Measured and Simulated Energy Savings and Comfort Improvement of a Smart Residential Ventilation Control Strategy: Preliminary Results for North America and Europe

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ABSTRACT

Mechanical ventilation is vital in modern homes to insure adequate indoor air quality. However, builders, homeowners and policy makers may perceive best practice as a risk, especially if invoked during peak outdoor thermal conditions which may compromise comfort and energy use. In North America, ASHRAE Standard 62.2-2016 defines best practice, yet ventilation code specifications vary internationally. Although enthalpy heat recovery is advocated in efficient home design, taking advantage of the natural daily and seasonal temperature and humidity cycles can provide further comfort and energy reduction advantages.

We describe a smart ventilation system which uses the simple idea of modulating outdoor air depending on departure of prevailing weather from desirable indoor comfort conditioning. The system uses outdoor temperature and moisture based control. The main principle is to shift ventilation from time periods that have large indoor-outdoor temperature and moisture differences to periods when these differences are smaller and their energy and comfort impacts are expected to be less. Fan flow rates are reduced when the outside temperature and moisture falls outside of optimum levels, yet overall air exchange is maintained to ensure chronic and acute exposure to pollutants remains relative to best practice. Online weather and smart thermostat data can be used as control inputs, so no specific measurement devices are needed.

Using the smart ventilation scheme demonstrated 10% average cooling season energy savings in two full-scale identical side by side test homes in Florida. Parametric simulations show similar savings for heating and cooling across North American and European climates demonstrating smart ventilation as a robust efficiency measure, particularly for cooling. We posit that a weather-responsive ventilation scheme has world-wide application.

KEYWORDS
Smart, Ventilation, Energy, Savings

1. INTRODUCTION

Whole-house mechanical ventilation is a critical component to a comprehensive strategy for good indoor air quality (IAQ). Smart ventilation controls (SVC) help reduce risk factors by optimizing mechanical ventilation operation to reduce the heating and/or cooling loads, potentially improve comfort while maintaining IAQ equivalence according to ASHRAE Standard 62.2 (Sherman, Walker, and Logue 2012).

Previous studies by Lawrence Berkeley National Laboratory (LBNL) have incorporated smart ventilation strategies that included the effects of other fans operating in the home as well as passive ventilation systems (Sherman and Walker 2011). These studies included development of a ventilation model to include control algorithms and IAQ calculations suitable for evaluating performance of variable ventilation rate systems. LBNL used these simulations to develop a smart ventilation algorithm based on a temperature threshold (Less, Walker, and Tang 2014). Recently, LBNL simulations have been used to investigate the effect of smart ventilation control on indoor relative humidity (RH) (Less and Walker 2016). Until now, no prior published research on lab or field testing of smart ventilation control systems has been available.

LBNL work on ventilation equivalence for intermittent ventilation systems was adopted by ASHRAE Standard 62.2-2016 in the form of Appendix C. This provides a procedure to calculate pollutant exposure resulting from varying ventilation rates, relative to a continuous rate, and termed "relative exposure" (RE). Averaged exposure over a chosen time period achieving a value of 1.0 dictates that exposure to pollutants is equivalent to a continuously operating mechanical ventilation system. At no time can a time-varying ventilation system produce an RE that exceeds five times the baseline.

In Europe, ventilation standards vary from one country to the next, but tend to be somewhat greater than that shown by ASHRAE Standard 62-2 (Kunkel et al., 2015). Demand Controlled Ventilation (DCV) schemes have been widely advocated as a method to achieve energy-related savings, although often not with a weather-responsive scheme attached to methods to improve IAQ. Tight construction and ERV's are commonly used.

2 A SMART VENTILATION ALGORITHM

This paper describes a mathematical weather-responsive algorithm for SVC that varies mechanical ventilation airflow through interpretation of current and historical outdoor temperature and absolute humidity (W). The algorithm optimizes delivery of mechanical ventilation airflow on a daily cycle to minimize sensible and latent load impacts. Simulations were conducted to tune the algorithm with differing flow targets and seasonal adjustment factors:

1. Maximize heating and cooling energy savings compared to continuous ventilation,
2. Maintain similar indoor RH, and
3. Achieve equivalent RE with respect to ventilation standards.

In all locations globally, optimizing ventilation according to outdoor temperature appears desirable. However, in central Florida as well as other humid locations, outdoor moisture levels are a legitimate concern for ventilation since outdoor dew points are frequently above 21.1°C.

To account for these factors, the algorithm examines the preceding 24-hour period and compares the recursively weighted hours with the current hour and seeks to minimize the sum of the square deviations from multiple targets: difference between indoor and outdoor temperature and difference between indoor and outdoor W, along with user selected importance weighting for each parameter (X).

$$RSS = \sqrt{(\Delta T * X_T)^2 + (\Delta W * X_W)^2} \tag{1}$$

where

ΔT (°C) = (indoor temperature) – (outdoor temperature)
X_T = delta temperature weight
ΔW (g/m^3) = (indoor moisture) – (outdoor moisture)
X_W = delta moisture weight

The time weighted RSS (Average (RSS_1:RSS_{23})/RSS_{24}) becomes a multiplier to adjust total ventilation flow (mechanical + natural), which is proportional to RE. There may be other constraints to ventilation (e.g. occupancy) that could be optimized with this multi-parameter optimization approach.A simulation tool was developed to test the algorithm using typical meteorological year (TMY3) weather data.

Similar results were seen in multiple climates with either forward or backward differency schemes, leading to the conclusion that the seasonal shape of the typical or average daily weather pattern is likely more predictive of variable ventilation savings than are short term periods. Therefore, to enhance potential for savings, seasonal adjustment factors were determined iteratively using the simulation tool to ensure the RE target is achieved. The adjustment factors considered include changes to the target ventilation flow and flow overrides based on outdoor temperature and moisture:

$$\text{Hourly Fan Flow} = (\text{Target Fan Flow} * (\text{Average } (RSS_1:RSS_{23})/RSS_{24}) \tag{2}$$

Where flow targets vary as follows:

- Cooling period target if outdoor temperature > given threshold
- Heating period target if outdoor temperature < given threshold
- Floating period target if outdoor temperature is in between cooling and heating thresholds

3. PHASE I SCHEME DESCRIPTION AND RESULTS

Parametric simulations were conducted to arrive at an optimized set of parameters to later test in the laboratory (Table 1). The logic for the chosen flow targets for Phase I were cooling energy savings focused: the maximum floating season flow target was set at the capacity limit of the fan, the Standard 62.2 continuous fan flow value for the laboratory building was assigned for Florida's limited heating season target, and the cooling season target was dropped below the heating season target by 9.4 L/s. Simulation results showed temperature to be a much greater influence on energy savings than moisture, so those parameters were weighted 2:1. The indoor temperature target is set intentionally below a typical thermostat set point temperature as simulations showed such a low value required to generate algorithm response that would result in cooling energy savings. The indoor W target of 12 g/m^3 corresponds to an RH of 55% at 23.9°C.

Table 1: Phase I scheme parameters and values

Period Temp.) (defined by hourly outdoor	Parameter	Phase I Scheme Values
Cooling	Outdoor temp. range for cooling period target	>22°C
	Cooling period target fan flow	26 L/s
	Outdoor temp. range for fan lockout (0 L/s)	n/a
Heating	Outdoor temp. range for heating period target	<15.6°C
	Heating period target fan flow	35.4 L/s
Floating	Outdoor temp. range for floating period target	<=22°C; >=15.6°C
	Floating period target fan flow	65 L/s (fan limit)
All	Indoor temp.	18°C
	Delta-temp. weight (X_T)	2
	Indoor moisture (W)	12 g/m^3
	Delta-moisture weight (W_W)	1

3.1 Phase I Simulation Results

Simulation results for the smart ventilation scheme chosen for Phase I, using TMY3 Orlando weather data, resulted in an average annual fan flow of 37.2 L/s, slightly higher than the 62.2 Standard continuous fan flow requirement of 35.4 L/s. Hourly fan flow ranged from 8.0 L/s to the upper-limit of the laboratory fan, 65 L/s. Total annual average ventilation rate was 38 L/s, determined hourly by adding the modified natural infiltration to the fan component. Annual RE averaged 1.08, reaching a maximum of 2.09 for a single hour, well below the 5.00 threshold provided by the 62.2 standard. The simulation results are displayed graphically in Figure 1. Hourly fan flow of the smart ventilation system is plotted in light blue with average daily RE in red. The black line represents the 62.2 constant fan flow recommended for the buildings at 8.0 L/s and an associated RE of 1.00.

The plot shows two dominant seasons: cooling and floating. The smart ventilation algorithm creates a dynamic fan response, especially from October - May with the fan frequently flowing at its maximum when outdoor conditions are ideal, often at night. The increased floating period fan flow accommodates the restricted cooling period flow, balancing out the annual average RE, with the goal of generating cooling energy savings.

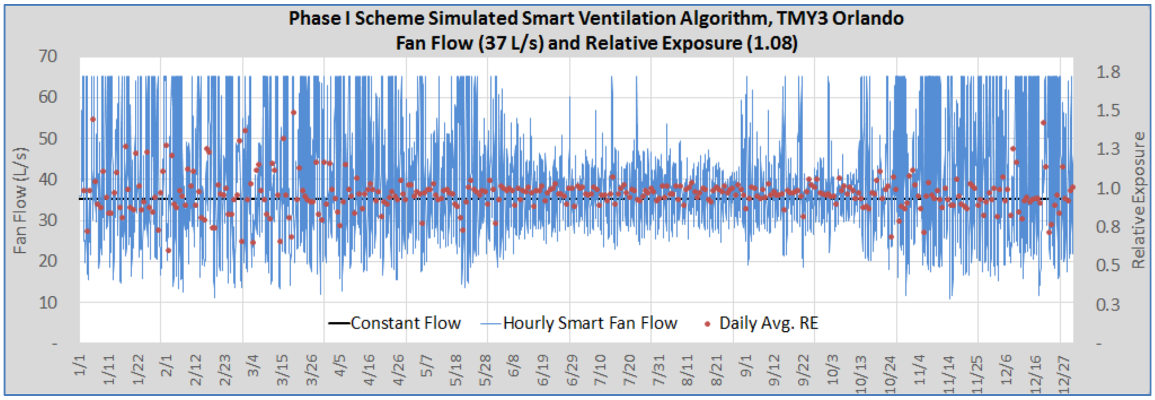

Figure 1: Phase I smart ventilation scheme simulated hourly average fan flow and daily average RE.

Simulated seasonal differences in sensible and latent ventilation load between the constant or fixed fan scheme and this smart ventilation scheme are presented in Table 2. Negative numbers in the table represent heat or moisture leaving the building, positive numbers represents heat or moisture entering the building. Compared to a fixed fan, the simulation suggests that on an hourly average, the smart ventilation scheme delivers 59 W/h less heat (reducing cooling load) and 0.14 kg less moisture to the building in summer. On average, more heat is also being removed during the non-summer floating hours as well, which is beneficial in the hot humid climate and could act to further reduce cooling hours later in the day by pre-cooling the building. However, slightly more moisture is being introduced on average by the smart ventilation system (0.055 kg/h) than with the constant fan.

Table 2: Simulated ventilation load and fan power for the Phase I scheme and continuous ventilation.

Season/ Period	Sensible (W)			Latent (kg/h)			Fan Power (Average Watts)			Average for Smart System	
	Fixed	**Smart**	**Δ**	**Fixed**	**Smart**	**Δ**	**Fixed**	**Smart**	**Δ**	**Flow (L/s)**	**RE**
Summer[a]	73	15	0.59	0.85	0.71	0.14	40	28	11.62	31	1.22
Non-Summer Cooling[b]	414	12	2.93	0.18	0.11	0.07	40	17	22.59	19	1.30
Non-Summer Floating[b]	(270)	(391)	120	(0.03)	0.5	(0.08)	40	50	(10.11)	55	0.76
Heating[c]	(598)	(440)	(161)	(0.82)	(0.61)	(0.26)	40	24	16.22	26	1.27
Annual										37	1.08

[a] The period between May 1 and Oct. 31.

[b] The hours outside of the summer period when the outdoor air temperature falls within set parameters – Cooling >22°C; Floating ≤22°C, ≥10°C.

[c] The hours when the outdoor air temperature falls below 10°C.

The changes in loads were used to estimate energy savings and are shown in Table 3. These results assume a cooling and heating system with efficiency of seasonal energy efficiency ratio 3.8 cooling COP/COP 1 (as was present in the laboratory buildings during later experimentation), 75% sensible heat ratio, and a 20% distribution loss.

Fan power is also converted into energy and summed annually in the Table 3. The smart ventilation scheme saves fan energy during the cooling when flows are lower, but uses more fan energy during the heating and especially the floating hours when flow is higher. The table shows potential for 7% annual energy savings, and over the 183-day period defined as summer in Central Florida (May 1–Oct. 31), the Phase I system is estimated to save 1.2 kWh/day versus the constant speed ventilation system.

Table 3: Simulated space conditioning energy use for the Phase I scheme and continuous ventilation.

Season/ Period	Sensible (kWh)			Latent (kWh)			Fan (kWh)			Total Savings	
	Fixed	**Smart**	**Savings**	**Fixed**	**Smart**	**Savings**	**Fixed**	**Smart**	**Savings**	**(kWh)**	**%**
Summer[a]	140	30	110	397	331	65	175	124	51	226	32
Non-Summer Cooling[b]	20	6	15	21	13	8	44	76	(31)	(8)	-10
Non-Summer Floating[b]							117	219	(102)	(102)	-87
Heating[c]	232	170	62				12	104	(91)	(29)	-12
Annual	392	206	186	418	344	74	349	522	(173)	87	7

[a] The period between May 1 and Oct. 31.

[b] Hours outside of the summer period when the outdoor temperature falls within: – Cooling >22°C, Floating ≤22°C, ≥10°C.

[c] Hours when the outdoor air temperature falls below 10°C.

3.2 Phase I Laboratory Evaluation

Experimental work was conducted in FSEC's *Flexible Residential Test Facility* (FRTF), which features two full scale, geometrically identical side-by-side residential energy research facilities as shown in Figure 2. The slab-on-grade buildings have uninsulated concrete block walls, single pane windows, RSI-5.3 ceiling insulation, and COP 3.8 air conditioners with electric resistance heat. Additional characteristics of the 143 m^2 single-story buildings (volume = 370 m^3) including details of the general instrumentation package and schedule and methods for simulating occupancy by generating indoor sensible and latent loads are provided elsewhere (Parker 2014). One building acted as a control, and utilized a fixed, continuous ventilation rate. The other building varied the ventilation rate with a fan operated with a smart controller via a programmable data logger.

Air leakage across the buildings' envelopes is controllable; however, for these experiments both buildings were set to their "tight" condition, resulting in approximately 2.2 air changes per hour (ACH) at 50 Pa. Under this condition, Standard 62.2 requires 35 L/s of whole-house mechanical ventilation fan flow, which was provided to the control building continuously, on a supply basis, directly into the zone via an inline fan. The 35 L/s is determined as the fan component of total continuous ventilation required by Standard 62.2, including natural infiltration modified by use of superposition to dictate interactive effects of the desired unbalanced ventilation system, as described in the ASHRAE Standard.

Figure 2: Identical buildings that comprise FSEC's Flexible Residential Test Facility.

Components of the Phase I ventilation system in each home included a centrifugal inline fan, for which the maximum produced flow at full output was measured at 65 L/s once installed. Variation of airflow rates in the experimental building is achieved by altering the runtime of the inline fan with the programmable data logger as dictated by the smart ventilation algorithm. That is, the fan itself runs at its fixed, maximum speed while operating, but runtime is varied during each 15-minute period to match the total flow called for. Temperature and RH are measured at the entrance and exit of the ventilation duct when the fan is running. Indoor temperature and RH measurements were taken near the thermostat and HVAC energy measurements were recorded.

One important finding during setup for the Phase I laboratory evaluation was that the outdoor air temperature measured at the ventilation air intake under the soffit was almost always warmer than the outdoor air temperature measured above roof height. Solar heating of the east wall under the air intake contributes to this temperature imbalance. Ventilation air entering the building is even warmer due to fan heat and gains on the outdoor air duct located in the vented attic. During July and August, average temperature at roof height (4.6m), at the air intake (2.7m), and the air discharge into the building were 26.9^{o}C, 28.6^{o}C, and 29.1^{o}C respectively. As outdoor air temperature is an input to the smart ventilation algorithm, this has implications on the application of weather station data, taken at height and supplied via an internet source, on a locally operating system.

3.2.1 Phase I Laboratory Results: 2016 Cooling and 2016–17 Floating Periods. Measured monthly energy savings for the cooling and floating periods are provided in Table 4, and average RE, fan flow, and indoor and outdoor conditions in Table 5. The smart ventilation algorithm delivered 36 kWh/month or 1.2 kWh/day and 5.5% cooling energy savings for this 180-day period. Results are improved slightly, to 6.2% when fan energy is considered. Average monthly savings ranged from 1% to 17%. The smallest cooling savings were experienced during the hottest months when air delivered by the smart ventilation system was less than that of the control. As shown in Figure 3, during these months the AC ran nearly constantly and sometimes failed to deliver the indoor set point temperature of 23.3°C. In August, the smart building with reduced ventilation is better able to maintain desired indoor conditions (yellow) than the control (red).

Table 4: Measured energy use during cooling and floating periods: Phase I scheme and continuous ventilation.

Month	Cooling Energy (kWh)			Fan Energy (kWh)			Total (kWh)			
(n = days of good data)	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	% Savings
Aug. (n = 21)	1,312	1,295	16	29	18	11	1,340	1,313	27	2%
Sep. (n = 15)	1,011	1,013	(2)	29	18	10	1,039	1,031	8	1%
Oct. (n = 25)	671	624	47	29	21	8	700	645	55	8%
Nov. (n = 9)	295	246	49	29	25	3	324	271	53	16%
Dec. (n = 31)	286	234	52	29	27	2	314	261	53	17%
Jan. (n = 15)	300	248	53	29	25	3	329	273	56	17%
Average	646	610	36	29	22	6	674	632	42	6.2%

Table 5: Measured environmental conditions during cooling and floating periods for the Phase I scheme and continuous ventilation.

Month (n = days of good data)	Smart Flow (L/s)	Smart RE	Outdoor OA Inlet Temp. (°C)	Control Indoor Temp. (°C)	Smart Vent Indoor Temp. (°C)	Outdoor Air Inlet Dew Pt (°C)	Control Indoor RH%	Smart Vent Indoor RH%
Aug. (n = 21)	27	1.33	29.1	23.1	23.1	24.2	52.1%	51.2%
Sep. (n = 15)	28	1.31	27.5	23.1	23.3	23.1	53.1%	53.9%
Oct. (n = 25)	31	1.25	24.9	23.4	23.4	18.8	50.5%	50.6%
Nov. (n = 9)	39	1.08	21.3	23.3	23.4	15.6	50.9%	53.3%
Dec. (n = 31)	41	1.03	20.9	23.3	23.3	16.1	54.0%	56.2%
Jan. (n = 15)	39	1.06	18.5	23.5	23.3	12.2	48.3%	52.8%

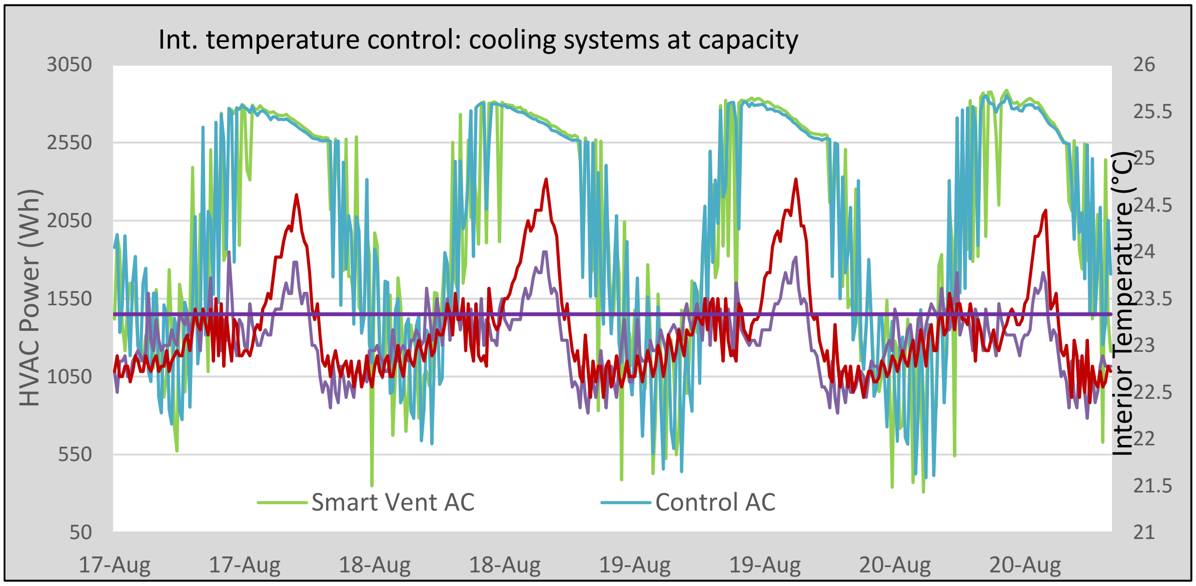

Figure 2: Measured data from August showing reduced indoor temperature generated by the smart ventilation scheme despite air conditioners running at peak capacity.

4. PHASE II SCHEME DESCRIPTION AND RESULTS

In effort to achieve reduced RE, better energy savings, and improved indoor comfort conditions from the smart ventilation system, changes were made prior to the onset of the 2017 cooling season. A more powerful fan with a maximum flow of 99 L/s (tested *in situ*) was installed to allow greater ventilation flow during moderate outdoor conditions, and the simulation tool was revisited to test additional added parameters. Based on 2016 experiences, ventilation during the hottest periods with a limited cooling system capacity led to elevated indoor temperatures that would likely not be considered favorable. Thus, a key evaluated parameter included a fan lockout above 31°C outdoor air temperature. A complete list of the Phase I/ II parameters is in Table 6.

Table 6: Phase I and II scheme parameters and values

Period (defined by hourly avg. outdoor Temp.)	Parameter	Phase I Scheme Values	Phase II Scheme Values
Cooling	Outdoor temp. range for cooling period target	>22°C	>22°C
	Cooling period target fan flow	26 L/s	35 L/s
	Outdoor temp. range for fan lockout (0 L/s)	n/a	>=31°C
Heating	Outdoor temp. range for heating period target	<15.5°C	<15.5°C
	Heating period target fan flow	35 L/s	35 L/s
Floating	Outdoor temp. range for floating period target	<=22°C; >=15.5°C	<=22°C; >=15.5°C
	Floating period target fan flow	65 L/s (fan limit)	99 L/s (fan limit)
	Outdoor W range to adjust floating period target	n/a	>=15g/m3
	Floating period target adjusted for W	n/a	35 L/s
All	Indoor temp. (T)	18°C	18°C
	Delta-temp. weight (X_T)	2	2
	Indoor moisture (W)	12 g/m3	12 /m3
	Delta-moisture weight (X_W)	1	1

4.1 Phase II Simulation Results

Simulation results for the Phase II smart ventilation scheme with TMY3 Orlando weather data suggested 45 L/s average annual fan flow, an increase from that of the Phase I smart ventilation scheme of 37 L/s. Total annual ventilation averaged 46 L/s. Along with the increased flow, results suggested an improved annual RE, which averaged 1.01 and reached a maximum of 3.63 for a single hour, still below the 5.00 threshold suggested by Standard 62.2. The Phase II Scheme simulation results are displayed graphically in Figure 4.

Simulated seasonal differences in the sensible and latent ventilation loads between the constant fan and the Phase II smart ventilation scheme are presented for summer in Table 7. This simulation suggests the revised smart ventilation scheme reduces sensible cooling load by 97 W/hr and moisture load by 0.04 kg/h.

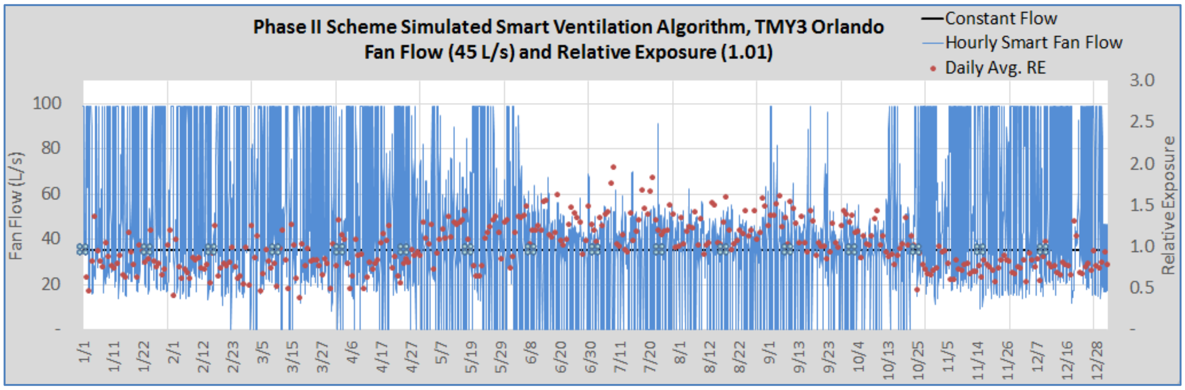

Figure 4: Phase II smart ventilation scheme simulated hourly average fan flow and daily average RE.

The Phase II ventilation loads and fan power are converted into energy impacts as shown in Table 8. The power use of the larger fan increased from 59 Watts to 114 Watts in the Phase II scheme. While this increase in fan energy will negatively impact overall savings, the primary intent of the experiments was to investigate impact of ventilation flow modulation.

Table 7: Simulated ventilation load and fan power: Phase II scheme and continuous ventilation.

Season/ Period	Sensible (W/h)			Latent (kg/h)			Fan Power (Average Watts)			Average	
	Fixed	Smart	Δ	Fixed	Smart	Δ	Fixed	Smart	Δ	Flow (L/s)	RE
Summer[a]	73	(23)	97	0.88	0.82	0.06	40	41	(1.38)	36	1.19
Non-Summer Cooling[b]	41	6	35	0.18	0.14	0.04	40	28	11.88	24	1.15
Non-Summer Floating[b]	270	(504)	234	(0.03)	(0.01)	(0.02)	40	80	(40.46)	69	0.66
Heating[c]	598	(440)	161)	(0.82)	(0.61)	(0.21)	40	30	9.97	26	1.25
Annual										45	1.01

[a] The period between May 1 and Oct. 31.

[b] The hours outside of the summer period when the outdoor air temperature falls within set parameters – Cooling >22°C; Floating ≤22°C, ≥10°C.

[c] The hours when outdoor air temperature falls below 10°C.

Table 8: Simulated space conditioning energy use: Phase II scheme and continuous ventilation.

Season/ Period	Sensible (kWh)			Latent (kWh)			Fan (kWh)			Total Savings	
	Fixed	Smart	Savings	Fixed	Smart	Savings	Fixed	Smart	Savings	(kWh)	%
Summer[a]	140	(46)	186	397	380	17	175	181	(6)	196	28
Non-Summer Cooling[b]	20	3	17	21	16	5	44	123	(78)	(56)	-65
Non-Summer Floating[b]							117	352	(235)	(235)	-200
Heating[c]	232	170	62				12	131	(119)	(57)	-23
Annual	392	128	264	418	396	22	349	787	(438)	(152)	-13

[a] The period between May 1 and Oct. 31.

[b] The hours outside of the summer period when the outdoor air temperature falls within set parameters – Cooling >22°C; Floating ≤22°C, ≥10°C.

[c] The hours when the outdoor air temperature falls below 10°C.

4.2 Phase II Laboratory Results: 2017 Cooling Season

The Phase II scheme was implemented into the FRTF smart-controlled building May 1, 2017. Measured monthly energy savings are provided in Table 9, and average fan flow, RE, and indoor and outdoor conditions in Table 10. Although the results are limited to three months, the smart ventilation algorithm with the modified scheme and more powerful fan delivered savings far superior to the prior scheme, generating measured 12.4% AC savings in May (89 kWh/month, 3.0 kWh/day), 8.8% in June (73 kWh/month, 2.4 kWh/day), and 8.7% in July (88 kWh/month, 2.9 kWh/day), averaging 9.8% AC savings for the total period.

Table 9: Measured energy use during cooling and floating periods for the Phase II scheme

Month	**Cooling Energy (kWh)**			**Fan Energy (kWh)**			**Total Energy (kWh)**			
(n = days of good data)	**Fixed**	**Smart**	**Savings**	**Fixed**	**Smart**	**Savings**	**Fixed**	**Smart**	**Savings**	**% Savings**
May (n=22)	719	630	89	29	36	(7)	748	666	82	11.0%
Jun (n=22)	822	749	73	29	20	8	851	770	81	9.5%
Jul (n = 26)	1,012	924	88	29	26	2	1,040	950	90	8.6%
Average	851	768	83	29	27	1	880	795	84	9.6%

Table 10: Measured conditions during cooling and floating periods for Phase II scheme.

Month (n = days of good data)	**Smart Flow (L/s)**	**Smart RE**	**Outdoor OA Inlet Temp. (°C)**	**Control Indoor Temp. (°C)**	**Smart Vent Indoor Temp. (°C)**	**Outdoor Air Inlet Dew Point (°C)**	**Control Indoor RH**	**Smart Vent Indoor RH**
May (n=22)	43	0.99	24.7	24.4	24.4	4.2	49.1%	50.4%
Jun (n=22)	34	1.10	26.8	24.4	24.6	15.6	52.3%	52.4%
Jul (n = 26)	31		1.27	24.4	24.5	16.3	49.0%	49.3%

The average indoor relative humidity in May was slightly higher in the smart building than the control, but overall the RH in the smart ventilation building was more closely aligned with that in the constant flow building than it was in Phase I.

The average daily profile for June is highlighted in Figure 5, with ventilation scheme savings at 11.3%. The increased fan flow in the smart ventilation building during the morning hours has little impact on relative humidity while still achieving impressive energy savings. The AC energy savings of the smart ventilation scheme are more pronounced during midday, when the outdoor temperature rises and the fan flow is reduced.

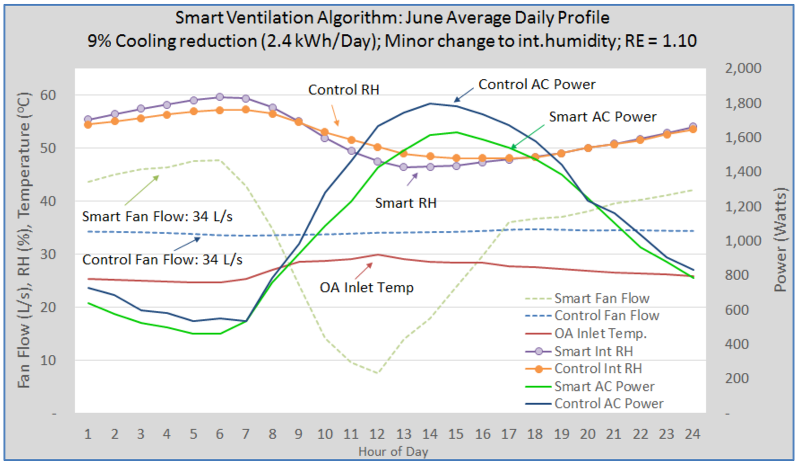

Figure 5. The June average day profile summarizes Phase II scheme performance.

5. SIMULATED RESULTS FOR OTHER U.S. CLIMATES

To estimate the ability of the smart ventilation algorithm to reduce space conditioning energy in other climates, whole building energy simulations were conducted. The National Renewable Energy Laboratory's (NREL) BEOpt software, which uses the EnergyPlus simulation engine, was used. NREL provided a customized input capability for BEOpt version 2.6.0.1 that allowed for hourly specification of total infiltration rate and fan energy. The FSEC FRTF laboratory was modeled to serve as the test building, with a few changes to envelope and mechanical system components to create a single building representative of average new construction in different climates. These include walls insulated to RSI 3.24 (K. m^2/W), RSI-6.5 ceiling insulation, low-e argon fill windows, a COP_{cool} 4.7_{heat} heat pump, and a balanced ventilation system with no heat recovery.

Hourly total infiltration rate and fan energy were obtained using a developed simulation tool. TMY3 data was input for each of five representative climates, and algorithm parameters adjusted to ensure RE compliance. The parameters used for each climate are identical to the Phase II scheme values shown in Table 6, except for target flows and high/low temperature flow lockouts that were determined iteratively for each climate. The 62.2 Standard continuous mechanical ventilation flow for each climate was assigned for heating and cooling flow targets, and the 99 L/s flow limit of the Phase II laboratory fan was assigned for the floating target. Table 12 shows the simulated space conditioning energy for each climate modeled, along with the flow target used. Results show that across a variety of climates, space conditioning savings of > 5% can be achieved with the simple approach used to set algorithm parameters. While increased fan energy for the smart ventilation scheme erodes savings, additional optimization of the fan choice could help maximize savings.

Table 12: Heating/cooling flow targets: energy savings & relative exposure for multiple climates.

Location	Heating/Cooling Flow Target (L/s)	Annual Average RE	Max Hourly RE	Annual Space Conditioning Energy Savings (kWh/%)	Annual Space Conditioning Energy + vent fan Savings (kWh/%)
Orlando, FL	31	1.0	3.6	211 / 8.0	155 / 5.2
Atlanta, GA	30	1.0	3.6	182 / 5.4	117 / 3.2
Minneapolis, MN	28	1.0	3.2	777 / 5.8	753 / 5.5
Chicago, IL	29	1.0	3.2	621 / 6.9	592 / 6.3
Phoenix, AZ	31	1.0	3.3	311 / 6.8	229 / 4.6

6. APPLICATION TO RESIDENTIAL VENTILATION IN EUROPE

Ventilation standards in Europe vary considerably across the European Union (EU) member states (Kunkel et al., 2018). Each country has its own ventilation standard, often integrated into energy standards. For example in France and Belgium buildings may use Demand Controlled Ventilation (DCV) using CO_2 and/or humidity sensing as a surrogate for occupancy and pollutant concentration to obtain credit in the energy code. Advances in sensor technology are now allowing control based upon Volatile Organic Compounds (VOCs) with a variety of smart ventilation approaches within European standards (Guyot, Walker and Sherman, 2018).

In the United Kingdom and Europe, ventilation compliance calculations tend to use room-by-room ventilation requirements rather than the total specified in 62.2 (Dimitroulopoulou, 2012). This is because it is not typical to connect all the rooms in homes with forced air ventilation systems in Europe. However, when evaluated on a whole building basis, the ventilation requirements usually are about 0.5 ACH (more than ASHRAE Standard 62.2). Older buildings in the EU typically use exhaust ventilation while newer construction often utilizes balanced mechanical ventilation with efficient Energy Recovery Ventilators (ERVs) that recover both sensible and latent heat. Another relevant difference in the European building stock is that new residential dwellings are often very tight and well insulated as the *Passivhaus* standards see increasing application.

Although a detailed assessment of the potential of a weather-responsive scheme is not possible due to variations due to prevailing standards and building types, we performed a preliminary assessment. Although the ERVs often used with high performance are quite efficient when rated at 0 ºC, their efficiency falls off steeply below freezing given the need for defrost cycles. Thus, a weather-adaptive scheme has potential to significantly improve ERV effectiveness during winter conditions. During summer nights when outdoor conditions are potentially helpful to meet cooling loads, such a system can help to avoid more energy-intensive vapor compression air conditioning using ventilation *without* heat recovery. Also, most DCV strategies in the EU attempt to limit condensation potential and the described method can help limit outdoor moisture sources. Finally, within the minimization of the sum of square of deviation from ideal values, it is potentially possible to optimize multiple signals (e.g. temperature, enthalpy, CO_2 and/or VOC) at once.

In an illustration below, we simulate a high performance home, based on previous simulation work done with the BEopt simulation to evaluate Near Zero Energy Buildings (NZEBs) in Europe (D'Agostino and Parker, 2018). We assume a very well insulated 119 m^2 building is very tight (0.6 ACH @ 50 Pa), but with mechanical ventilation to provide 0.5 ACH or 40.3 L/s constant in the base case. Because of the efficient ERV, the impact of ventilation loads sensible & latent are ~ 6 L/s if there had been no heat recovery. Simulated heating and cooling energy in Milan, Italy in the base case configuration showed a total heating and cooling energy budget of 12.9 kWh/m^2 (heating: 1280 kWh, cooling 261 kWh). Simulation parameters are given in the original work.

We then examine how providing this target flow rate can result in space heating and cooling energy savings when using the weather responsive scheme described above with the constraint that RE >= 1.0. We simulated this case in five different European climates using hourly IWEC files: Frankfurt, Germany (cold), Lisbon, Portugal (mild), Milan, Italy (temperate), Stockholm, Sweden (very cold) and Seville, Spain (hot-arid). Given the tight building simulated, we assumed that the flow of the ERV could only be reduced to 25% of the standard value (40 L/s) during the "turn-down" conditions. Results are shown below:

Table 14. Heating/cooling flows, energy savings & relative exposure for European climates.

Location	Heating/Cooling Flow Target (L/s)	Annual Avg & Max RE	Temp Turndown Heat /Cool	Annual Space Heating Energy Savings (kWh/%)	Annual Space Cooling Energy Savings (kWh/%)
Frankfurt, DEU	40.3	1.0 / 4.9	-2.3°/27.8 °	32 / 2.4%	26 / 16.1%
Lisbon, PRT	40.3	1.0 / 4.0	5.6 °/27.8 °	-9 / -75.0%	111 /17.6%
Milan, ITA	40.3	1.0 / 4.8	-6.1 °/28.3 °	37 / 2.9%	44 / 16.9%
Stockholm, SWE	40.3	1.0 / 4.8	-9.4 °/26.1 °	64 / 2.4%	44 / 35.8%
Seville, ESP	40.3	1.0 / 5.0	4.4 °/32.2 °	-9/ -100.0%	120 /12.1%

It will be noted from the results above that the savings are small in magnitude for heating given the efficiency of the ERVs and the very low level of space heating with the highly insulated building. Even so, an approximately 2-3% heating energy savings can be obtained in heating dominated climates by shaping the introduction of ventilation air to the diurnal conditions outdoors. This may be conservative since no effect of ERV defrost below freezing was simulated. We did see that the very efficient ERV served to reduce the heating savings of the weather-sensitive ventilation scheme.

However, the potential for cooling was much greater. Reductions to space cooling are seen in all locations given the simulated ability of providing high levels of ventilation air during advantageous outdoor conditions in cooling-dominated climates such as Seville or Lisbon. Very small increases to heating are seen in such climates, but were dwarfed by the cooling energy savings which were large in magnitude.

7. CONCLUSIONS

A weather-adaptive algorithm for smart ventilation control was developed that interprets immediate and diurnal patterns of measurements of outdoor temperature and moisture and varies ventilation to minimize sensible and latent load impacts. Simulations were conducted to tune the algorithm with differing flow targets and seasonal adjustment factors to maximize heating and cooling energy savings compared to continuous ventilation. The scheme maintains similar indoor relative humidity, and Relative Exposure (RE) targets with respect to ASHRAE Standard 62.2. Simulation suggested that compliant annual average and acute RE could be maintained with 73% sensible and 9% latent load reductions during cooling conditions.

A ventilation system controlled by the “smart” algorithm was implemented in one of two side-by-side identical laboratory test homes with the control home operating with continuous mechanical ventilation. Average cooling energy savings of 10% were measured during three months of evaluation due to the reduction in sensible and latent load created by the advanced controls. A fan with a maximum flow capacity three times greater than the continuous fan was required to achieve these savings. Added fan energy needs to be carefully considered so as not to erode potential savings. The experimental testing utilized sensor-based measurements of occupancy and weather parameters collected at the actual test homes, but commercialized systems could leverage both weather and interior data available from internet-connected devices such as smart thermostats.

Whole building energy simulations were conducted and predict at least 5% space conditioning energy savings across differing climates in the U.S. assuming the ventilation fan is optimized for energy savings. A preliminary analysis was also completed for several varied European climates using a highly insulated, tight residential building prototype with a very efficient ERV as the baseline. Analysis showed that the heating savings were much lower after accounting for the ERV efficiency – typically 2-3%. However, cooling energy savings remained significant – on the order of 12-36% and were potentially large in cooling-dominated climates.

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