Since the MRD unit produces energy in the form of heat (negative value in column 4 of each table), there is a decrease in the energy inputs into the Section 3 zone when the unit is running as measured and noted in Tables 2-1 and 2-2
- The overall energy requirement of the MRD unit is less in both 2019 and 2021 compared to traditional ventilation, even when no additional transpiration is incurred as a result of venting
- When there is an additional heat loss of 20 and 40% due to the potential for additional transpiration during venting, the gap between energy requirement of the MRD system and traditional ventilation widens, making the MRD more economical

The average monthly energy cost in 2019 and 2021 when using MRD compared with the estimated energy cost when using traditional ventilation method is provided in Table 2-5 based on 2021/2022 energy rates (natural gas rate $7.70/GJ, electricity price for Class A program $0.07/kWh). The data provided includes the cost to run the MRD, the energy cost to heat the greenhouse zone while the MRD is running, and the sum of these energy costs (green highlighted columns). In comparison the calculated energy costs for traditional ventilation are highlighted in yellow.

Table 2-6 shows the average winter (January/February) and shoulder (November/December and March/April) monthly energy cost in 2021 per 100 m^2 of ground area in the Section 3 zone when using MRD compared with estimated energy cost when using traditional ventilation method when using energy rates from 2019 and 2021.

Table 2-7 shows the estimated additional energy requirement by MRD compared to the estimated heat loss through ventilation to fully achieve 80% RH in 2019 and 2021. Recall that the MRD unit was unable to meet the 80% RH set point consistently in the treatment zone (Tables 2-1, 2-2). While a calculation, the additional energy required was determined based on our sample data from various months at differing indoor climate conditions (and is not linear as typically the the higher temperature and humid the conditions are, the more energy it takes to remove moisture).

Table 2-5 Monthly energy cost in the flower greenhouse when using MRD compared with estimated energy cost when using traditional ventilation method in 2019 and 2021.

Month	2019 results				2021 results			
	Total MRD power consumption ($/mo)	Total heating consumption when MRD is on ($/mo)	Total energy cost when MRD is on ($/mo)	Estimated total energy cost due to ventilation ($/mo)	Total MRD power consumption ($/mo)	Total heating consumption when MRD is on ($/mo)	Total energy cost when MRD is on ($/mo)	Estimated total energy cost due to ventilation ($/mo)
Jan	1070	2076	3146	3196	513	2776	3289	4219
Feb	934	1796	2730	2768	410	2461	2872	3647
Mar	697	1795	2492	2516	356	2458	2814	3383
Apr	557	1584	2141	2153	350	1925	2275	2888
May	499	1485	1984	2023	269	1936	2206	2634
Jun	298	1264	1562	1603	80	1793	1873	2000
Jul	51	1338	1389	1360	134	813	947	1020
Aug	126	1448	1574	1589	n/a			
Sep	327	1288	1615	1598	117	2062	2179	2258
Oct	852	1478	2330	1625	268	2367	2635	2952
Nov	1082	2865	3947	2693	322	2205	2527	3160
Dec	1072	3834	4906	2913	377	2950	3328	3725

Table Notes:

1. 2019 year-round natural gas rate was $6.0/GJ. Electricity price for Class A program was $0.15/kWh.
2. 2021 year-round natural gas rate was $7.7/GJ. Electricity price for Class A program was $0.07/kWh.
3. The MRD unit requires electricity to function; heat for the zone is generated with natural gas.

Table 2-6 Averaged winter and shoulder monthly energy costs when using 2021 data from the MRD compared with traditional ventilation method when using different energy rates.

Season	2021 energy costs if using 2019 rates				2021 energy costs if using 2021 rates			
	Total MRD power consumption ($/100m²/mo)	Total heating consumption when MRD is on ($/100m²/mo)	Total energy cost when MRD is on ($/100m²/mo)	Estimated total energy cost due to ventilation ($/100m²/mo)	Total MRD power consumption ($/100m²/mo)	Total heating consumption when MRD is on ($/100m²/mo)	Total energy cost when MRD is on ($/100m²/mo)	Estimated total energy cost due to ventilation ($/100m²/mo)
Winter	58.8	123.5	182.3	185.5	27.4	155.5	182.9	233.5
Shoulder	44.7	112.5	157.2	155.1	20.9	141.6	162.5	195.3

Table Notes:

1. 2019 year-round natural gas rate was $6.0/GJ. Electricity price for Class A program was $0.15/kWh.
2. 2021 year-round natural gas rate was $7.7/GJ. Electricity price for Class A program was $0.07/kWh.
3. Winter month includes Jan and Feb. Shoulder months includes Mar, Apr, Nov, and Dec. Other months are excluded because temperatures were high (>10°C on average), and vents were opened to cool the greenhouse, therefore the unit wasn't running sufficiently for the months to be considered.
4. The MRD unit requires electricity to function; heat for the zone is generated with natural gas.

Table 2-7 Estimated extra moisture removal requirement and potential monthly power consumption by MRD or heat loss through ventilation to achieve the RH set point (80%) at the flower greenhouse.

	2019 Estimate				2021 Estimate			
Month	Extra moisture removal requirement to reach 80% (L/mo)	Additional estimated power consumption by MRD (kWh/mo)	Total additional energy requirement when MRD is on (kWh/mo)	Estimated heat loss through ventilation to achieve the 80% due to ventilation (kWh/mo)	Extra moisture removal requirement to reach 80% (L/mo)	Additional estimated power consumption by MRD (kWh/mo)	Total additional energy requirement when MRD is on (kWh/mo)	Estimated heat loss through ventilation to achieve the 80% due to ventilation (kWh/mo)
Jan	6938	1613	-4555	8932	7280	2348	-4710	9064
Feb	8256	1920	-5421	10403	3681	1187	-2381	4783
Mar	5281	1228	-3467	6538	3824	1234	-2473	4481
Apr	9955	2315	-6529	11334	2258	728	-1459	2623
May	10218	2376	-6696	11067	2461	794	-1590	2364
Jun	8462	1968	-5545	8302	11471	3700	-7408	9730
Jul	14501	3372	-9499	13035	11755	3792	-7592	10587
Aug[1]	15975	3715	-10466	14020	9398	3032	-6064	8101
Sep	12556	2920	-8227	11570	5282	1704	-3412	5179
Oct	13564	3154	-8895	14024	8267	2667	-5343	8281
Nov	10393	2417	-6823	12153	4968	1603	-3210	5690
Dec	11895	2766	-7807	14322	8611	2778	-5564	4095

Table Notes:

August data is included here to provide an estimate of energy requirement if the unit is operating to maintain 80% RH.

Results Summary:

- Depending on the electricity and natural gas rates, the cost-effectiveness of using the MRD varied. In 2019 when the natural gas rate was lower, there was negligible difference in the savings by using MRD in the treatment zone. However, when natural gas prices increased in 2021, a more significant savings was realized (Table 2-5).
- Table 2-6 provides the energy cost per 100m^2 per month using both 2019 and 2021 energy rates, so it can be extrapolated to other facilities, highlighting the average costs for the winter and shoulder months when the unit is most likely to be in operation
- To consistently achieve the 80% RH set point, traditional ventilation uses far more energy than having the MRD operating. Even if another MRD unit is required to achieve the RH management, it is still more energy efficient than venting.

MRD ON and OFF Trials in 2022

In the absence of a proper control zone, the method used to evaluate the energy/cost savings performance of the units were based on "on/off trials" during which the units were manually turned off for a week at a time (contiguous with weeks where the unit was on) to provide a better comparison of ventilation and dehumidification system performance under similar environmental conditions. During "On" days, the units were controlled automatically via the greenhouse computer control system and included periods where the units did not run based on the greenhouse set points. When the units were manually turned off, these constituted "off" days for the trial. The "On" periods ranged from one to two weeks (e.g., Jan-April 2 weeks, 1 week Oct-Nov), while "off" periods typically lasted for one week (see example Figure 2-2). The data were averaged to per week values for each calendar month.

To evaluate the relative benefits of the MRD unit, the dehumidification performance and the total energy consumption while the system was operating were compared with the traditional ventilation option for managing relative humidity or 'RH'. The parameters considered included the overall energy consumption by the MRD system, the estimation of the operation cost (which is based on the prices for electricity and natural gas from the farms) compared to the potential energy consumption and heat loss, and ultimately operational costs using ventilation under similar conditions. Calculations were based on representative data for each month the dehumidification unit was in operation. Note that because supplemental light energy, CO_2 burner energy consumption, and power consumption of other production equipment are the same whether or not the dehumidification units are running, their energy requirements are not considered in the following evaluations.

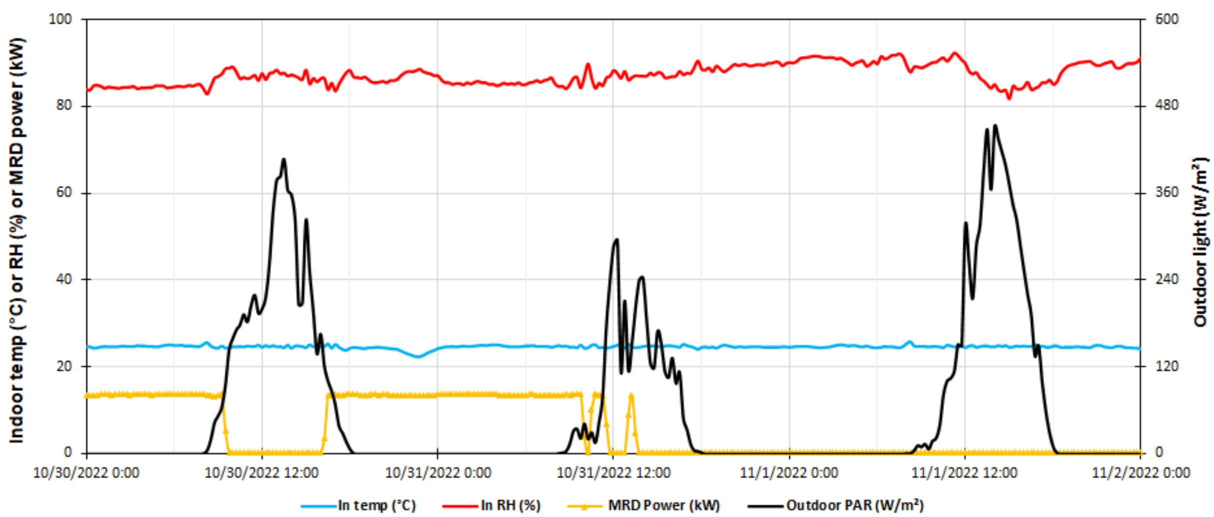


Figure 2-2 Example greenhouse indoor air conditions when MRD was on from October 30 until October 31, 2022 when it was turned off midday. The first two days of the 'off' period is November 1-2nd.

In Table 2-8, savings in heat energy are noted in the "% Heat Reduction" column and converted to total heating cost impacts based on 2021/2022 energy rates (natural gas rate $7.70/GJ, electricity price for Class A program $0.07/kWh). Positive values indicate a savings by using the MRD. Note that the settings at the greenhouse were different in 2022 compared to previous years (2019 data presented above), as the farm used more heat to achieve dehumidification after 2020.

Table 2-1 Energy comparison between the MRD unit on and off from January to November in 2022.

Month	Unit status	Out Temp (°C)	Unit running time (hrs/day)	Heat energy (kWh/wk)	Unit power (kWh/wk)	Heat reduction (%)	Total heating cost ($/wk)	Total unit operation cost ($/wk)	Total heating cost reduction ($/wk)
Jan	ON	-5.5	23.3	33233	1641	**11.4**	921	115	**118**
	OFF	-5.8	0.0	37507	0		1039	0	
Feb	ON	-2.2	21.5	24284	1524	**18.5**	673	107	**153**
	OFF	-3.9	0.0	29813	0		826	0	
Mar	ON	3.2	18.9	22058	1335	**14.7**	611	93	**105**
	OFF	0.5	0.0	25852	0		716	0	
Apr	ON	6.9	15.4	18752	1113	**13.3**	519	78	**80**
	OFF	4.9	0.0	21638	0		599	0	
May	ON	15.9	6.4	18983	462	**5.5**	526	32	**30**
	OFF	10.9	0.0	20080	0		556	0	
Oct	ON	11.0	12.6	16417	912	**8.3**	455	64	**41**
	OFF	11.0	0.0	17907	0		496	0	
Nov	ON	8.4	15.8	14993	979	**17.5**	415	69	**88**
	OFF	7.8	0.0	18164	0		503	0	

Table Notes:

1. When temperatures exceed 10°C, vents open as there is an override with the computer control system
2. Natural gas rate was $7.7/GJ. Electricity price for Class A program was $0.07/kWh.
3. Actual observed energy savings are lower than theoretical values estimated in Tables 2-3 and 2-4.

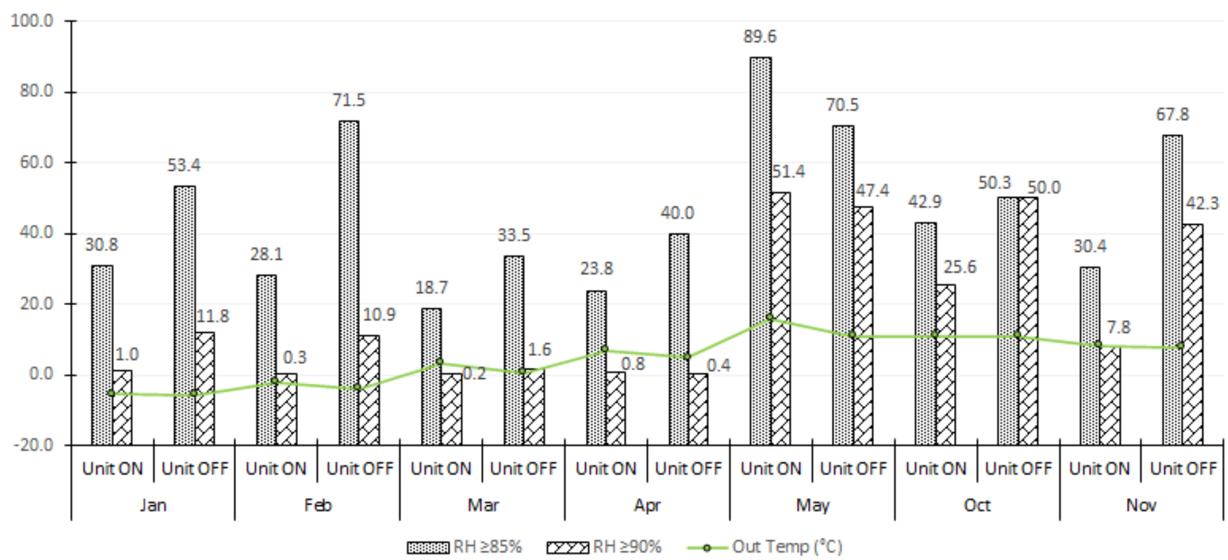


Figure 2-1 Indoor RH percentages over 85% and 90% when unit was on and off in 2022.

Results Summary:

- Using the MRD realized heating energy and cost savings in spring and winter seasons
- In January, only save about $3/week (heating cost reduction – unit operation costs) but Figure 2-3 illustrates that RH is controlled much better when the units are on
- MRD was effective in reducing the indoor RH (Figure 2-3) in all months except for May
- The indoor RH was lower during the nighttime and early morning when MRD was running from October 30th to 31st than when it was off on November 1st (Figure 2-2)
- The 5°C temperature difference in May between the on and off weeks makes a big difference in the effectiveness of the MRD system (unit only operated about 6 hrs/d). Vents had to be opened to reduce temperatures indoors.
- Based on Figure 2-2, it was observed that the night and early morning RH was generally higher and less well controlled when the MRD unit was turned off.
- Note that the greenhouse was also using heat to dehumidify the greenhouse, and this had an impact on the results – essentially, the greenhouse control system was not depending on the dehumidification systems to do the work
- Always a bit of ventilation occurring – that affects performance! If the vents are open and there is high RH, the units have to work a lot harder.

Overall (MRD): Recommended (with appropriate design configuration). Cost savings are directly impacted by relative energy source costs.

3.0 Liquid Desiccant Dehumidification (LDD)

Liquid Desiccant Dehumidification (LDD) systems were installed at two greenhouses (for system specifications and installation details at both the flower and herb greenhouses, refer to Appendix 2). The dehumidification performance and the total energy consumption while the LDD systems were operating were compared with the traditional ventilation option for managing relative humidity or 'RH'. Due to maintenance issues with the LDD systems at both greenhouses, on/off trials were not possible during this project. Note that the units all needed repairs in 2022 and were not functional for most of the experimental period. One of the four units at the herb greenhouse was brought back online at the end of November 2022 but could only provide 25% of the required dehumidification capacity for that zone, preventing the collection of useful data.

The parameters considered included the overall energy consumption of the LDD unit, the energy required to heat the zone, the estimation of the operation cost (which is based on the prices for electricity and natural gas from the farms), and the potential energy consumption and heat loss through ventilation under similar conditions. Calculations were based on representative data for each month the dehumidification unit was in operation. The LDD system depends on electricity to operate the unit itself, but also requires hot water for re-generating the liquid desiccant (brine). Note that because supplemental light energy, CO_2 burner energy consumption, and power consumption of other production equipment are the same whether or not the dehumidification units are running, their energy requirements are not considered in the following evaluations.

The general performance and greenhouse operating conditions are provided for both farms where the LDD units were installed. A comparison of the data when the units were running under the greenhouse control system logic versus traditional ventilation was completed for 2019 (GRET project data) and 2021 data (GCII project data).

LDD Compared to Traditional Ventilation in 2019 and 2021 at the Flower Greenhouse

The data collected for the LDD system included the average operation time per day of the unit, the overall energy consumption of the system (the sum of the total hot water heating energy, the power consumption of each unit, the dehumidification hot water usage or the total heat released by the unit), the moisture removal (the amount of water that was removed from the air), and the total heat energy released by the operation of the units. The indoor and outdoor temperatures and relative humidity (RH) were also monitored throughout both GRET and GCII projects. Tables 3-1 and 3-2 provide the average monthly LDD performance in 2019 and 2021, respectively, in the Section 4 zone. The greenhouse RH set point was 80%. Figure 3-1 illustrates the average monthly flower greenhouse conditions for the zone.

Note that the LDD unit operation in 2019 was intermittent, and the unit has been turned off since October 2021 due to maintenance issues which have not yet been addressed. Data used in the calculations is limited to selected months in 2019, and January through September 2021.

Table 3-1 Average monthly LDD performance and environmental conditions at the flower greenhouse in 2019.

Month	Average LDD unit running time (hrs/day)	Total LDD unit power consumption (kWh/mo)	LDD Dehumidification hot water consumption (kWh/mo)	Total moisture removal (L)	Total latent heat released by LDD (kWh/mo)	Average of In T_i (°C)	Average of In RH_i (%)	Average of Out T_o (°C)	Average of Out RH_o (%)
Jan	23.6	1691	15118	10306	-7000	23.1	86.5	-4.8	75.0
Feb	23.3	1502	12894	8680	-5898	22.7	88.2	-2.8	76.8
Mar	16.8	1207	10488	6245	-4242	22.9	85.4	-1.2	72.3
Apr	13.6	947	7186	3657	-2483	23.6	87.2	4.6	80.7
Dec	18.8	1414	11249	7247	-4921	23.3	86.6	0.5	77.5

Table 3-2 Average monthly LDD performance and environmental conditions at the flower greenhouse in 2021.

Month	Average LDD unit running time (hrs/day)	Total LDD unit power consumption (kWh/mo)	LDD Dehumidification hot water consumption (kWh/mo)	Total moisture removal (L)	Total latent heat released by LDD (kWh/mo)	Average of In T_i (°C)	Average of In RH_i (%)	Average of Out T_o (°C)	Average of Out RH_o (%)
Jan	21.95	1653	12434	6810	-4645	23.88	84.07	-0.83	74.19
Feb	19.56	1327	9271	5018	-3423	24.12	85.42	-3.58	70.43
Mar	15.15	1138	7856	3678	-2505	24.43	84.95	-0.98	58.60
Apr	13.32	951	7013	3314	-2257	24.64	81.91	7.14	76.51
May	9.63	696	5009	2085	-1421	24.69	81.06	16.09	66.28
Jun	2.94	205	1395	604	-411	25.16	86.81	20.97	68.51
Jul	2.65	186	1789	693	-471	24.91	88.77	20.76	78.53
Aug	0.44	31	183	86	-58	25.90	89.58	23.21	75.46
Sep	2.64	181	747	510	-347	24.70	88.48	18.33	74.07

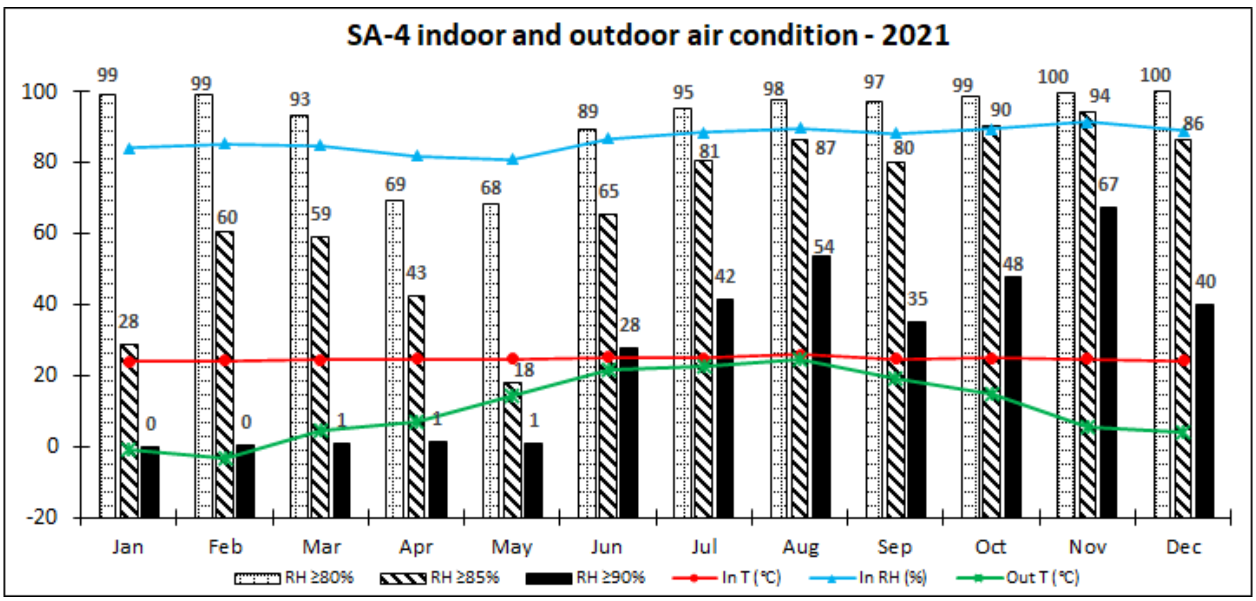


Figure 3-1 Indoor and outdoor conditions at the LDD section of the flower greenhouse (SA-4) in 2021.

Results summary

- Since the LDD unit produces energy in the form of heat (negative value in column 6 of each table), there is a decrease in the required energy inputs into the Section 4 zone when the unit is running
- For both years of collected data, the unit ran nearly 24h/day during the winter months, and very few hours during the summer months

- The data presented was averaged over each month, as the unit was left on continuously through these periods
- The additional heat generated by unit's operation could be diverted outside of the greenhouse during the summer months by attaching a damper on the exhaust
- RH was not maintained at the 80% set point, it frequently exceeded the 80, 85 and 90% levels as seen in Figure 3-1.

To compare the LDD performance to traditional ventilation, the energy inputs were metered for the LDD, and the net energy consumption when the LDD units were running was calculated. To determine the estimated heat loss due to ventilation, the ventilation rate was calculated based on the humidity ratio difference between inside and outside conditions, which then is used in the heat loss calculation. These results are summarized in Tables 3-3 (2019) and 3-4 (2021). The first few columns carry down the LDD performance measurements from Tables 3-1 and 3-2, with the sixth column (green highlighted) summing the average monthly net energy requirement for LDD operation. The total monthly energy requirement for the zone if vented traditionally was calculated and provided in the remaining columns (yellow highlighted).

Variable transpiration rates should be considered when calculating the heat loss through ventilation if venting is used to remove the same amount of the moisture from the greenhouse as the dehumidification unit does. When vents are opened and additional heat is pumped into the greenhouse (bottom supply) to compensate for the drop in indoor temperature, this fluctuation in temperature (specifically, the difference in convective heat flux) induces increased water consumption by the plants (externally induced transpiration), resulting in further humidification of the greenhouse air (Assaf & Zieslin, 1996). These researchers observed an increase in night water loss of up to 57%, requiring even further management of RH through venting. To reflect the potential for increased energy consumption when there is a higher difference in convective heat flux, the savings were calculated with 20 and 40% additional heat energy input as conservative estimates compared to the 57% observed in the research study. The additional energy required as the percentage increases from 0 to 40% (Tables 2-3 and 2-4) is found in the yellow-orange highlighted columns at the right of the tables.

Table 3-3 Monthly energy consumption in Section 4 when using LDD compared with traditional ventilation method in 2019.

						If heat loss from ventilation does not induce increased transpiration		If ventilation results in 20% more heat loss due to increased transpiration		If ventilation results in 40% more heat loss due to increased transpiration	
Month	Total heating supply to GH when LDD is on[1] (kWh/mo)	Total LDD unit power consumption[2] (kWh/mo)	LDD Dehumidification hot water usage[3] (kWh/mo)	Total latent heat released by LDD[4] (kWh)	Total energy requirement when LDD is on[5] (kWh/mo)	Estimated heat loss through ventilation[6] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)	Estimated heat loss through ventilation[8] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)	Estimated heat loss through ventilation[9] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)
Jan	73237	1691	15118	-7000	90046	13302	93539	21361	101598	61267	141504
Feb	50774	1502	12894	-5898	65169	10877	67549	17153	73824	42853	99524
Mar	65881	1207	10488	-4242	77576	7887	78010	12463	82586	31213	101336
Apr	73042	947	7186	-2483	81175	4228	79753	6345	81870	12808	88333
Dec	81541	1414	11249	-4921	94204	8747	95209	13480	99942	29950	116412

Table 3-4 Monthly energy consumption in Section 4 when using LDD compared with traditional ventilation method in 2021.

						If heat loss from ventilation does not induce increased transpiration		If ventilation results in 20% more heat loss due to increased transpiration		If ventilation results in 40% more heat loss due to increased transpiration	
Month	Total heating supply to GH when LDD is on[1] (kWh/mo)	Total LDD unit power consumption[2] (kWh/mo)	LDD Dehumidification hot water usage[3] (kWh/mo)	Total latent heat released by LDD[4] (kWh)	Total energy requirement when LDD is on[5] (kWh/mo)	Estimated heat loss through ventilation[6] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)	Estimated heat loss through ventilation[8] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)	Estimated heat loss through ventilation[9] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)
Jan	71197	1653	12434	-4645	85284	8560	84401	12424	88266	26751	102593
Feb	75757	1327	9271	-3423	86356	6509	85690	9530	88710	22030	101211
Mar	74016	1138	7856	-2505	83010	4435	80956	6352	82874	12714	89235
Apr	54693	951	7013	-2257	62657	4006	60956	5681	62631	10952	67902
May	51089	696	5009	-1421	56793	2367	54876	3252	55762	5789	58299
Jun	37316	205	1395	-411	38916	664	38391	887	38614	1430	39157
Jul	21928	186	1789	-471	23902	834	23232	1132	23531	1851	24250
Aug	n/a										
Sep	57105	181	747	-347	58033	617	58069	834	58286	1357	58809

Table Notes:

1. Measured from hot water pipes (note – accounts for the latent heat generated by the unit that adds to overall section heat)
2. Measured from current sensor
3. Measured from hot water pipes
4. Calculated based on the amount of water condensed by LDD
5. Total energy requirement when LDD is on = Total heating supply when LDD is on (includes the calculated latent heat released by LDD) + LDD power consumption + LDD Dehumidification hot water usage
6. Calculated as if the same amount of water condensed by LDD is removed through traditional ventilation system, assuming 0% extra transpiration
7. Estimated total energy requirement when using traditional ventilation method = Total heating supply when LDD is on (1) - Total latent heat released by LDD (4) + Heat loss through ventilation (6)
8. Calculated as if the same amount of water condensed by LDD is removed through traditional ventilation system, assuming that 20% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).
9. Calculated as if the same amount of water condensed by LDD is removed through traditional ventilation system, assuming that 40% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).

Results Summary:

- The overall energy requirement of the LDD unit is generally slightly lower in both 2019 and 2021 compared to traditional ventilation during the winter and shoulder months, even when no additional transpiration is incurred as a result of venting (Tables 3-3 and 3-4)
- When there is an additional heat loss of 20 and 40% due to the potential for additional transpiration during venting, the gap between energy requirement of the LDD system and traditional ventilation widens, making the LDD more economical

The average monthly energy cost in 2019 and 2021 when using LDD compared with the estimated energy cost when using traditional ventilation method is provided in Table 3-5 based on 2021/2022 energy rates (natural gas rate $7.70/GJ, electricity price for Class A program $0.07/kWh). The data provided includes the cost to run the LDD, the energy cost to heat the greenhouse zone while the LDD is running, and the sum of these energy costs (green highlighted columns). In comparison the calculated energy costs for traditional ventilation are highlighted in yellow.

Table 3-6 shows the average winter (January/February) and shoulder (March/April) monthly energy cost in 2021 per 100 m^2 of ground area in the Section 4 zone when using LDD compared with estimated energy cost when using traditional ventilation method when using energy rates from 2019 and 2021.

Table 3-7 shows the estimated additional energy requirement by LDD compared to the estimated heat loss through ventilation to fully achieve 80% RH in 2019 and 2021. Recall that the LDD unit was unable to meet the 80% RH set point consistently in the treatment zone (Figure 3-1). While a calculation, the additional energy required was determined based on our sample data from various months at differing indoor climate conditions (and is not linear as typically the the higher temperature and humid the conditions are, the more energy it takes to remove moisture).

Table 3-5 Average monthly energy costs when using LDD compared traditional ventilation method in 2019 and 2021.

Month	2019 results				2021 results			
	Total LDD power consumption ($/mo)	Total heating consumption when LDD is on ($/mo)	Total energy cost when LDD is on ($/mo)	Estimated total energy cost due to ventilation ($/mo)	Total LDD power consumption ($/mo)	Total heating consumption when LDD is on ($/mo)	Total energy cost when LDD is on ($/mo)	Estimated total energy cost due to ventilation ($/mo)
Jan	586	1611	2197	2058	460	1972	2432	2338
Feb	509	1117	1626	1486	350	2098	2448	2374
Mar	412	1449	1861	1716	297	2050	2347	2242
Apr	300	1607	1907	1755	261	1515	1776	1688
May					187	1415	1603	1520
Jun					53	1034	1087	1063
Jul					63	607	670	644
Aug					n/a	n/a		n/a
Sep					33	1582	1615	1609
Dec	460	1794	2253	2095				

Table Notes:

1. 2019 year-round natural gas rate was $6.0/GJ. Electricity price for Class A program was $0.15/kWh.
2. 2021 year-round natural gas rate was $7.7/GJ. Electricity price for Class A program was $0.07/kWh.

Table 3.6 2021 winter and shoulder monthly energy cost in Section 4 when using LDD compared with estimated energy cost when using traditional ventilation method when using different energy rates.

	Using 2019 rates				Using 2021 rates			
Season	Total LDD power consumption ($/100m²/mo)	Total heating consumption when LDD is on ($/100m²/mo)	Total energy cost when LDD is on ($/100m²/mo)	Estimated total energy cost due to ventilation ($/100m²/mo)	Total LDD power consumption ($/100m²/mo)	Total heating consumption when LDD is on ($/100m²/mo)	Total energy cost when LDD is on ($/100m²/mo)	Estimated total energy cost due to ventilation ($/100m²/mo)
winter	13.3	96.0	109.3	111.1	6.2	120.9	144.9	139.9
shoulder	9.3	84.1	93.4	92.7	4.3	105.9	122.4	116.7

Table Notes:

1. 2019 year-round natural gas rate was $6.0/GJ. Electricity price for Class A program was $0.15/kWh.
2. 2021 year-round natural gas rate was $7.7/GJ. Electricity price for Class A program was $0.07/kWh.
3. Winter season includes January and February. Shoulder months include March and April. The other months are excluded because temperatures are high (>10°C on average), and vents are open to cool the greenhouse, therefore the unit wasn't running much, or because the units were shut down due to equipment failure.

Table 3-7 Estimated extra moisture removal requirement and potential monthly power consumption by LDD or heat loss through ventilation to achieve the RH set point (80%).

Month	2019 Estimate					2021 Estimate				
	Extra moisture removal requirement to reach 80% (L/mo)	Additional estimated power consumption by MRD (kWh/mo)	Additional estimated hot water usage by LDD (kWh/mo)	Total additional energy requirement when LDD is on (kWh/mo)	Estimated heat loss through ventilation to achieve the 80% due to ventilation (kWh/mo)	Extra moisture removal requirement to reach 80% (L/mo)	Additional estimated power consumption by LDD (kWh/mo)	Additional estimated hot water usage by LDD (kWh/mo)	Total additional energy requirement when LDD is on (kWh/mo)	Estimated heat loss through ventilation to achieve the 80% due to ventilation (kWh/mo)
Jan	9998	2272	15382	10863	12784	5865	1333	9023	6375	7286
Feb	11362	2582	17481	12343	14091	7200	1636	11077	7828	9124
Mar	8482	1928	13050	9216	10405	7616	1731	11717	8282	8775
Apr	10025	2278	15423	10896	11425	5437	1236	8365	5914	6151
May						3668	834	5644	3990	3620
Jun						10913	2480	16789	11872	9133
Jul						11787	2679	18134	12821	10491
Aug[1]						11850	2693	18230	12897	9877
Sep						9812	2230	15095	10671	9234
Dec	11446	2601	17610	12438	13658					

Table Notes:

1. August data is included here to provide an estimate of energy requirement if the unit is operating to maintain 80% RH.

Results Summary:

- Depending on the electricity and natural gas rates, the cost-effectiveness of using the LDD varied slightly, but generally it appeared that the LDD used more energy overall than traditional ventilation (Table 3-5)
- When compared in the winter and shoulder seasons, using the LDD the winter months appeared to be slightly more efficient than traditional ventilation when calculated over a standard unit area (Table 3-6)
- To consistently achieve the 80% RH set point, traditional ventilation uses more energy than having the LDD operating (Table 3-7) during the winter and shoulder months. Even if another LDD unit is required to achieve the RH management, it may still be more energy efficient than venting.

LDD Compared to Traditional Ventilation in 2021 at the Herb Greenhouse

At the herb greenhouse, four LDD units were installed in zone 7 where basil is grown (see Appendix 2 for installation and setup information). Zone 8 was left as a control zone to evaluate traditional ventilation as it had a similar size and exterior walls, however, a different crop was produced in this section that had less transpiration and a cooler growing temperature (Table 3-8). Zone 10 is a propagation zone and also has different climate conditions compared to zone 7. The greenhouse RH target is 75% for this zone, lower than at the flower greenhouse. Note that due to the nature of the crop in zone 8, there was less irrigation and subsequently less transpiration, meaning that the zone RH rarely exceeded 75%. It is not possible to include data from 2019 in the comparisons as the GCII project location is different than the original farm location at the beginning of the GRET project, and re-installation delays limited the available data prior to 2020. The LDD units functioned well from January until June 2021, after which the units required additional maintenance. Due to COVID-19 delays in technical support and shipping delays, there was no opportunity to collect additional data in 2022 as planned.

The data collected for the LDD system included the average operation time per day of the unit, the overall energy consumption of the system (the sum of the total hot water heating energy, the power consumption of each unit, the dehumidification hot water usage or the total heat released by the unit), the moisture removal (the amount of water that was removed from the air), and the total heat energy released by the operation of the units. Table 3-9 provides the average monthly LDD performance in 2021 in the Zone 7. Figure 3-2 illustrates the average monthly herb greenhouse conditions for the zone.

Table 3-8 Indoor air conditions in Zone 7, 8, and 10 in 2021 (January – June 2021).

	Zone 7		Zone 8		Zone 10	
Month	Average of In T_i (°C)	Average of In RH_i (%)	Average of In T_i (°C)	Average of In RH_i (%)	Average of In T_i (°C)	Average of In RH_i (%)
Jan	21.2	75.3	21.4	64.9	18.1	54.5
Feb	21.6	75.5	22.9	55.9	21.4	59.7
Mar	21.8	76.6	24.5	50.0	22.4	64.1
Apr	20.4	79.6	24.5	53.9	21.3	72.5
May	21.7	76.4	25.9	53.8	21.1	70.5
Jun	24.7	77.9	29.4	53.9	24.3	71.2

Table 3-9 Average monthly LDD performance and environmental conditions in Zone 7 at the herb greenhouse in 2021 (January – June 2021).

Month	Average LDD unit running time (hrs/day)	Total LDD unit power consumption (kWh/mo)	LDD Dehumidification hot water consumption (kWh/mo)	Total water removal (L)	Total latent heat released by LDD (kWh/mo)	Average of In T_i (°C)	Average of In RH_i (%)	Average of Out T_o (°C)	Average of Out RH_o (%)
Jan	19.3	6129	53402	27760	-18894	21.2	75.3	-1.1	72.7
Feb	19.9	6483	56580	27412	-18653	21.6	75.5	-3.6	70.4
Mar	11.8	4313	37648	17499	-11909	21.8	76.6	4.0	61.1
Apr	4.3	1323	11460	5639	-3844	20.4	79.6	6.7	71.5
May	6	2435	21313	10119	-6897	21.7	76.4	13.3	64.0
Jun	7.0	2748	24009	11784	-8022	24.7	77.9	21.0	68.5

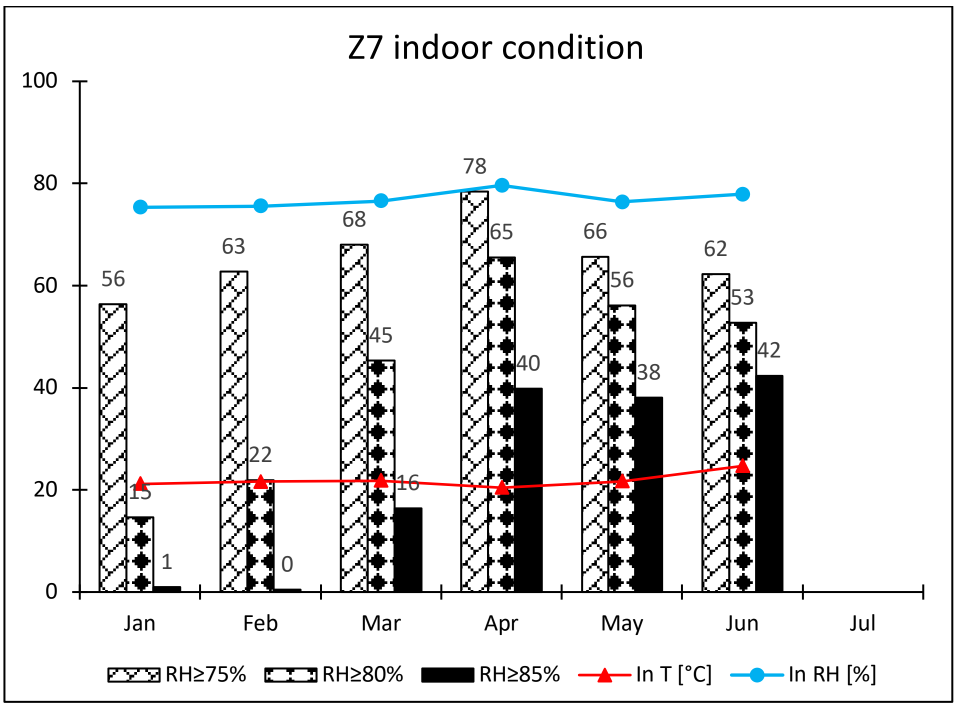


Figure 3.2 Monthly average indoor high RH occurrence percentages in Zone 7 in 2021 at the herb farm.

Results summary

- Since the LDD unit produces energy in the form of heat (negative value in column 6 of each table), there is a decrease in the required energy inputs into zone 7 when the unit is running
- The unit ran ~20h/day during the winter months, and was turned off after June
- The data presented was averaged over each month; the unit was left on through these periods and controlled by the greenhouse computer control system
- RH was not maintained at the 75% set point in Zone 7; it frequently exceeded the 75, 80 and 85% levels as seen in Figure 3-2.

To compare the LDD performance to traditional ventilation, the energy inputs were metered for the LDD, and the net energy consumption when the LDD units were running was calculated. To determine the estimated heat loss due to ventilation, the ventilation rate was calculated based on the humidity ratio difference, which then is used in the heat loss calculation. These results are summarized in Table 3-10 using 2021 data. The first few columns carry down the LDD performance measurements from Table 3-9, with the sixth column (green highlighted) summing the average monthly net energy requirement for LDD operation. The total monthly energy requirement for the zone if vented traditionally was calculated and provided in the remaining columns (yellow highlighted).

Variable transpiration rates should be considered when calculating the heat loss through ventilation if venting is used to remove the same amount of the moisture from the greenhouse as the dehumidification units do. When vents are opened and additional heat is pumped into the greenhouse (bottom supply) to compensate for the drop in indoor temperature, this fluctuation in temperature (specifically, the difference in convective heat flux) induces increased water consumption by the plants (externally induced transpiration), resulting in further humidification of the greenhouse air (Assaf & Zieslin, 1996). These researchers observed an increase in night water loss of up to 57%, requiring even further management of RH through venting. To reflect the potential for increased energy consumption when there is a higher difference in convective heat flux, the savings were calculated with 20 and 40% additional heat energy input as conservative estimates compared to the 57% observed in the research study. The additional energy required as the percentage increases from 0 to 40% (Tables 2-3 and 2-4) is found in the yellow-orange highlighted columns at the right of the tables.

The average monthly energy cost in 2021 when using LDD compared with the estimated energy cost when using traditional ventilation method is provided in Table 3-11 based on 2021/2022 energy rates (natural gas rate $7.70/GJ, electricity price for Class A program $0.07/kWh). The data provided includes the cost to run the LDD, the energy cost to heat the greenhouse zone while the LDD is running, and the sum of these energy costs (green highlighted columns). In comparison the calculated energy costs for traditional ventilation are highlighted in yellow.

Table 3-12 shows the average winter (January/February) and shoulder (March/April) monthly energy cost in 2021 per 100 m^2 of ground area in zone 7 when using LDD compared with estimated energy cost when using traditional ventilation method when using energy rates from 2019 and 2021.

Table 3-13 shows the estimated additional energy requirement by LDD compared to the estimated heat loss through ventilation to fully achieve 75% RH in 2021. Recall that the LDD unit was unable to meet the 75% RH set point consistently in the treatment zone (Figure 3-2). While a calculation, the additional energy required was determined based on our sample data from various months at differing indoor climate conditions (and is not linear as typically the the higher temperature and humid the conditions are, the more energy it takes to remove moisture).

Table 3-9 Average monthly energy consumption in Zone 7 when using LDD compared with traditional ventilation method (January – June 2021) at the herb greenhouse.

Month	Total heating supply[1] (kWh/mo)	Total LDD unit power consumption [2] (kWh/mo)	LDD Dehumidification hot water usage[3] (kWh/mo)	Total latent heat released by LDD[4] (kWh)	Total energy requirement when LDD is on[5] (kWh/mo)	If heat loss from ventilation does not induce increased transpiration		If ventilation results in 20% more heat loss due to increased transpiration		If ventilation results in 40% more heat loss due to increased transpiration	
						Estimated heat loss through ventilation[6] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)	Estimated heat loss through ventilation[8] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)	Estimated heat loss through ventilation[9] (kWh/mo)	Estimated total energy requirement[7] (kWh/mo)
Jan	176264	6129	53402	-18894	249032	38853	234011	65394	260552	233987	429145
Feb	190422	6483	56580	-18653	261281	39341	248416	67564	276639	301156	510231
Mar	95729	4313	37648	-11909	142401	22801	130439	36852	144490	105580	213218
Apr	32992	1323	11460	-3844	45339	6844	43680	10582	47418	24076	60912
May	27069	2435	21313	-6897	52104	10607	44573	15380	49346	29028	62994
Jun	1395	2748	24009	-8022	29898	11611	21028	16072	25489	27297	36714

Table Notes:

1. Measured from hot water pipes (note – accounts for the latent heat generated by the unit that adds to overall section heat)
2. Measured from current sensor
3. Estimated value by using the data collected from other units
4. Calculated based on the amount of water condensed by LDD
5. Total energy requirement when LDD is on = Total heating supply when LDD is on (includes the calculated latent heat released by LDD) + LDD power consumption + LDD Dehumidification hot water usage
6. Calculated as if the same amount of water condensed by LDD is removed through traditional ventilation system, assuming that there is no extra transpiration
7. Estimated total energy requirement when using traditional ventilation method = Total heating supply when LDD is on (1) - Total latent heat released by LDD (4) + Heat loss through ventilation (6)
8. Calculated as if the same amount of water condensed by LDD is removed through traditional ventilation system, assuming that 20% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).
9. Calculated as if the same amount of water condensed by LDD is removed through traditional ventilation system, assuming that 40% of the heat loss results in increased transpiration due to ventilation (Assaf and Zieslin, 1996; Parbst, 2016).

Table 3-10 Average monthly energy cost for 2021 in Zone 7 when using LDD compared with estimated total energy cost with traditional ventilation method at the herb greenhouse

Month	Total LDD operation cost ($/mo)	Total heating consumption when LDD is on ($/mo)	Total energy cost when LDD is on ($/mo)	Traditional Ventilation: Estimated total energy cost if no extra transpiration due to ventilation ($/mo)	Traditional Ventilation: Estimated total energy cost with 20% increased heat loss due to transpiration ($/mo)	Traditional Ventilation: Estimated total energy cost with 40% increased heat loss due to transpiration ($/mo)
Jan	1641	4883	6524	6482	7217	11887
Feb	1738	5275	7013	6881	7663	14133
Mar	1157	2652	3808	3613	4002	5906
Apr	353	914	1267	1210	1313	1687
May	654	750	1404	1235	1367	1745
Jun	737	39	776	582	706	1017

Table Notes:

1. 2021 year-round natural gas rate was $7.7/GJ. Electricity price for Class A program was $0.07/kWh.

Table 3-11 Average winter and shoulder monthly energy costs for 2021 in Zone 7 when using LDD compared with traditional ventilation method when using different energy rates.

Season	Using 2019 rates: Total LDD power consumption ($/100m^2/mo)	Using 2019 rates: Total heating consumption when LDD is on ($/100m^2/mo)	Using 2019 rates: Total energy cost when LDD is on ($/100m^2/mo)	Using 2019 rates: Estimated total energy cost due to ventilation ($/100m^2/mo)	Using 2021 rates: Total LDD power consumption ($/100m^2/mo)	Using 2021 rates: Total heating consumption when LDD is on ($/100m^2/mo)	Using 2021 rates: Total energy cost when LDD is on ($/100m^2/mo)	Using 2021 rates: Estimated total energy cost due to ventilation ($/100m^2/mo)
winter	32.1	136.8	209.9	180.0	15.0	172.3	238.9	226.6
shoulder	14.3	48.0	80.7	65.0	6.7	60.5	90.2	81.8

Table Notes:

1. 2021 year-round natural gas rate was $7.7/GJ. Electricity price for Class A program was $0.07/kWh.
2. 2019 year-round natural gas rate was $6.0/GJ. Electricity price for Class A program was $0.15/kWh.
3. Winter month is Jan-Feb. Shoulder months includes Mar and Apr. Other months are excluded due to outdoor temperatures

Table 3-12 Calculated extra moisture removal requirement and potential monthly energy consumption by LDD or heat loss through ventilation to achieve the RH set point (75%).

Month	Extra moisture removal requirement to reach 75% (L/mo)	Additional estimated power consumption by LDD (kWh/mo)	Additional estimated hot water usage by LDD (kWh/mo)	Estimated latent heat released by LDD (kWh/mo)	Total additional energy requirement when LDD is on (kWh/mo)	Estimated heat loss through ventilation to achieve the 75% if no extra transpiration due to ventilation (kWh/mo)	Estimated heat loss through ventilation to achieve the 75% with 20% increased transpiration (kWh/mo)	Estimated heat loss through ventilation to achieve the 75% with 40% increased transpiration (kWh/mo)
Jan	3944	896	6890	-2684	5102	5184	8386	22480
Feb	5174	1176	9213	-3520	6869	6918	11295	32470
Mar	11868	2697	22647	-8071	17273	14013	21426	46973
Apr	16243	3692	31411	-11061	24042	19619	30201	66947
May	15763	3582	30677	-10721	23538	16850	24682	47698
Jun	19669	4470	38866	-13338	29998	17895	24654	40428

Results Summary:

- The overall energy requirement of the LDD unit is generally slightly higher in 2021 compared to traditional ventilation during the winter and shoulder months, when no additional transpiration is factored as a result of venting (Table 3-10)
- When there is an additional heat loss of 20 and 40% due to the potential for additional transpiration during venting, the gap between energy requirement of the LDD system and traditional ventilation widens, making the LDD more economical
- When compared by standard unit area, there's no improvement in the energy consumption/costs by using LDD systems
- These results are different compared to previous results observed by both flower and herb greenhouse operators. Variation in the data may be due to the nature of the crop in the greenhouses during the project
- Availability of mildew-resistant basil cultivars means that RH control is not as critical for herb greenhouses, but where fungal infections are a serious concern for a crop the LDD may have significant benefit
- Upgrades to the LDD systems were offered and partially paid for by manufacturer. COVID-19 supply issues made the upgrades and maintenance timeframes more challenging.

Overall (LDD): Recommended for certain crops (with appropriate design configuration). Cost savings are directly impacted by relative energy source costs.

4.0 Energy Recovery Ventilator (ERV)

The Energy Recovery Ventilator (ERV) is technically called a State Point Liquid Desiccant System (SPLDS), but this is a very complicated acronym to remember, so we'll use ERV instead! The ERV is a prototype of a novel combination of HRV and LDD technologies, uniquely set up to maximize the potential for energy savings with a wide variety of outdoor and indoor greenhouse climate conditions. The installation and setup of the ERV at the tomato greenhouse is detailed in Appendix 2.

While the prototype unit was functional through the GRET project, most of the time it was operating in the HRV mode, and not utilizing the full capacity of the technologies. After the beginning of the GCII project, in early 2021, the facility had crop issues and the wall partition between the two zones was removed as the farm dealt with decreased crop canopy and production. The system was recalibrated in 2021 and a short period of data was collected before the crop was removed in the fall. The farm re-planted a pepper crop in 2022 which has very few diseases and literally no RH concerns, so the unit remained unused throughout the final year of the project.

ERV Performance 2021

Figure 4-1 is an example of the daily fluctuation in greenhouse climate conditions with ERV unit running in HRV mode from September 16 to 18, 2021. The biggest concern for the vegetable greenhouse is the period through the early morning where humidity can increase as the plants are rapidly transpiring. The RH drops in the early morning while the HRV unit is running and light levels are increasing.

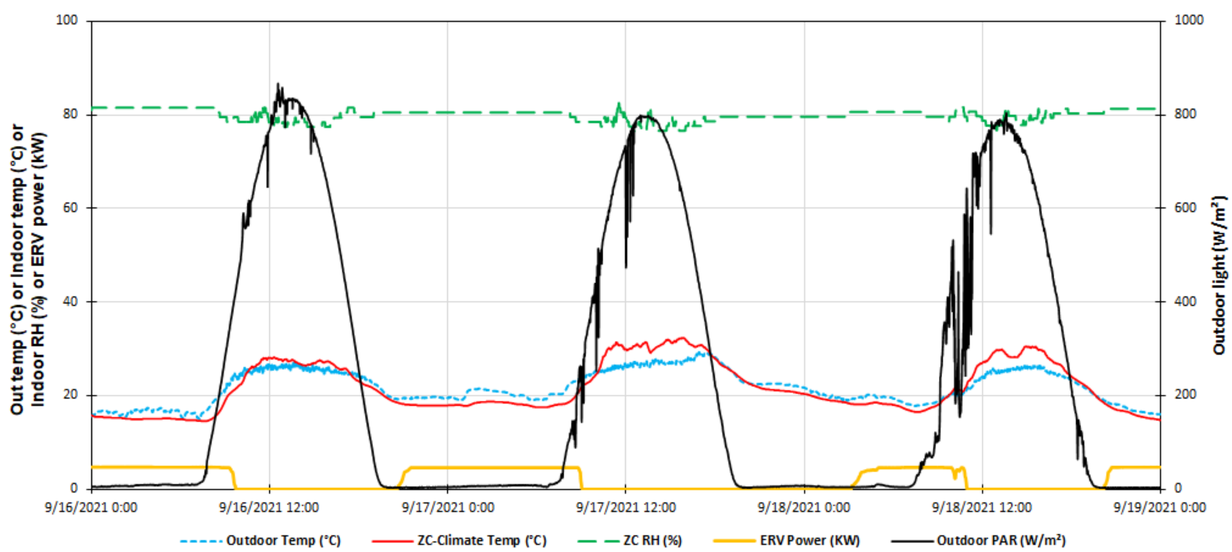


Figure 4-1 Example tomato greenhouse climate conditions and ERV unit power from September 16 to 18, 2021. Illustrated are the indoor (red line) and outdoor (blue dashed) temperatures, relative humidity (green dashed), outdoor photosynthetically active radiation (black) and ERV power (yellow).

The greenhouse indoor and outdoor air conditions are provided in Table 4-1 along with the ERV unit power consumption and observed moisture removal rate. Since the partition between the control (ZB) and ERV (ZC) zone was removed, these values are more representative of the system functioning in the entire greenhouse area. The energy factor is the calculated amount of moisture removed by the ERV unit using 1kWh. These results are displayed in a graph format in Figure 4-2.

Table 4-1 Average daily tomato greenhouse indoor and outdoor air conditions and ERV performance 2021 as measured in the ERV section of the greenhouse (ZC).

Month	Date	Out temp (°C)	ZC in temp (°C)	ZC in RH (%)	ERV running time (hrs/day)	ERV power (kWh)	ERV moisture removal (kg/day)	Energy factor (L/kWh)
Aug	31	22.2	22.9	79.5	5.4	20.1	0.1	0.28
Sep	01	19.8	21.1	80.0	12.9	57.7	0.2	0.98
Sep	02	18.9	21.0	80.0	13.2	60.2	33.2	1.11
Sep	03	18.2	20.0	80.3	12.8	56.6	26.4	1.05
Sep	04	21.9	21.0	80.0	9.7	44.1	32.0	2.77
Sep	05	21.8	22.7	79.4	6.0	23.6	26.9	1.29
Sep	06	20.0	21.3	79.7	13.1	59.5	60.8	1.08
Sep	07	21.6	21.5	80.0	9.4	43.3	37.8	1.30
Sep	08	21.8	22.5	79.4	6.8	27.7	28.2	1.40
Sep	09	16.6	17.8	80.8	14.8	67.0	61.1	1.17
Sep	10	18.7	19.1	80.7	13.6	61.7	45.6	1.05
Sep	11	22.8	21.6	79.4	9.7	43.8	19.0	0.00
Sep	12	24.1	23.7	78.7	0.0	0.0	0.0	0.61
Sep	13	20.8	20.2	79.5	6.0	22.2	3.9	0.27
Sep	14	23.7	22.9	78.8	8.0	24.9	1.3	0.64
Sep	15	20.5	20.7	79.8	8.5	27.9	4.6	0.78
Sep	16	20.9	20.2	80.2	13.1	58.9	14.6	2.87
Sep	17	23.6	23.6	79.4	9.1	41.2	2.2	0.40
Sep	18	20.8	21.2	80.1	11.6	49.2	2.7	0.38
Sep	19	20.2	19.9	80.7	13.5	60.9	10.1	0.76
Sep	20	23.0	21.8	79.3	9.3	42.0	6.5	0.00
Sep	21	21.9	21.0	79.3	0.0	0.0	0.0	0.64
Sep	22	13.9	15.2	81.2	23.7	110.1	38.8	2.14
Sep	23	11.1	15.5	80.7	24.0	105.8	209.2	2.39
Sep	24	17.0	21.0	79.7	10.7	47.8	113.2	0.75

Table Notes:

1. The ERV was set to run mainly when the indoor air temperature was lower than 18°C.
2. The ERV ran between August 31 and September 24, 2021.
3. Note that the ERV unit was primarily functioning as a heat recovery ventilation system (HRV).

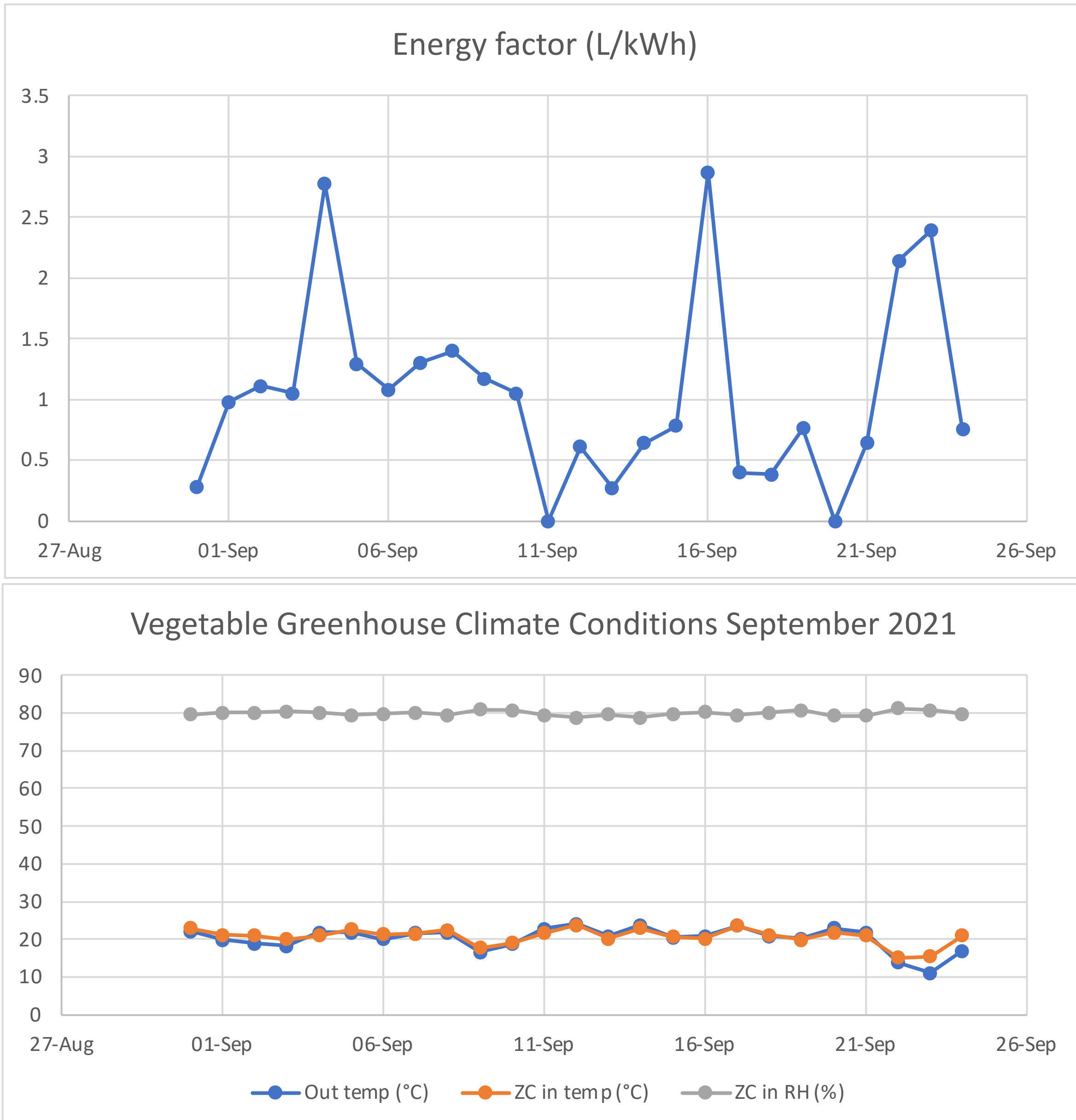


Figure 4-2 Energy factor and concurrent greenhouse conditions in September 2021 (a graphic of the Table 4-1 data).

Data collected during the GRET project supported our current findings that the operation of the HRV component of the system ("Dry Mode") under Southern Ontario climate conditions did not result in significant energy savings. However, when the LDD component of the ERV was functioning ("Wet Mode"), energy savings of 15-16% were realized. In addition, the system was able to manage RH better in the treatment zone compared to the control zone. Figure 4-3 is based on data collected in 2019, illustrating the amount of time (%) the RH exceeded 80 and 85% in the control and treatment zones of the tomato greenhouse.

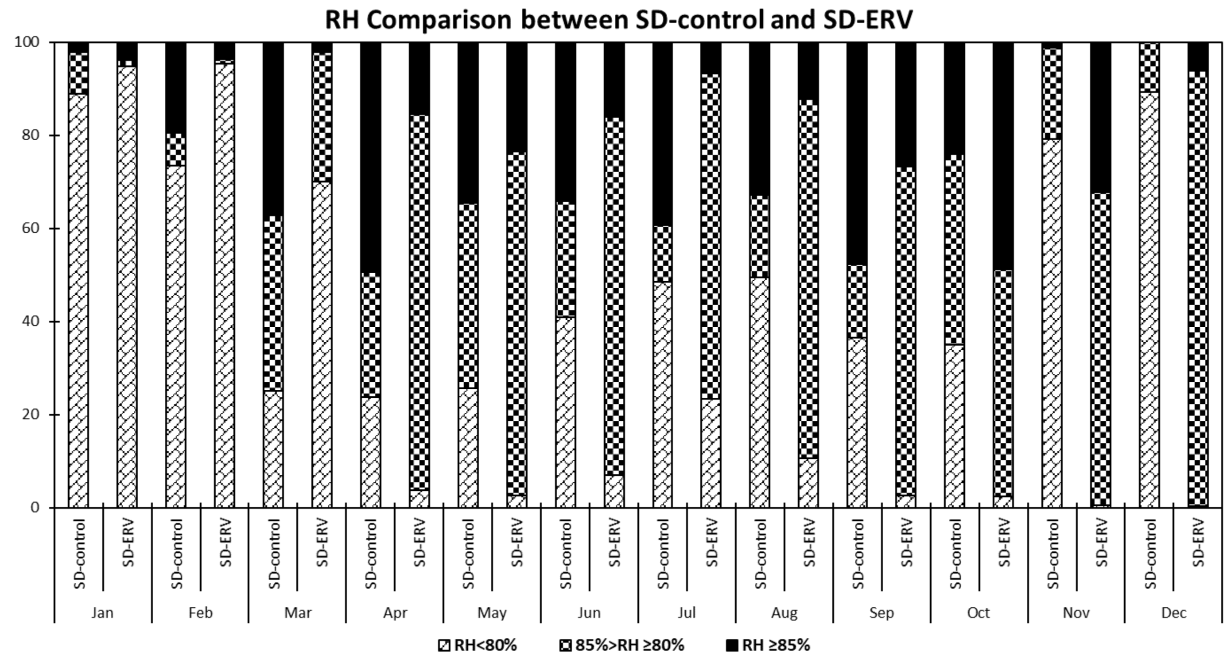


Figure 4-3 Monthly RH comparison between SD-ERV Zone and the SD-Control Zone in 2019.

Main findings:

1. The ERV unit has higher moisture removal rate (L/kWh) when the outdoor temperature is much lower than the indoor air temperature.
2. The moisture that is removed by the ERV unit operating in HRV mode (dry mode) was mainly affected by the outdoor air conditions.
3. Due to crop failure and changes at the greenhouse, it was not possible to collect additional supportive data on the LDD mode (wet mode) operation of the ERV.

Leaf Wetness Protocols

High relative humidity in the greenhouse can result in condensation on the greenhouse cover surface in addition to plant surfaces, especially during the early morning and at night. Not only is light transmittance reduced during the day and heat loss increased at night by increased condensation on the greenhouse cover, but the dripping of excessive condensation on the plant leaf surface can also lead to fungal diseases. One of the purposes of adding a dehumidification system in a greenhouse is to reduce the relative humidity to avoid the condensation. It is important to get a better understanding of if the dehumidification system reduces condensation occurrence and by how much the condensation is reduced.

There is no well-accepted method for measuring condensation rates in a building like a greenhouse. Han and Guo (2018) developed a simple and reliable method by using a commercially available leaf wetness sensor (LWS) to detect and measure condensation rate. The sensor was proved effective not only for leaf wetness detection, but also for greenhouse cover condensation measurements. The sensor is leafshaped and made of fiberglass. Its surface is very sensitive to moisture. Tiny amounts of water/ice on the surface can be detected with different amounts of voltage output.

Methods

In this experiment, three leaf wetness sensors (Decagon Devices Inc., Pullman, WA, USA) were installed at Zone B and another three were installed at Zone C in the vegetable greenhouse in March 2021 (Figure 4-4). All six sensors were attached to the greenhouse cover surface. There was also a leaf wetness sensor placed in each zone, directly on the plant or near the leaf surface within the canopy (Figure 4-5). The sensors placed directly on the leaves needed to be moved periodically to ensure vitality of the leaf, but in practice, the air movement in the greenhouse typically prevented the sensor from staying directly on the leaf, so measurements were considered 'on the leaf' but were actually within the canopy. The voltage output of the sensors was recorded by the greenhouse control system. The data are based on the measurements made in 2021, while there was still a crop in production at the greenhouse.

The linear relationship between the leaf wetness sensor voltage output and the amount of condensate on the sensor surface is determined by the following formula:

$$C = 0.0025 \times V - 0.70 \qquad (1)$$

where C is the amount of water condensate on the sensor surface, in g; V is the leaf wetness sensor voltage output, in mV.

Note that light transmission data was not collected throughout the GCII project as the loggers were found to be defective.

Figure 4-4. Leaf wetness sensor (LWS) at the greenhouse cover level in the vegetable greenhouse.

Figure 4-5 Leaf wetness sensor in the canopy of the vegetable greenhouse.

Results

Average moisture over the course of a day on the leaf surface is shown in Figure 4-6. The leaf wetness sensors were moved to a new leaf/area in the canopy for each of the three testing periods so that the portion of the leaf under the sensor was fresh and results were from viable surfaces. The sensors monitored leaf wetness from March-April, May to August, and again from September-October.

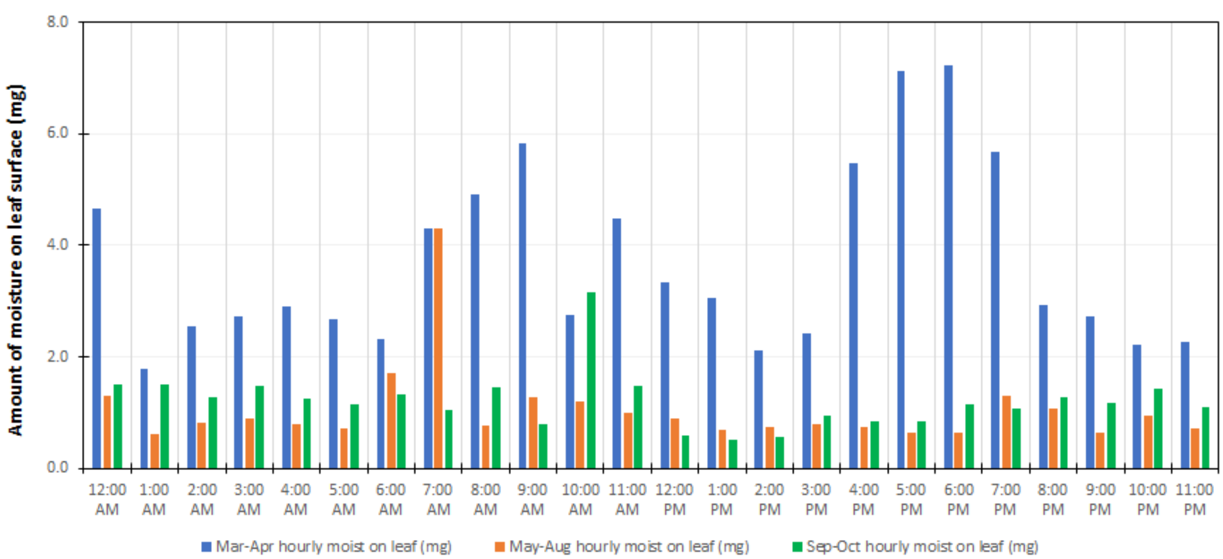


Figure 4-6 Measured hourly average moisture on leaf surface from March until October 2021.

Main findings:

1. In March & April: a significant amount of moisture was observed on leaf surfaces in late afternoon, dropping slightly overnight until the early morning (with a peak at midnight), and another peak was observed a few hours after sunrise until mid-afternoon
2. From May until August: the leaf surface is mainly dry, but some moisture was observed on the leaf surface during the early morning right after sunrise
3. In September & October: some moisture on leaf at night (more than the summer months)

The leaf wetness sensor data was converted to the measured hourly condensation rate (CR) for each month from March until October (Tables 4-2 for the control ZB, and 4-3 for the ERV ZC), and then these data were averaged over the month. Yellow highlighted values indicate the periods of higher condensation. Table 4-4 contains the summary of the monthly condensation rate data, plus the estimated latent heat due to condensation.

Table 4-2 Measured condensation rate at ZB (control) in 2021.

Unit: kg/hr	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
0:01 - 1:00	18.1	7.5	2.7	3.5	8.8	8.9	19.0	17.9
1:01 - 2:00	24.2	7.3	3.4	3.4	6.8	8.8	17.0	20.9
2:01 - 3:00	26.9	9.4	5.4	4.5	6.3	11.9	16.6	17.5
3:01 - 4:00	16.0	7.3	7.1	5.3	5.5	14.1	20.5	19.7
4:01 - 5:00	17.7	6.6	6.8	3.0	5.2	14.3	16.0	18.2
5:01 - 6:00	12.3	7.9	20.3	3.8	5.6	7.3	16.4	14.0
6:01 - 7:00	12.1	24.9	10.0	0.0	3.2	9.2	18.4	13.5
7:01 - 8:00	0.0	6.2	5.4	0.0	0.0	0.0	12.6	12.6
8:01 - 9:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9
9:01 - 10:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10:01 - 11:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11:01 - 12:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12:01 - 13:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13:01 - 14:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14:01 - 15:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15:01 - 16:00	0.0	0.0	0.0	0.0	0.3	0.9	0.0	6.4
16:01 - 17:00	4.5	5.9	0.8	0.8	0.7	1.6	1.4	11.9
17:01 - 18:00	11.0	8.5	6.2	1.0	2.2	1.9	2.7	10.9
18:01 - 19:00	12.8	15.7	3.0	1.3	2.3	2.0	1.9	13.2
19:01 - 20:00	23.4	17.9	3.2	3.4	2.9	4.0	4.9	19.5
20:01 - 21:00	40.7	18.7	6.1	2.0	3.7	5.6	7.4	21.5
21:01 - 22:00	33.3	12.8	5.7	3.9	6.9	7.0	10.2	20.5
22:01 - 23:00	30.7	7.7	1.4	3.4	6.2	6.7	13.4	15.0
23:01 - 24:00	30.4	7.3	2.4	2.9	6.2	7.4	16.9	16.5
Average	**20.9**	**10.7**	**5.6**	**3.0**	**4.5**	**7.0**	**12.2**	**15.3**

Table 4-3 Measured condensation rate at ZC (ERV) in 2021.

Unit: kg/hr	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
0:01 - 1:00	9.7	17.0	15.0	5.7	14.6	10.7	9.2	15.1
1:01 - 2:00	9.2	27.6	14.6	7.3	2.7	8.2	12.6	21.1
2:01 - 3:00	14.3	32.3	14.8	10.2	2.1	6.8	14.2	17.5
3:01 - 4:00	17.2	30.6	17.5	8.5	5.8	9.1	16.5	16.3
4:01 - 5:00	14.0	22.1	21.4	1.4	0.1	5.8	6.4	16.9
5:01 - 6:00	17.1	19.6	17.5	4.1	1.6	0.0	11.6	13.6
6:01 - 7:00	14.3	27.4	0.8	0.0	2.2	1.7	9.1	10.7
7:01 - 8:00	12.0	22.5	7.3	0.0	0.0	0.0	2.4	13.2
8:01 - 9:00	24.7	13.5	2.0	0.0	0.0	0.0	0.0	0.0
9:01 - 10:00	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10:01 - 11:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11:01 - 12:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12:01 - 13:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13:01 - 14:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14:01 - 15:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15:01 - 16:00	0.0	0.0	0.0	0.0	1.3	0.0	0.0	6.3
16:01 - 17:00	1.1	0.0	0.0	0.0	0.6	0.9	0.0	9.8
17:01 - 18:00	14.2	0.0	4.4	0.0	0.0	1.1	1.2	1.7
18:01 - 19:00	32.5	25.0	7.2	4.7	0.0	0.0	1.1	6.0
19:01 - 20:00	31.1	41.4	4.8	3.5	2.8	8.0	7.2	14.2
20:01 - 21:00	19.1	42.1	13.8	0.0	6.3	5.4	6.5	8.1
21:01 - 22:00	17.7	32.6	9.5	5.5	2.9	2.8	11.0	10.7
22:01 - 23:00	12.0	38.6	6.7	4.8	7.5	0.2	8.2	11.5
23:01 - 24:00	12.0	40.2	10.6	3.4	17.3	5.6	6.4	12.6
Average	**15.4**	**28.8**	**10.5**	**4.8**	**4.1**	**4.2**	**8.2**	**12.1**

Table 4-4 Measured condensation rate and estimated latent heat due to condensation near the greenhouse cover.

Month	Out Temp (°C)[1]	ZB - control		ZC - ERV	
		Hourly average of CR[2] (kg/hr)	Total released latent heat due to condensation (kWh/mo)[3]	Hourly average of CR[2] (kg/hr)	Total released latent heat due to condensation (kWh/mo)[3]
Mar	5.5	20.9	6654	15.4	5866
Apr	8.2	10.7	3517	18.8	6265
May	13.4	5.6	1903	10.5	3556
Jun	21.2	3.0	860	4.8	1183
Jul	21.9	4.5	1535	4.1	1372
Aug	23.4	7.0	2347	4.2	1330
Sep	18.6	12.2	4002	8.2	2533
Oct	14.6	15.3	5803	12.1	4344

Table Notes:

1. Out temp is the average temperature when condensation occurs.
2. Hourly average CR (condensate rate) is the total condensate on the whole greenhouse cover.
3. Total released latent heat is calculated based on the measured condensate rate. This could account for a significant amount of heat loss if the total latent heat is lost to the outside through the greenhouse cover at night and during the early morning.

Main Findings:

1. Condensation mainly occurs at night and in the early morning after sunrise through all the months where the sensor was utilized
2. More condensation occurs in the colder months (March, October)
3. When condensation occurs, especially at night and during the early morning, there is some heat loss through the greenhouse cover.
4. Dehumidification is an effective way to help to reduce the condensation occurrence while keeping the indoor RH at an acceptable level. It also helps to save heating energy (with the exception of April/May/June at the demonstration greenhouse because the indoor temperature at ERV zone was lower than ZB, but RH was higher in the meantime)

Environmental conditions of the greenhouse and outdoors are important factors in understanding the effectiveness of the ERV, and are detailed in Table 4-5 and Figure 4-6.

Table 4-5 Measured outdoor temperature in 2021.

Unit: °C	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
0:01 - 1:00	4.7	7.2	11.9	19.3	20.2	21.8	17.4	13.9
1:01 - 2:00	4.7	7.0	11.6	19.2	20.0	21.6	17.2	13.8
2:01 - 3:00	4.3	6.8	11.4	19.0	19.8	21.2	17.1	13.6
3:01 - 4:00	4.0	6.6	11.2	18.8	19.7	20.8	16.6	13.4
4:01 - 5:00	3.5	6.5	10.9	18.8	19.5	20.5	16.6	13.4
5:01 - 6:00	3.2	6.3	10.6	18.7	19.2	20.5	16.5	13.3
6:01 - 7:00	2.8	6.1	10.7	19.0	19.1	20.4	16.2	13.1
7:01 - 8:00	3.0	6.6	12.3	20.4	20.0	21.1	16.3	13.0
8:01 - 9:00	4.4	8.1	14.3	21.7	21.6	23.2	17.9	13.4
9:01 - 10:00	6.2	9.2	15.4	22.8	22.8	24.6	19.6	14.6
10:01 - 11:00	7.3	10.3	16.2	23.4	24.1	25.8	21.0	15.5
11:01 - 12:00	8.2	11.0	17.2	24.3	25.0	26.9	22.1	16.4
12:01 - 13:00	9.2	11.4	17.8	25.0	25.6	27.6	22.8	17.2
13:01 - 14:00	9.7	12.1	18.3	25.6	26.3	28.1	23.2	17.8
14:01 - 15:00	10.2	12.8	18.6	25.8	26.6	28.5	23.4	18.2
15:01 - 16:00	10.6	13.2	18.9	25.8	26.6	28.7	23.5	18.2
16:01 - 17:00	10.6	12.4	19.0	25.8	26.4	28.2	23.3	17.6
17:01 - 18:00	9.9	12.0	18.3	25.3	25.8	27.6	23.1	17.3
18:01 - 19:00	8.7	11.1	17.4	24.9	25.1	27.2	22.4	16.3
19:01 - 20:00	6.7	10.0	16.2	23.7	24.4	25.8	20.8	15.0
20:01 - 21:00	5.4	8.8	14.6	22.1	22.9	24.0	19.4	14.4
21:01 - 22:00	5.0	8.1	13.4	20.7	21.4	22.8	18.5	14.2
22:01 - 23:00	4.8	7.8	12.7	20.1	20.7	22.3	17.9	14.1
23:01 - 24:00	4.7	7.5	12.5	19.8	20.4	21.9	17.5	14.0
Average	**6.3**	**9.1**	**14.6**	**22.1**	**22.6**	**24.2**	**19.6**	**14.6**

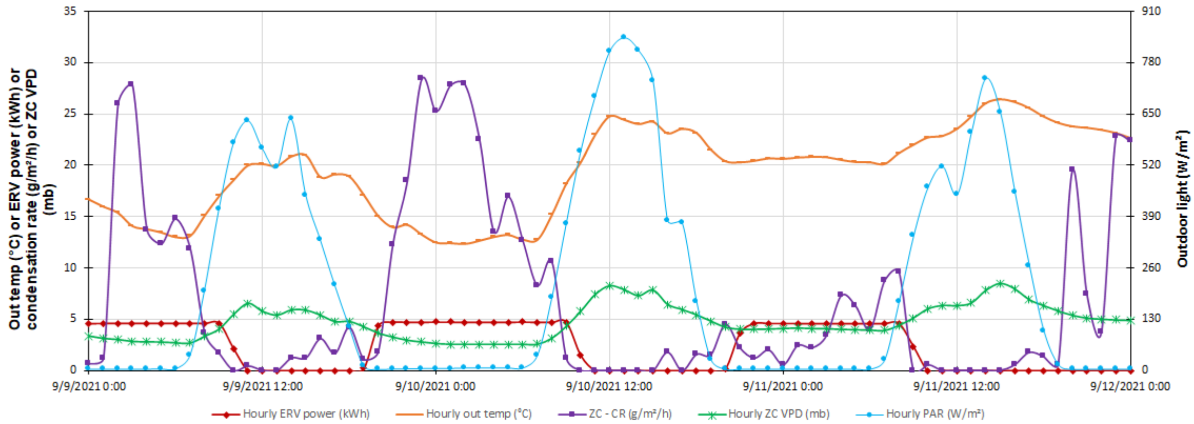


Figure 4-6 Environmental conditions and measured condensation rate at Zone C when ERV was running from September 09 to 11.

Main Findings:

1. When the ERV starts to run, condensation will be decreased within a few hours.
2. More condensation occurs after sunset, and it also peaks after sunrise. Then when the solar radiation gets strong, the condensation decreases. That is because after sunset, the greenhouse cover temperature gets lower than the indoor air dew point. After the sunrise, the plant starts to evaporate, however, the vents are still closed due to the cold outside air, and more moisture is kept into the greenhouse causing the higher RH. Therefore, condensation rate increases.
3. ERV can help to reduce the condensation occurrence. In the meantime, it also helps to remove the moist greenhouse air by pushing it outside and the exchange system gets the dry outside air into the greenhouse.
4. With the ERV running in early September, there was less condensation occurring on leaf surface at night and during the early morning with approximately 0.20 mg of moisture on leaf surface from 8pm to 9am, and 0.40 mg of moisture on leaf surface from 10am to 7pm.

Overall (ERV): The prototype ERV dehumidification system has potential to save both energy and operating cost, and is useful for humidity control. Cost savings are dependent on energy pricing.

5.0 Air Quality & Petrifilms Monitoring

Preliminary work was conducted in the GRET project to determine if the $3M^{TM}$ $Petrifilm^{TM}$ Rapid Yeast & Mold (RYM) method could be used as a simple, on-farm tool to assess the levels of fungal populations circulating in greenhouse air as a measure of risk for air-borne fungal plant pathogens. The RYM plates are a culture medium system consisting of a cold-water-soluble gelling agent containing nutrients, an antibiotic supplement to suppress bacterial growth, and an indicator to facilitate yeast and mold enumeration. A detailed description of the system can be found at the following site: https://multimedia.3m.com/mws/media/236251O/interpretation-guide-3m-petrifilm-yeast-and-mold-count-plate.pdf. Petrifilms have been used to measure general levels of air-borne contamination in the food industry, but the method is quite novel for the greenhouse industry. It was demonstrated in the GRET project that the method compares very well with the standard air monitoring method in which a known quantity of air is collected on a filter, and the filters sent to a specialty lab assessment.

Colony morphology on the Petrifilms differs between fungal types, but there has been very little work on determining if specific genera can be identified by visual inspection.

In the current study, this method was used to a) assess the levels of fungal populations entering and leaving the dehumidification units to determine if the dehumidification systems performed differently with respect to their impact on greenhouse air quality, and b) determine if specific plant pathogens could be identified by their colony morphology on the Petrifilm RYM plates.

Method

3M Rapid Yeast & Mold Petrifilms were prepared for use by hydrating with 1mL sterile phosphate buffer at least an hour before use according to standard directions given on the 3M website: https://multimedia.3m.com/mws/media/241111O/environmental-monitoring-procedures-article.pdf.

Rehydrated Petrifilms were exposed for 5 or 10 minutes in the air intake vents of each of the units. Five replicate plates were spread across each of the 2 inflow vents of each of the units as shown in Figures 5.1 and 5.2, resulting in 10 replicate samples. For the outflow, rehydrated plates were attached to a small rectangular plate held up in the outflow vents and exposed for 2 and 5 minutes (Figures 5-1, 5-2). Each exposure was replicated twice, for a total of 8 outflows plates. Air velocities were measured with an anemometer, and the results normalized based on a standard flow volume for the in and out measurements. Testing was done on nine dates for the MRD unit at Site 1 and four dates for the LDD unit at Site 2.

Petrifilms were incubated for 3 days at 25^{o}C, and colonies counted. Typical plates following incubation are shown in Figure 5-3.

Figure 5-1 Petrifilm tests for MRD in and out.

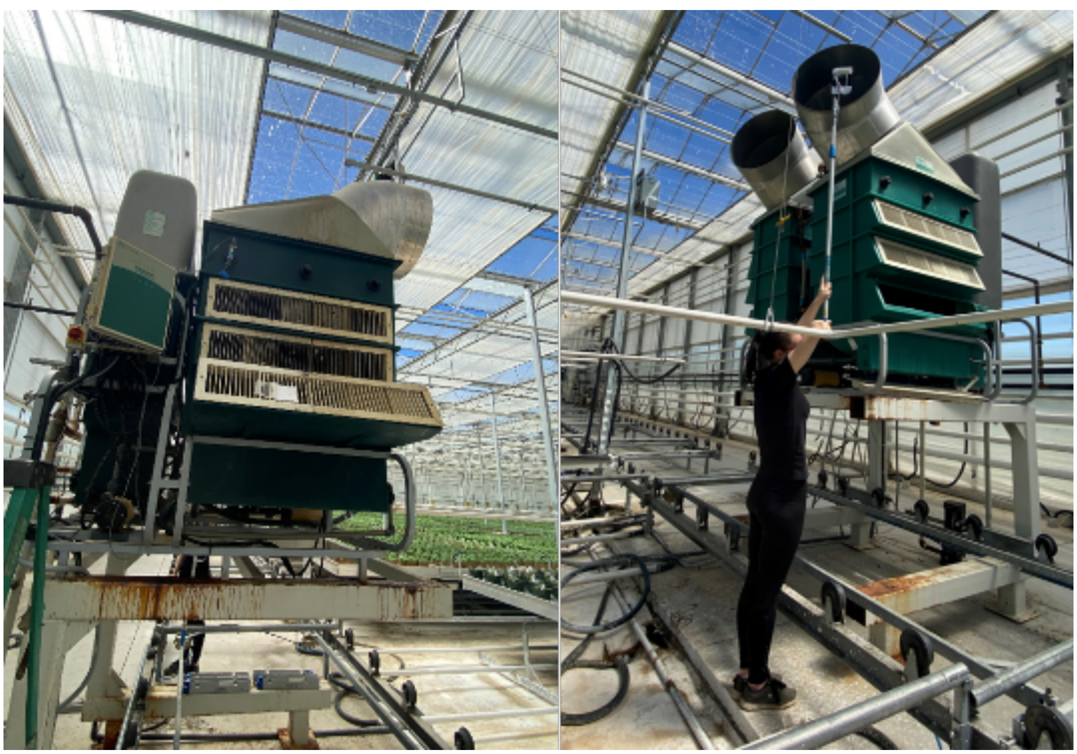


Figure 5-2 Petrifilm tests for LDD in and out.

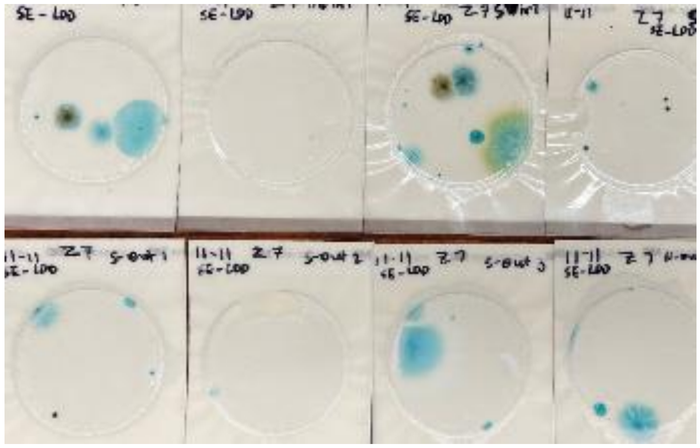


Figure 5-3 Typical RYM Petrifilm plates following incubation.

Results

The average RYM plate counts for the in versus out testing on 4 dates for the LDD units at Site 2 and 9 dates for the MRD at Site 1 are shown in Table 5-1. In all cases the colony counts on the RYM plates were higher in the outflow than the inflow. This is likely due to accumulated contamination within the units themselves. However, the proportional increase (difference between #in and #out divided by #out) was significantly less (P=0.04) for the LDD. This would indicate that the process of air passing through the liquid desiccant is reducing to some extent the risk of recirculating air-borne pathogens through the greenhouse. The testing also indicates that regular cleaning of the dehumidification units would be beneficial to maintain good air quality in the greenhouse.

Table 5-1 RYM colony counts for inflow and outflow from the LDD and MRD units.

Unit	Sampling Date	Colony counts		Proportional Increase**
		In (Average*, n=10)	Out (Average*, n=8)	
LDD	2021-04-15	5.49	12.55	1.29
	2021-05-27	1.36	2.84	1.08
	2021-10-27	2.76	8.41	2.05
	2022-11-11	0.94	1.01	0.07
MRD	2021-12-15	0.31	2.02	5.61
	2021-12-28	0.63	2.77	3.43
	2022-01-14	0.43	1.40	2.30
	2022-02-09	0.63	2.69	3.31
	2022-02-28	0.38	1.91	4.09
	2022-04-06	0.44	1.07	2.42
	2022-05-06	0.63	0.99	0.58
	2022-09-23	0.83	2.97	2.61
	2022-11-11	0.55	2.96	4.39

*Counts have been normalized to 5mins 1m/s to account for differences in air flow rates going into and out of the units
** Proportional increase calculated as: (#out-#in)/#out

Identification of Fungal colonies

In order to determine if specific genera could be identified by colony morphology on Petrifilms, and if any fungal plant pathogens are captured by the described method, 32 colonies of interest were sent to EMC Scientific Laboratories for identification. As well 8 Petrifilms with 'comparable' colonies were submitted to University of Guelph Laboratory Services for DNA Multiscan as confirmation, and to identify, if possible, any specific pathogenic species.

Thirty of the colonies submitted are shown in Figure 5-4. The majority of colonies identified were of the *Aspergillus* genus, followed by *Penicillium*, and then *Cladosporium*. All are very common air-borne contaminants. For *Aspergillus* in particular, there was a wide range of colony morphologies among different (presumably) species, but identification to species level was outside the scope of the project, and of less interest to growers since these are not plant pathogens. *Penicillium*, *Cladosporium*, and *Alternaria* were also identified, and certain species are potential plant pathogens, but they were not differentiated here. *Fusarium* was isolated as well (small intense colonies), and is of great concern to growers, particularly in the herb facility, since it is a severe threat to basil. It can also compromise roses. *Fusarium* was identified in the DNA multiscans. *Trichoderma* was easily identifiable due to its rapid growth habit. *Cunninghamella*, *Acladium* and *Geotrichum* were also isolated at low population levels, and many of these would be difficult to identify by colony morphology because of their similarity to *Aspergillus* colonies.

Overall, this method could be developed as a monitoring tool for specific groups of fungal contaminants but would require a more robust study and training development.

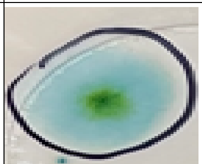
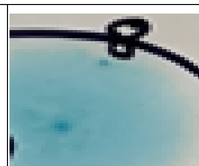
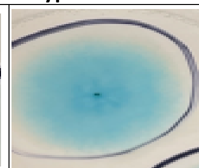
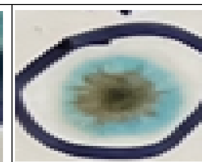
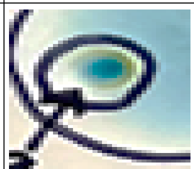
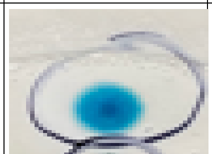
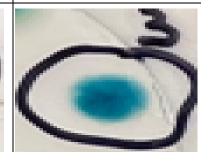
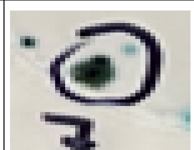
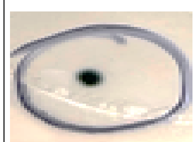
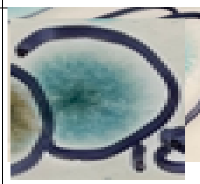
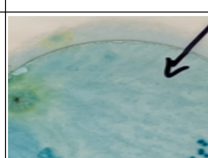
Genera Identified	Typical Colonies				
Aspergillus					
Penecillium					
Cladopsporium					
Alternaria					
Fusarium					
Trichoderma					

Figure 5-4 Colonies isolate on RYM plates and identified to genus.

General Recommendations

Individual farms should investigate their options before committing to a particular dehumidification system. HRV, MRD, LDD and ERV systems do work, but the farm needs to ensure the units are adequately sized for their operation. Actual energy savings are not possible to be determined without installation of energy monitoring equipment, and field conditions rarely meet the manufacturer's claims. Currently, only HRV, MRD and LDD systems are commercially available, with MRD and LDD systems more commonly implemented in Europe and in the cannabis sector in Canada.

While energy savings may be limited to the 10-20% range observed in this study, clearly there is an advantage to better humidity management, for example where the crop is highly vulnerable to blight and powdery mildew diseases, or natural venting does not adequately control humidity, or even where the greenhouse structure is prone to holding humidity (e.g., where vents don't open properly due to snow accumulation). Energy savings have also been observed by the participating farms at up to 40% of their overall natural gas usage, which is substantial! Optimal settings and maintenance are key to realizing the full potential of these systems.

Grower experience with the manufacturers' technical support was impacted by the COVID-19 pandemic, with supplies and personnel unable to reach the farms in a timely manner. The experiences during the GCII project are not representative of 'normal' technical support.

How to figure this out for my farm:

Some general considerations for making decisions on which dehumidification systems are suitable for a specific greenhouse operation are presented in the table at the end of this section.

Very generally, the size or number of a dehumidification unit(s) required for a particular zone or section under consideration will be determined by the volume of air in the area to be dehumidified and the amount of water to be removed from that volume (driven primarily by transpiration), and the air processing capacity of a particular system (cubic feet per minute; CFM), but there are many factors that influence the details of that calculation and the cost efficiencies that are achievable. Information that will be required by the manufacturers as well as information required on which to determine the relative cost benefits of the various systems include the following.

1. Greenhouse configuration:

- Greenhouse covering: wall and roof materials (will affect condensation, heat loss etc.)
- Do you have energy curtains, HVAC system, or other greenhouse modifications that might affect relative humidity and condensation rates?
- How leaky is the greenhouse? While some degree of leakiness is normal and tolerable, dehumidifying a very leaky greenhouse would not be cost effective.
- **The size and configuration of individual zones where dehumidification is most critical**, e.g., sensitive crops or crop stages. There will be areas where dehumidification is not desirable (e.g., transplanting, germination areas etc.). It is likely that dehumidification systems are not required in all areas, but also note that these areas should be isolated from each other by automatic doors etc.
- Venting type: roof or side wall vents, other (dictates venting efficiencies)

2. Energy

- Sources: natural gas, biomass, Co-gen, electrical, other (will dictate relative cost savings)
- Energy use for each source to track annual patterns (over several years if possible)
- Light source(s) and use regime: natural, artificial (HPS, LED, mix) (will affect heat requirement)
- Heat source: hot water, steam etc. (will dictate how units need to be installed)
- Heating configuration: top/crop/bottom (will dictate how units should be integrated in the greenhouse to achieve most benefit to overall energy consumption i.e., how to best use latent heat from unit operation)

3. Production

- Crop(s): flower/vegetable/herb/cannabis
- Crop tolerances - disease prone vs hardy
- Type: potted, cut, coir/rockwool, in-ground, trays/troughs/flood floors etc.
- Crop production cycle: e.g., mature plants year-round vs annual seeding/transplanting to mature crop over year (will dictate watering and transpiration rates and therefore the dehumidification requirements and energy/cost savings over the year)
- **Current seasonal irrigation and leaching rates** (will dictate the amount of water that needs to be removed by dehumidification or venting; transpiration represents 97% or more of water the crop takes up, i.e., = 0.97(irrigation rate-leachate))

4. Control system (provides information on how the units can be best incorporated into the greenhouse operating system so as to derive maximum energy-use efficiency, e.g., dehumidification units called on first before venting and allowing enough 'space' between setpoints to allow the units to achieve their maximum dehumidification capacity before ventilation is called upon to supplement)

- Capacity to accommodate additional controls
- Humidity set points and tolerances (how much and how rapidly water needs to be removed)
- Temperature set points and tolerances
- Information on seasonal changes in RH, temperature conditions, venting rates/frequency etc.

5. Annual weather

- external temp and RH conditions over the year (will dictate when dehumidification vs venting makes sense to meet crop requirements)

Matrix of Dehumidification Systems Compatibilities and Specifications.

	Energy					Crop Considerations			Specifications	
Dehumidification System	Uses Electricity	Uses Natural Gas	Produces Latent Heat	Requires Heat (Regeneration)	Energy Savings?	Cold Crops	Warm Crops	Manages Humidity?	CFM*	Max moisture removal capacity* (L/h)
HRV	✓				?	✓		?	7200	varies
MRD	✓		✓		✓		✓	✓	12950	45
LDD	✓	✓	✓	✓	✓		✓	✓	6356	20
ERV (HRV+LDD prototype)	✓	✓	✓	✓	✓	✓	✓	✓	4500	Depends on outdoor RH (20)

* units tested in this project

Acknowledgements

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Appendix 1 – Description of Dehumidification Technologies

Heat recovery ventilation - HRV

For greenhouses where CO_2 enrichment is used to increase production such as large vegetable operations, ventilation is still required to regulate the air quality, and heat recovery from the exhaust air becomes important. Heat recovery ventilation system (HRV) is a commercially available system designed by Nortek Air Solutions that exchanges indoor and outdoor air while recovering some portion of heat from the exhausting indoor air. The recovered heat energy can be used to pre-heat or pre-cool the outdoor airstream before entering the building. Figures 1 and 2 below shows the system's working principle and outdoor portion.

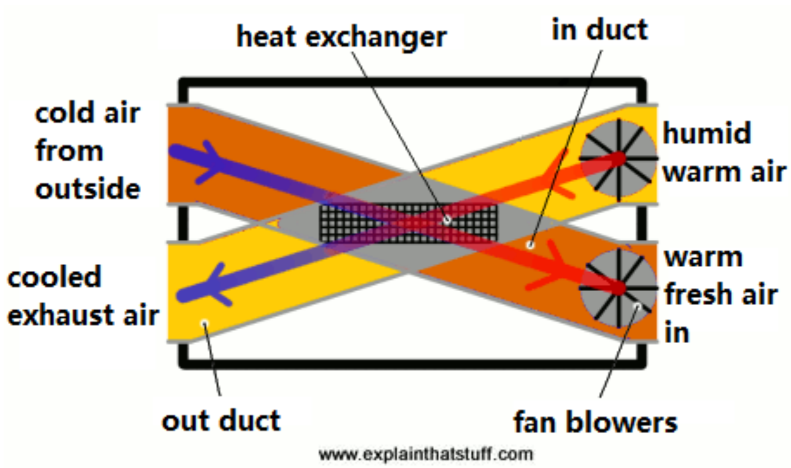

Figure 1 Nortek HRV airflow diagram.

Figure 2 Nortek HRV system.

Mechanical refrigeration dehumidifier - MRD

Mechanical refrigeration dehumidification system is also widely used in different kinds of buildings. Humid air is sucked into the system by passing over a refrigerated cold coil and then moisture gets removed by condensation on the cold coil surface. The air becomes drier and hotter due to the latent heat released during the condensation process. By using it as an internal dehumidification system, it can reduce heat energy consumption in a greenhouse by releasing latent heat while avoiding heat loss to the surroundings.

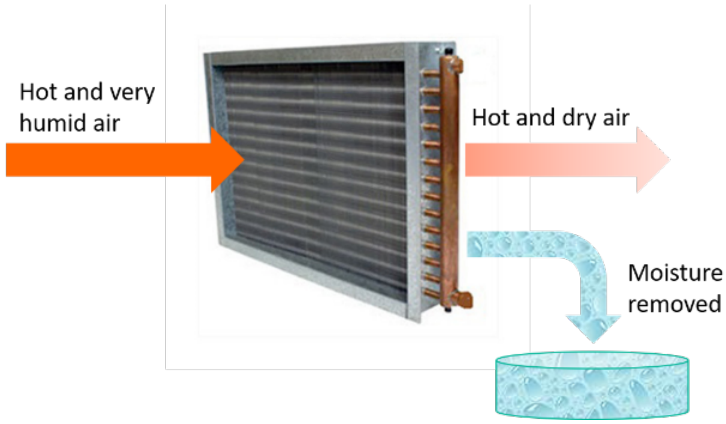

Figure 3 Mechanical refrigeration dehumidifier airflow diagram.

Chemical liquid desiccant dehumidifier – LDD

Liquid desiccant dehumidifier is the latest dehumidification technology that can recover both sensible and latent heat of condensation. The following graph shows the airflow pattern inside the system. As the humid air passes through the hot desiccant, it captures some sensible heat as well as latent heat. This type of dehumidification system requires heat to regenerate the diluted desiccant. In most cases, it needs hot water system for the desiccant regeneration process. The testing system in this study also has a hot water radiator system that can be used to provide extra heat to the greenhouse by suppressing bottom heat which stimulates night plant transpiration.

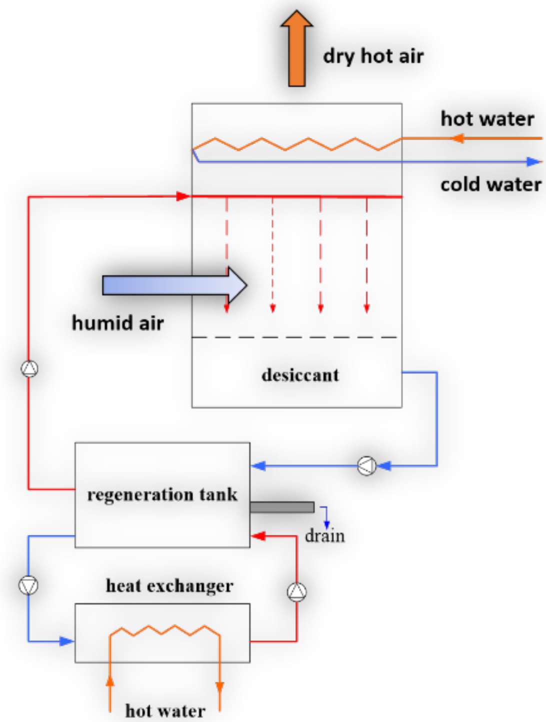

Figure 4 Liquid desiccant dehumidifier airflow diagram.

Energy recovery ventilator – ERV (state point liquid desiccant system)

The fourth system tested in this study is a novel air dehumidification system, designed by Nortek Air Solutions, called state point liquid desiccant system. It integrates the liquid desiccant dehumidification and heat recovery technologies; and is termed an energy recovery ventilation system (ERV). It was specifically designed for greenhouse applications, where dehumidification is required through the whole year and indoor air temperature is controlled by another independent system.

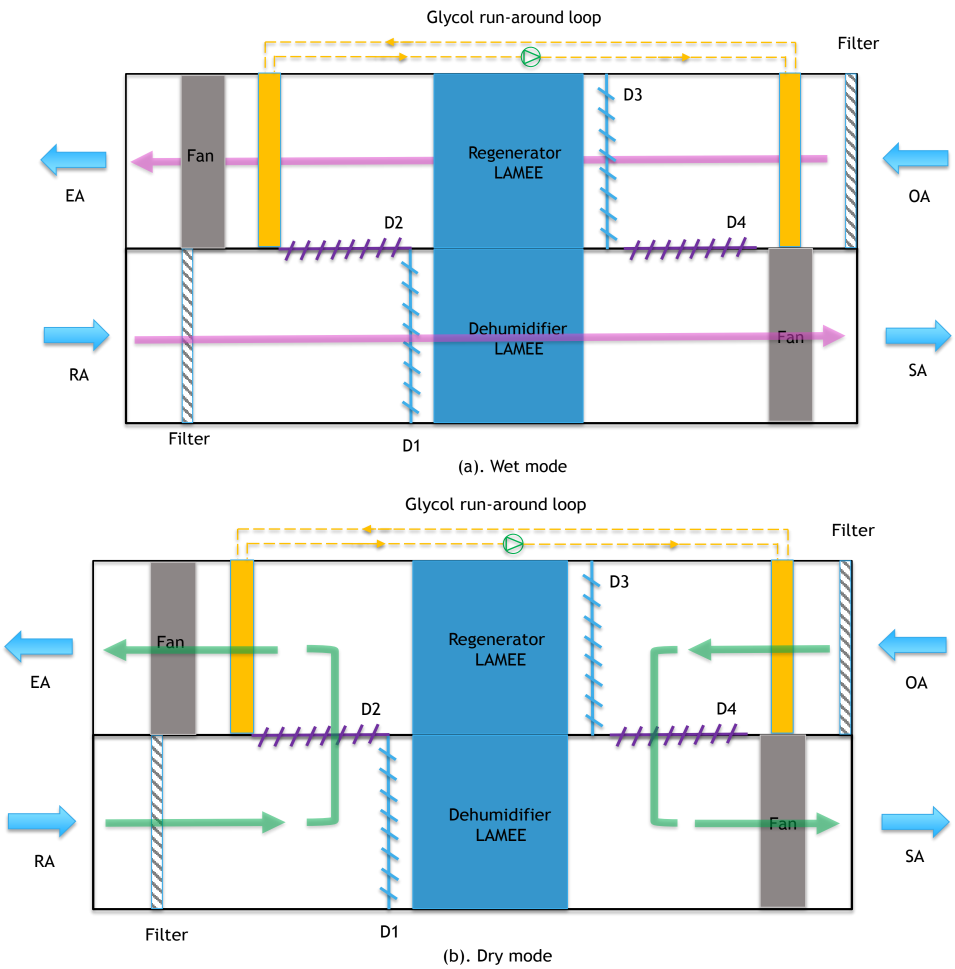

Figure 5 Airflow diagrams of the ERV unit in (a) wet operating mode and (b) dry operating mode.

It has two main operating modes – (a) wet mode and (b) dry mode. In wet mode, it works as a liquid desiccant dehumidifier (LDD), while in dry mode it works as an air-to-air heat exchanger (HRV). The wet and dry modes of the operation are automatically transited depending on the humidity ratio difference between indoor and outdoor air. When it works as a liquid desiccant dehumidifier, it also requires hot water for the desiccant regeneration process. This unit is designed for year-round application either as an internal dehumidifier or heat recovery ventilation unit.

Appendix 2 – Site and Technology Installation Details

**include table of setpoints of each zone/GH/for each technology

Greenhouse specifications and dehumidification installation

At the flower and herb facilities, ultrasonic flowmeters were installed on hot water pipes at critical inflow and outflow points to measure flow rates and temperatures to enable comparative calculations of heat energy use in zones where the dehumidification systems, as well as a control zone at the herb facility. The vegetable greenhouse used steam heat, so magnetic flowmeters and temperature sensors were used. Baseline indoor and outdoor environmental data was also continually collected. The monitoring systems were connected to the greenhouse control system, making the data accessible on a continuous basis.

For the flower and herb facilities which use hot water pipes, total heat consumption is calculated on the basis of the measured hot water flow rate and the temperature of the hot water supply and return pipes using the following equation:

$$Q = C_p m \Delta T = C_p \rho V \Delta T = C_p \rho V \left(T_{supply} - T_{return}\right) = C_p \times \rho \times F_{flowrate} \times \left(T_{supply} - T_{return}\right)$$

Where: Q is the total heat input supplied by the hot water, in kWh; C_p is the specific heat capacity of the hot water, in 4.2 kJ/kg/°C; ρ is the density of the hot water, in 10^3kg/m^3; V is the volume of the hot water, in m^3/s; $F_{flowrate}$ is the hot water flow rate, in m^3/s; T_{supply} and T_{return} are the supply and return temperature of the hot water, respectively, in °C.

The setup of the flowmeters at both Farm A and Farm B are similar. In each section, three ultrasonic flowmeters were installed to measure the hot water flow rate at each level. There are three levels of heating pipes – top, crop, and bottom.

To enable the energy analysis, sensors were installed to measure temperatures, flow rates, and condensate production. Nine portable ultrasonic clamp-on flowmeters (Krohne optisonic 6300, Duisburg, Germany) were installed in early February in 2018 to measure the hot water flow rate through each level of the heating pipe at the three sections. The hot water supply and return temperatures in the heating pipes were monitored and recorded by the computer control system. The greenhouse indoor temperature and RH conditions, as well as the CO_2 concentration, solar radiation, HPS light on/off, CO_2 burner on/off, exhaust fan on/off, vent on/off, etc., are all monitored by the greenhouse computer control system.

Site descriptions

Site A, the potted flower greenhouse, is located in Beamsville, Ontario, and of polycarbonate construction. The greenhouse has exhaust fans on the south wall and vents on the north wall. It has three levels of hot water heating pipes: bottom, crop, and top. Within each section, there is an energy curtain, high-pressure sodium light fixtures, and CO_2 burners. Three technologies were tested in three adjacent sections at this facility – MRD, LDD, and HRV (Figure 1). Both MRD section (SA-3) and LDD section (SA-4) have four houses, with each house of 21ft wide and 216 ft long (18,144 ft^2/1684 m^2). The HRV section (SA-5) has six houses (27,216 ft^2/2527 m^2).

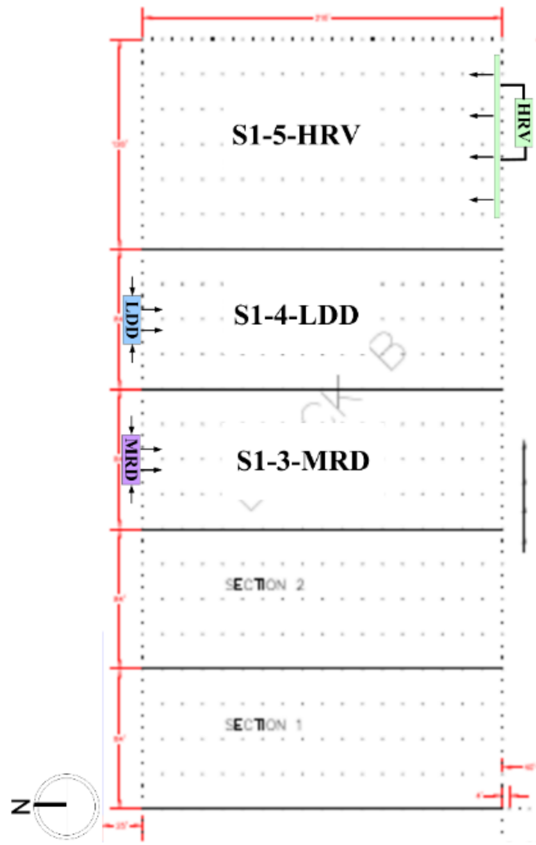

Figure 1 Site A plan view illustrating the location of the three dehumidification units at the flower greenhouse.

The herb greenhouse (Site C) is also located in Beamsville, Ontario, and is glass construction. Three levels of hot water heating pipes are used – top, crop and bottom heat. Four LDD units were installed at zone 7 (SC-7), which has 7 houses with each house of 21 ft wide and 216 ft long (31752 ft^2/2948 m^2). The adjacent zone 8, was used as a control zone. Originally, two standard MRD units were installed at zone 10 (SC-10), which has 6 houses (27216 ft^2/2526 m^2). The crop heat was disabled since 2020 because it was causing the crops to grow unevenly. However, in late 2020 the MRD systems were removed, and the section was designated for propagation (the crop doesn't transpire a lot and put a lot of humidity in the zone, so the RH is naturally very low).

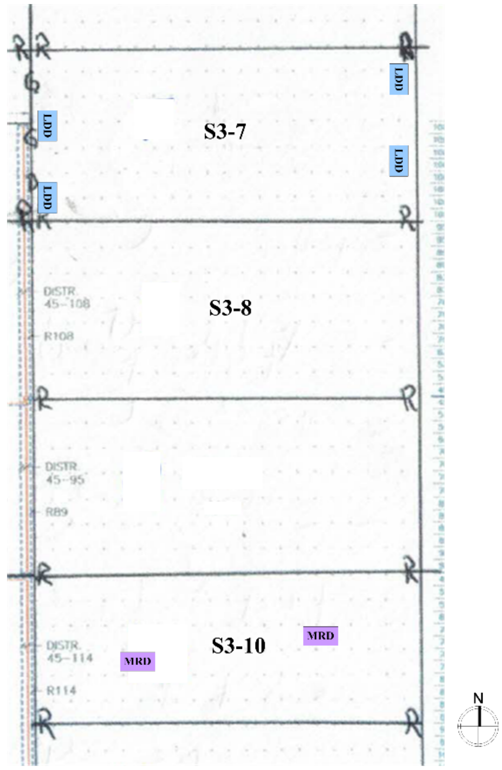

Figure 2 Site C plan view illustrating the location of the different dehumidification units at the herb greenhouse. Note that the MRD units were removed from zone 10 early in the GCII project.

The third site is an organic vegetable greenhouse (Site D), located in Kingsville, Ontario with glass construction. The ERV unit was installed at the outside of the south wall in zone C (SD-ERV), which has three houses with each house of 37.5 ft wide and 202 ft long (7575 sqft or 704m^2). However, the crop changed from tomatoes to peppers in 2022 and the partition wall between the control and ERV zones was removed before the GCII project.

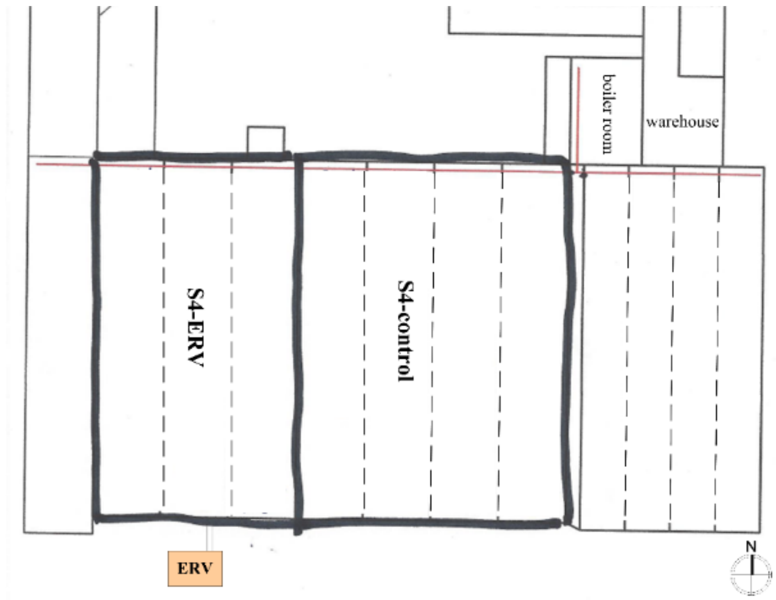

Figure 3 Site D plan view with ERV location.

Technology Installations

HRV

The HRV unit was sized by Nortek Air Solutions team based on the greenhouse dehumidification requirement. According to the studies by Han et al. (2015 & 2016), the capacity of the exhaust fans for dehumidification should provide an air flow rate of between 0.4 and 0.5 cfm/ft^2 of floor area. The HRV section (SA-5) has six houses (27,216 ft^2/2527 m^2); it is at the end of the greenhouse and therefore has an additional external wall. For the half acre trial section at Site A, the ventilation rate should be between 8800 CFM and 11000 CFM. However, the unit was quite large and very expensive. Therefore, it was scaled down to 7200 CFM, which can remove around 45 L/h of moisture when the humidity ratio difference between indoor and outdoor air is about 3 g/kg. The moisture removal capacity of the HRV unit highly depends on the outdoor weather conditions.

The HRV unit was delivered to the farm in June 2018, and the outside ductwork was installed to connect the outdoor unit to the interior of the greenhouse. In summer and early fall, a high rate of ventilation was required for indoor air temperature management, therefore, the unit was not operational until late October 2018. Shortly after start-up, the growers observed signs of an initial mildew outbreak due to the cold air being discharged from the HRV unit directly into the greenhouse. To make the incoming air mix well with the greenhouse air before it hit the crop, indoor ductwork was installed in November 2018. Figure 4 shows both the indoor and outdoor ductwork of HRV unit.

The greenhouse computer control system (Argus) was set to turn the HRV unit on at 80% RH. Note that the greenhouse system also was programmed to have the vents open in the case of higher greenhouse indoor temperatures – which made it difficult to evaluate the performance of the HRV. In addition, the HRV has the option of internal setpoints in addition to the greenhouse system.

Figure 4 HRV and indoor ductwork in SA-5.

MRD

The MRD unit was installed in the greenhouse in early June 2018. It's located at the north end, close to an evaporative cooling pad wall. The manufacturer claims that the MRD unit can remove 45 L/h of moisture at indoor conditions of 18°C and 80% RH. Figure 5 shows the MRD unit in SA-3. A remote rain gauge (RGR 126N, IDT Technology Limited, Hong Kong, China), which was used to measure the amount of moisture removed by the MRD, was installed in SA-3 in December 2018.

The greenhouse computer control system (Argus) was set to turn the MRD unit on at 80% RH. Note that the greenhouse system also was programmed to have the vents open in the case of higher greenhouse indoor temperatures – which made it more challenging to evaluate the performance of the system.

At the herb greenhouse, two standard MRD units were installed at zone 10 (SC-10), which has 6 houses (27216 ft^2/2526 m^2). The standard MRD unit has larger moisture removal capacity of 45 L/h than the ones at the old facility. At SC-10, there are only two levels of hot water heating pipes in use – the crop and bottom. However, these units were removed partially through the GCII project.

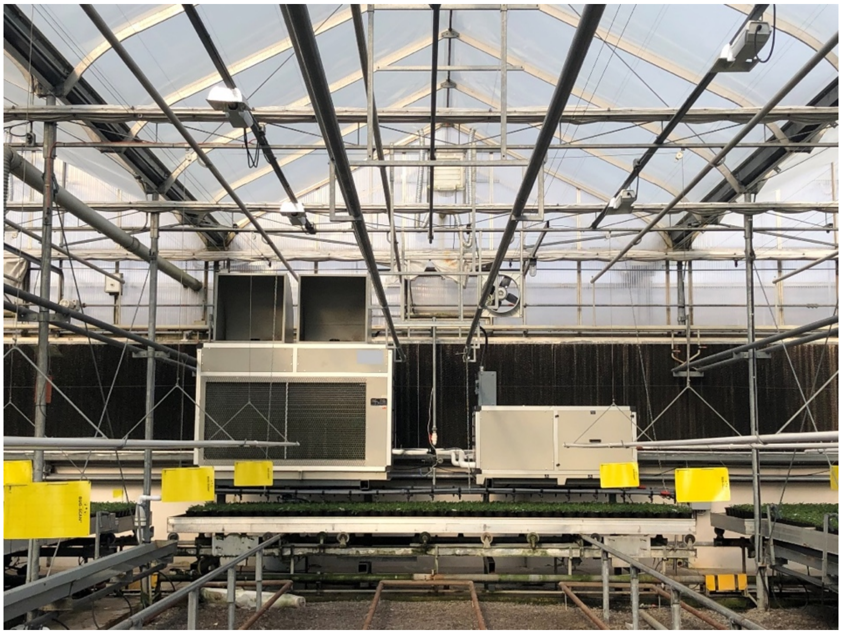

Figure 5 MRD in SA-3 at the flower greenhouse.

LDD

The LDD units have a maximum moisture removal capacity of 20 L/h at 18°C and 85% RH of indoor air. Hot water pipes were connected to the unit, either for desiccant regeneration, or for extra heat supply to the greenhouse. Re-installation of the flowmeters that were used to monitor the hot water pipes at the new herb greenhouse site were not installed until early January 2020. The moisture that condensed by both systems was planned to be measured by a pump, however, the signals from the pump did not connect to the greenhouse computer control systems correctly, so no useful data was recorded.

The greenhouse computer control system (Argus) was set to turn the LDD unit on at 80% RH at the flower greenhouse, and 75% at the herb greenhouse. Note that the greenhouse systems were also programmed to have the vents open in the case of higher greenhouse indoor temperatures – which made it difficult to evaluate the performance of the systems.

At the flower greenhouse, the original LDD unit installed in 2015 remained (Figure 6). At the new herb greenhouse, four LDD units (Figure 7, which were the same size as the previous ones at the original site) were installed at zone 7 (SC-7), which has 7 houses with each house of 21 ft wide and 216 ft long (31752 ft^2/2948 m^2). At the old herb greenhouse, there was no control zone for the treatments, while at the new site, zone 8 (SC-8), which is the same size as SC-7 was a control section for the LDD treatment.

Figure 6 LDD in SA-4 at the flower greenhouse.

Figure 7 LDD units at SC-7 at the herb greenhouse.

ERV

The ERV unit at the vegetable greenhouse has a maximum moisture removal capacity of 20 L/h in the wet mode (LDD), while its moisture removal capacity at dry mode depends on the indoor and outdoor air humidity ratio difference. The maximum supply and return air flow rate of the unit is 4500 CFM. Different from the other two facilities, the vegetable greenhouse uses steam as the heat source. However, the ERV unit requires hot water for the desiccant regeneration process, therefore, a steam-to-hot water heat exchanger was installed at the south wall in order to provide hot water energy to the ERV unit. There were two parts of ductwork involved in the system (Figure 8): the outside ductwork similar as the HRV system, and the indoor air distribution ductwork system. The indoor air ductwork system includes a header pipe which was installed along the south wall, and 18 polytubes going down the beds from south to north in order to distribute the dry air evenly inside the greenhouse. There is a control zone (SD-control) next to the ERV zone, which has four houses with each one of 37.5 ft wide and 202 ft long. All the environmental conditions are controlled the same way in both control zone and the ERV zone.

Figure 8 ERV and air ductwork at the vegetable greenhouse (Site D).