Energy and Indoor Air Quality Impacts of DOAS Retrofits in Small Commercial Buildings

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ABSTRACT

Heating, ventilating and air-conditioning (HVAC) typically accounts for 30% to 50% of commercial building energy use. Small commercial buildings often use oversized and inefficient rooftop air handling units (RTUs) to provide both air conditioning and ventilation. A conversion strategy to reduce energy consumption is the installation of a very high efficiency dedicated outdoor air system (DOAS) to provide ventilation with a separate heat pump system to provide heating and cooling. Decoupling the heating and cooling from ventilation allows for improved energy efficiency and control of space conditions. Upgrades to mechanical systems can also improve the indoor air quality (IAQ) and comfort through control of carbon dioxide (CO_2) concentrations, dry bulb temperature, and relative humidity (RH).

A pilot study of eight buildings was conducted to investigate the potential benefits of replacing existing RTUs with high efficiency heat recovery ventilators (HRVs) and air source heat pumps in the Pacific Northwest. This report contains results for a subset of seven buildings for which data is available. The building energy use before and after the conversion was determined using utility data, energy modeling and monitoring. Indoor environmental conditions were measured at hourly intervals for up to one year post-conversion using CO_2, temperature, and RH sensors. The data was analyzed to determine changes in energy use and IAQ before and after the conversion.

This paper presents the pilot building results pre- and post-conversion. While several factors need to be in place to ensure optimal performance and cost effectiveness, the pilot shows that replacing RTUs with DOAS systems in existing commercial buildings can both reduce energy use as well as improve indoor environmental conditions. This conversion type is viable for a wide variety of building types and scale-up of the retrofits has the potential to significantly improve a previously underserved segment of the building stock.

INTRODUCTION

Buildings account for approximately 40% of the total energy use in the United States (Sanders et al. 2010). In the commercial building segment, Heating, Ventilating and Air-Conditioning (HVAC) typically accounts for 30% to 50% of the energy end use (CBECS 2012). Small commercial buildings will often utilize a packaged rooftop unit (RTU) system that includes direct expansion (DX) cooling and natural gas heating to provide space conditioning and ventilation air from a single source. This coupling of the ventilation and air conditioning in a single system results in operational inefficiency. In addition, this equipment tends to be oversized, and as it reaches the end of its service life, contractors simply replace like for like. These practices, which are characteristic of small commercial buildings, compound the inefficiencies inherent in this type of HVAC system. Anecdotal evidence also indicates that outdoor ventilation air dampers in existing systems are often closed in these buildings, leading to poor indoor air quality.

An alternative design approach is to decouple the ventilation and air conditioning using a dedicated outdoor air system (DOAS) for ventilation and a heat pump system for space conditioning. The existing packaged RTU can be replaced with a DOAS system during planned retrofits, and can provide significant savings through reductions in both fan energy and energy used for conditioning ventilation air. If ventilation air is provided with an intelligent, very high efficiency heat or energy recovery ventilator (HRV or ERV), and if the heating and cooling functions are provided by right-sized, high efficiency systems, annual HVAC energy savings in existing small commercial buildings can exceed 50% over the existing system. The use of a DOAS system also allows for possible improvements to indoor air quality compared to the standard RTU design.

A pilot study sponsored by the Northwest Energy Efficiency Alliance (NEEA) was undertaken to predict and measure the energy savings from replacing packaged RTU systems with high-efficiency DOAS and heat pump systems in small commercial buildings throughout the Pacific Northwest. The target building sector for the pilot projects discussed in this paper is existing small commercial buildings (ideally under 25,000ft^2 (2,325m^2)) in selected occupancies (small office, retail, schools, restaurants, and small assembly). The small commercial building sector (<50,000ft^2 (4,650m^2)) overall comprises over half of the commercial building floor space in the Pacific Northwest (NEEA 2014). The 2012 CBECS data (table B39) indicates that 62% of all commercial building floor area in the United States in buildings smaller than 25,000ft^2 (2,325m^2) have a packaged heating system. This reflects a significant opportunity for improved HVAC systems performance in a market segment currently underserved by the standard practice of replacing like-for-like during a retrofit scenario.

This paper presents the results of predicted energy savings from calibrated whole-building energy modeling for the seven buildings analyzed for this paper. Monitoring data will also be presented to demonstrate the impact of retrofits on indoor air quality and comfort.

METHODOLOGY

Pilot Building and Conversion Descriptions

The pilot study recruited buildings intending to undergo a retrofit of an existing RTU system with a standard like-for-like replacement approach. A DOAS and heat pump (HP) system retrofit was proposed as an alternative and design assistance was provided to the contractors as required. The DOAS system was selected to provide the required building ventilation and the HP designed to meet the calculated heating and cooling loads. In some instances, this resulted in a “right-sizing” of the equipment which could also add to energy savings. The HRV used in all pilots had a minimum sensible effectiveness of 82% as certified by the Passive House Institute. The air source heat pumps selected varied by site and were a mixture of ductless split systems, ducted heat pump systems and Variable Refrigerant Flow (VRF) systems.

Descriptions of the buildings included in the pilot are provided in Table 1. The study buildings discussed in this work included five offices and two restaurants in Oregon, Washington, and Montana. All buildings included packaged RTUs that were intended to be replaced with like systems but instead were retrofitted with a DOAS HRV system with heat pump heating/cooling as an alternative.

Details of the pre-conversion and post-conversion HVAC systems are provided in Table 2. The building enclosure construction and operation was generally not changed during the conversion process.

Table 1: Pilot project building information

#	Location	Building Type	Occupied Hours	Conditioned Area, ft^2 (m^2)	Building Description
1	Portland, OR	Office	M-F, 7am-6pm	11,600 (1,080)	Combination of private offices, meeting/ conference rooms, and amenity spaces occupying the second storey of a heritage building.
2	Corvallis, OR	Office	M-F, 8am-5pm	13,200 (1,225)	Single storey office building with private offices around the perimeter and a large central conference room; also contains laboratory space and storage.
3	Corvallis, OR	Restaurant	Su-W, 11am-11pm Th-Sa, 11am-12am	1,600 (162)	Single storey pizza restaurant with basement storage and office. Seating area and take-out counter located on end of connected storefront unit.
4	Libby, MT	Office w/ Garage	M-F, 9am-5pm	5,600 (520)	Single storey office with attached truck garage located in a rural town center.
5	Portland, OR	Restaurant	M-F, 11am-9pm Sa-Su, 9am-9pm	1,150 (110)	Single storey restaurant with seating area located in the middle of a connected storefront unit.
6	Seattle, WA	Office	M-F, 9am-5pm	5,900 (550)	Third storey of a 3.5 storey mixed-use office and retail building in a strip commercial block in downtown Seattle.
7	Seattle, WA	Office	M-F, 8am-5pm	24,300 (2,260)	Two storey combined office and airport terminal building.

Table 2: Comparison of pre-conversion and post-conversion HVAC systems

#	Pre-Conversion System	Post-Conversion System
1	Nine packaged rooftop units with 519,000 Btu/h (152 kW) gas-fired heating and 215,000 Btu/h (63 kW)	Four high-efficiency HRVs for ventilation; 215,000 Btu/h (63 kW) heating, 192,000 Btu/h (56 kW) cooling, variable

	DX cooling for ventilation, heating, and cooling. RTUs operate 7 days, 7 AM to 7 PM	refrigerant flow (VRF) heat pump system with eight indoor units for zone-level heating and cooling. HRVs operate 7 days, 7 AM to 7 PM; VRF heat pump system operates 24/7 to maintain setpoint/setback.
2	Five packaged rooftop HVAC units with gas-fired heating and DX cooling. Two of the units serve the section of building included in the conversion with a combined 160,000 Btu/h (47 kW) heating and 70,800 Btu/h (21 kW) cooling. RTUs operate 7:15 AM to 5:00 PM, M-F	HRV conversion applies to 2 out of 5 zones, approximately 27% of the conditioned floor area. One high-efficiency HRV for ventilation; HRV operates 7:15am to 5:00pm M-F, otherwise off. Multi-zone ductless split heat pump with one outdoor unit (108,000 Btu/h heating (32 kW), 96,000 Btu/h (28 kW) cooling) and two indoor units for zone-level heating and cooling.
#	Pre-Conversion System	Post-Conversion System
3	One packaged rooftop unit with gas-fired heating and DX cooling for ventilation, heating, and cooling. Kitchen exhaust fans remove process loads and a swamp cooler provides make-up air. RTUs operate 7 days, 7 AM to 12 AM	One high-efficiency HRV for ventilation; 4 mini-split heat pumps for heating (141,600 Btu/h (41 kW)) and cooling (130,000 Btu/h (38 kW)). Kitchen exhaust fans remove process loads and swamp cooler provides make-up air. HRVs operate 7 AM to 12 AM Sunday through Wednesday and 7AM to 1AM Thursday through Saturday; heat pump system operates 24/7 to maintain setpoint/setback.
4	Two electric boilers for heating (273,000 Btu/h (80 kW)) with office baseboards and garage unit heaters. One packaged rooftop unit with HP for ventilation and 77,000 Btu/h (23 kW) cooling of the office. Two swamp coolers for cooling the garage. RTU operates 7 days to maintain setpoint/setback in the summer only. Boilers operate 24/7 to maintain setpoint/setback.	One high-efficiency HRV for ventilation; 2 outdoor HPs (total 54,000 Btu/h (16 kW) heating/cooling) with wall heads in offices and ducted units in garage. Boilers remain for supplemental heat. HRV operates 7 AM to 6 PM M-F at design flow and minimum flow otherwise, boost mode used when garage door activated; heat pump system operates 24/7 to maintain setpoint/setback.
5	One packaged rooftop unit with gas-fired heating and DX cooling for ventilation, heating, and cooling. Kitchen exhaust fans remove process loads and a swamp cooler provides make-up air. RTU operates 7 days, 7 AM to 12 AM	One high-efficiency HRV for ventilation; mini-split heat pumps for heating and cooling. Kitchen exhaust fans remove process loads and a swamp cooler provides make-up air. HRV operates 6AM to 12AM M-F, 7 AM to 12 AM Sa-Su; heat pump system operates 24/7 to maintain setpoint/setback.
6	One packaged RTU providing DX heating/cooling, and ventilation for the top 3 floors of the building	One high-efficiency HRV for ventilation; VRF system with 1 outdoor HP (188,000 Btu/h (55 kW) heating, 168,000 Btu/h (49 kW) cooling) and wall heads indoors to

	including the single storey included in the conversion. RTU operates 7 days to maintain setpoint/setback in the space.	provide air conditioning for the single storey included in the conversion. HRV operates in DCV mode from 8 AM to 6 PM M-F with a minimum flow rate of 175CFM (83 L/s) 24/7. The HP system operates 24/7 to maintain setpoint/setback.
7	Three constant volume rooftop multizone air handlers with gas-fired heating (1,105,000 Btu/h (325 kW)) and DX cooling (914,000 Btu/h (270 kW)) for ventilation, heating, and cooling. RTUs operate M-F, 7 AM to 6 PM	Three high-efficiency HRVs for ventilation; VRF heat pump system (323,000 Btu/h (95 kW) heating, 288,000 Btu/h (85 kW) cooling) with a mixture of ductless and ducted indoor units for zone-level heating and cooling. HRVs operate M-F, 7 AM to 6 PM; VRF heat pump system operates 24/7 to maintain setpoint/setback.

Modeling and Monitoring Methodology

Energy models were prepared for each building in the study using DesignBuilder. Models were calibrated using monthly utility bill data and actual meteorological year (AMY) weather files to match the year of utility bill analysis. The calibration was performed per ASHRAE® Guideline 14 for calibration of whole building energy simulation to monthly utility data with Coefficient of Variation of the Root Mean Squared Error (CVRMSE) < 10% and Normalized Mean Bias Error (NMBE) < 5%. An example of the calibrated to actual energy usage information is provided in Figure 1.

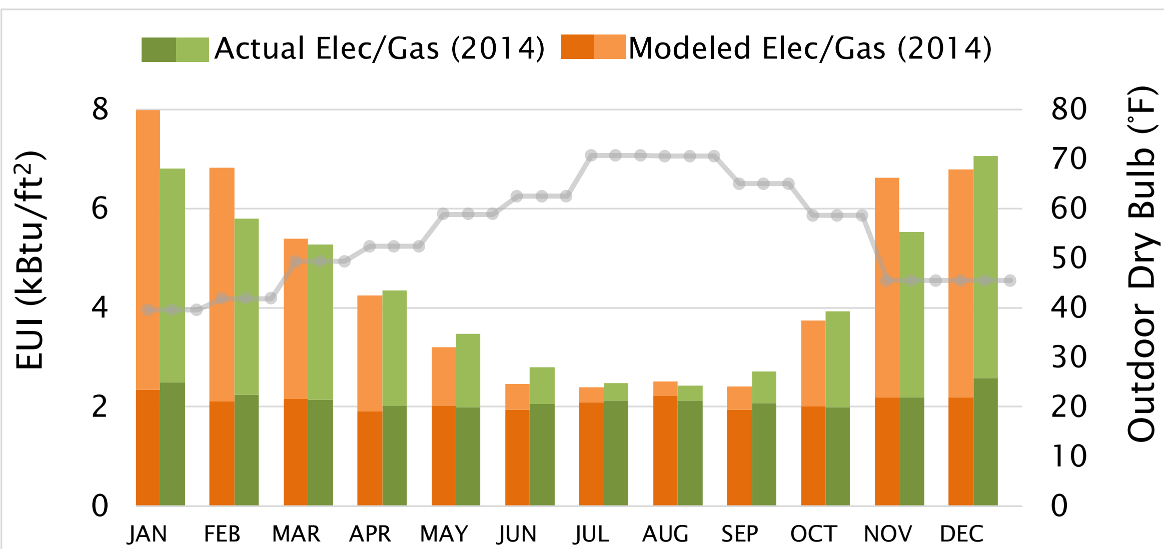


Figure 1: Example of a comparison of calibrated pre-conversion AMY model results to actual 2014 monthly utility bill data for Building #2 ($CVRMSE_{gas}$=6.42, $NMBE_{gas}$=-2.07, $CVRMSE_{elec}$=2.08, $NMBE_{ele}C$=3.77)

The energy models were then modified to use typical meteorological year (TMY) data to produce a pre-conversion baseline model for energy use comparison. The post-conversion model was then created by changing the HVAC system to match the post-conversion design. The predicted energy savings were determined by comparing the output of the pre-conversion baseline and post-conversion energy models using TMY weather files for the appropriate locations. This procedure is in alignment with the process outlined by the International Performance Measurement and Verification Protocol (IPMVP) Option D: Calibrated Simulation.

Electrical sub-metering equipment was installed on key building components to troubleshoot operation and for calibration of energy end use in the post-conversion models. It was used to ensure modeled system operation, such as HRV energy and flow, matched the observed conditions on site. The sub-metering was performed using energy monitoring equipment with current transducers installed in the site electrical panels. Data was recorded at 1-hr intervals for offline analysis.

Utility data is collected for a minimum of one year post-conversion, and in some cases, used for an interim calibration of the model and comparison of modeled to actual data to date. At the time of writing this paper, half of the projects had just reached or were nearing the end of their one year post-conversion period, while the others will reach this milestone in 2018.

Indoor environmental quality measurements were made using combined carbon dioxide, temperature, and relative humidity sensors. Sensors were placed in a subset of rooms in each building to capture key operation characteristics. Rooms monitored in office buildings included private office areas, open office areas, conference/meeting rooms, and/or lunch/breakrooms.

Data was collected both pre-conversion (when possible) and post-conversion to allow for comparison of building performance. Monitoring equipment was installed as soon as the project was confirmed as a pilot and typically lasted 2-4 months prior to installation of the new HVAC system. Post-conversion monitoring is scheduled for a minimum of one year, followed by model calibration to actual post-conversion utility data.

Building enclosure airtightness testing was performed both pre- and post-conversion to determine the impact of the HVAC conversion. The test procedure was performed in general conformance with the current US Army Corps of Engineers (USACE) test protocol. Prior to the testing, HVAC equipment was shut off with the dampers in their normal ‘off/closed’ position, all interior doors were propped open, and all exterior doors and windows were closed and locked. Computer-controlled fan-door systems were used to pressurize/ depressurize the building and measure and collect pressure data. Test pressures ranged from 20Pa to 80Pa during testing

RESULTS

Energy Modeling

The pre-conversion and post-conversion modeled (TMY) annual energy consumption is shown for each building in Figure 2. The solid bars represent the pre-conversion results and the patterned bars represent the post-conversion results. Data is separated to include the office buildings on the left and the restaurants on the right to account for differences in scale of energy consumption. The data is also summarized in Table 3.

All buildings in the study were predicted to consume less energy after the conversion. The conversions impact only the HVAC system and do not account for potential improvements from modification to other building characteristics such as lighting or process loads. Equipment and Process loads, such as lighting, or cooking, can add considerably to the energy use in the building and reduce the potential savings as a percentage of the total building energy consumption, especially in the case of the restaurants due to the high process loads used for cooking. The overall savings is predicted to range between 15% and 54% of the total annual energy consumption. When the HVAC system is isolated for comparison the savings figures are much larger with the range being 22% to 71% reduction.

The greatest energy reduction in all buildings was predicted to occur for the heating energy. This is a result of the heat recovery in the post-conversion model reducing the energy required to condition outdoor air in the winter. Heating energy savings also result from the higher efficiency system installed compared to the baseline. The heat pumps used have a typical COP of >3.0 compared to the use of natural gas heating in most pre-conversion RTUs. Energy savings also consistently result for fans loads comparing the post-conversion to the pre-conversion models. This is a result of the reduced fan size from decoupling of the ventilation system from the space conditioning which allows for lower total airflow rates in the building. The very high efficiency of the HRV fans also contributes to this reduction.

The largest absolute savings are predicted for the restaurant buildings due to the significant heating load required for conditioning outdoor make-up air. The average reduction in HVAC energy use is predicted to be 22 kBtu/ft^2 (69 kWh/m^2) (46%) for the office buildings and 151 kBtu/ft^2 (477 kWh/m^2) (62%) for the restaurants. The amount of energy saved from the HVAC system conversion is dependent on a number of variables including space use, pre-conversion design, and weather.

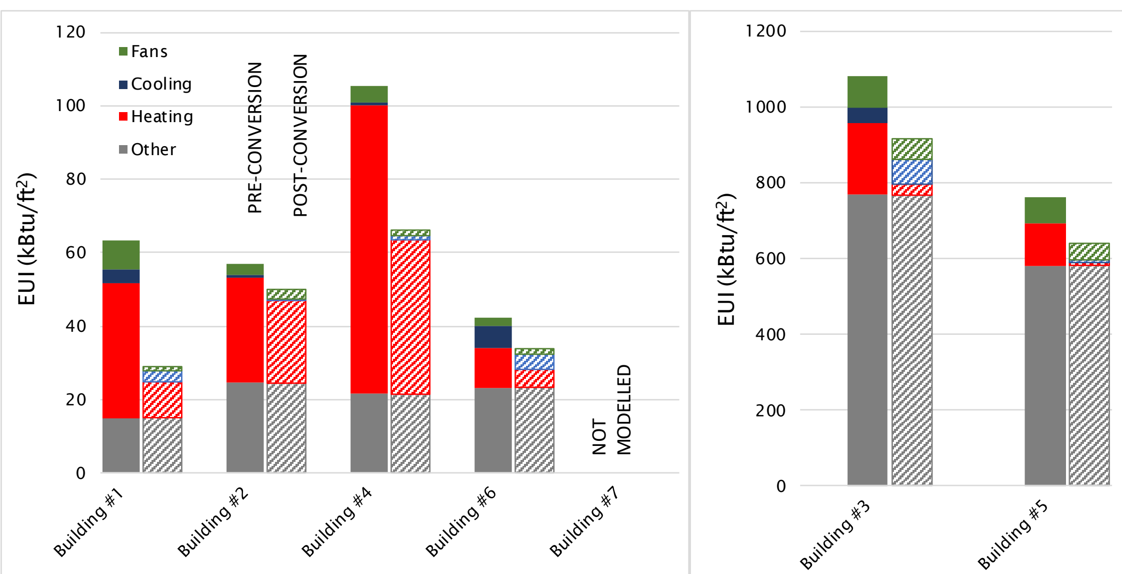


Figure 2: Comparison of pre-conversion and post-conversion energy consumption for office buildings (left) and restaurants (right)

Table 3: Comparison of pre-conversion and post-conversion energy modeling results

Project Number	Location	Occupancy	HVAC			Total		
			Pre, kBtu/ft^2	Post, kBtu/ft^2	Savings	Pre, kBtu/ft^2	Post, kBtu/ft^2	Savings

			(kWh/m^2)	(kWh/m^2)		(kWh/m^2)	(kWh/m^2)	
1	Portland, OR	Office	48 (153)	14 (44)	71%	63 (200)	29 (91)	54%
2	Corvallis, OR	Office	33 (103)	25 (80)	22%	57 (180)	50 (158)	13%[1]
3	Corvallis, OR	Restaurant	313 (990)	146 (461)	53%	1,082 (3,418)	914 (2,890)	15%
4	Libby, MT	Office/Garage	84 (265)	45 (141)	47%	105 (333)	66 (209)	37%
5	Portland, OR	Restaurant	193 (609)	58 (182)	70%	773 (2,444)	638 (2.017)	17%
6	Seattle, WA	Office	19 (60)	10 (33)	45%	42 (133)	34 (106)	20%
7	Seattle, WA	Office	TBD	TBD	TBD	TBD	TBD	TBD

The modeled pre-conversion and post-conversion GHG intensity was calculated for the buildings to determine reductions (Figure 3). Emissions factors used were the averages based on the state grid energy mix and included 0.091 lbs CO_2e/kBtu (0.14 kg CO_2e/kWh) in Oregon, 0.379 lbs CO_2e/kBtu (0.59 kg CO_2e/kWh) in Montana, and 0.066 lbs CO_2e/kBtu (0.10 kg CO_2e/kWh) in Washington (EPA 2017). The emissions factor used for natural gas was 0.116 lbs CO_2e/kBtu (0.18 kg CO_2e/kWh). The GHG intensity reductions vary significantly within the sample of study buildings depending on the energy savings, fuel sources, and location. The greatest savings as a percentage was for Building #1 (61%) as a result of fuel switching from natural gas heating to electric heating in a state with a low emissions electricity source (OR). All buildings in the study are predicted to reduce GHG intensity by over 15% compared to the baseline.

[1] **Note: The conversion of Building #2 included 2 of the 5 RTUs accounting for only 27% of the total floor area and would result in larger savings if a complete building conversion were to be performed.**

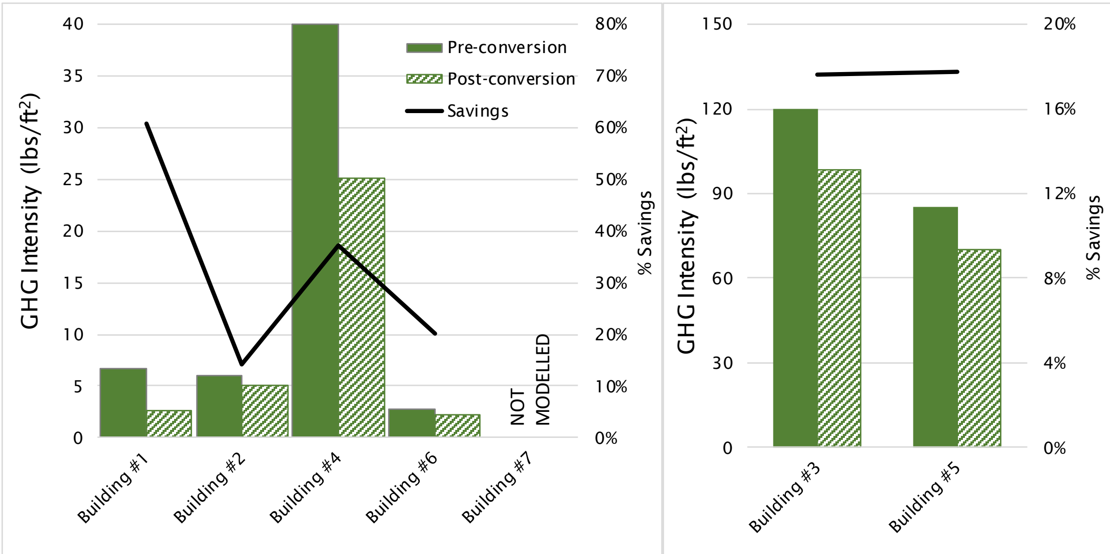


Figure 3: Comparison of pre-conversion and post-conversion GHG intensity for office buildings (left) and restaurants (right)

Enclosure Air Leakage Testing

The air leakage testing provided both qualitative and quantitative information for comparison between buildings. The use of smoke tracing during pressurization and depressurization allowed for a better understanding of where leakage was occurring. Common locations in a number of the buildings included windows, supply/return grilles, and mechanical penetrations. The leakage was found to occur predominantly around operable windows due to challenges with air seals. Airflow into or out of the supply/return ductwork both before and after conversion was attributed to leakage through dampers or from the existing ductwork. This was commonly found at washroom exhaust fans which typically had dampers that leaked during testing. The test in two of the buildings (#1 and #6) consisted of only a single floor in multi-storey buildings. In these cases, air leakage occurred through mechanical penetrations and shafts connecting the floors and represents leakage into other spaces within the building considered to be outside the test enclosure.

A summary of the pre- and post-conversion enclosure air leakage testing results is provided in Figure 4. A wide range of air leakage was found between the buildings both before and after implementing the HVAC conversion. The typical air leakage values were found to be approximately 0.2 to 0.5 cfm/ft^2 @75Pa (1.0 to 2.5 L/s·m^2). Building #3, a restaurant, was found to be an outlier with air leakage above 1.6 cfm/ft^2 @75Pa (8.1 L/s·m^2). This high leakage value was attributed to the kitchen ventilation equipment openings which were not taped off but rather left in normally closed positions during testing.

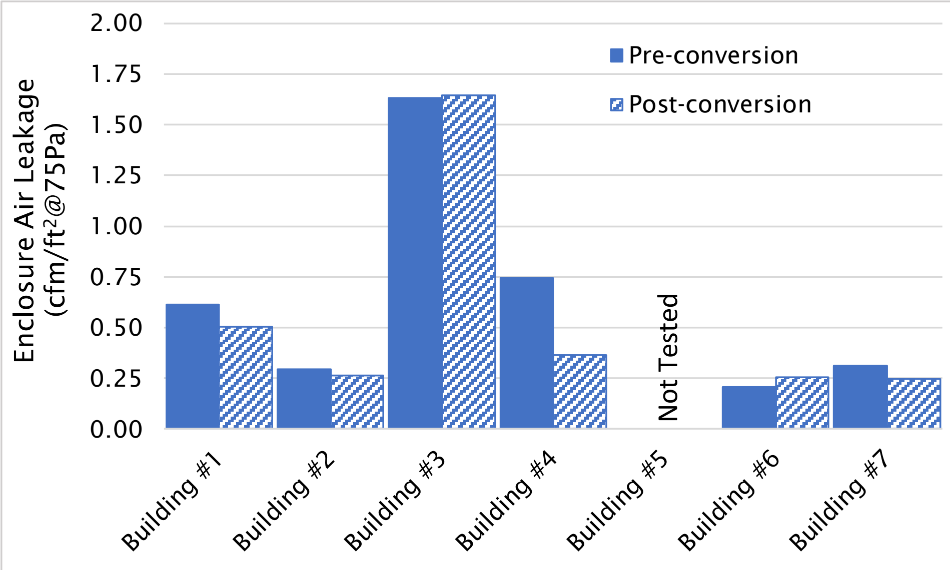


Figure 4: Comparison of pre-conversion and post-conversion enclosure air leakage testing results

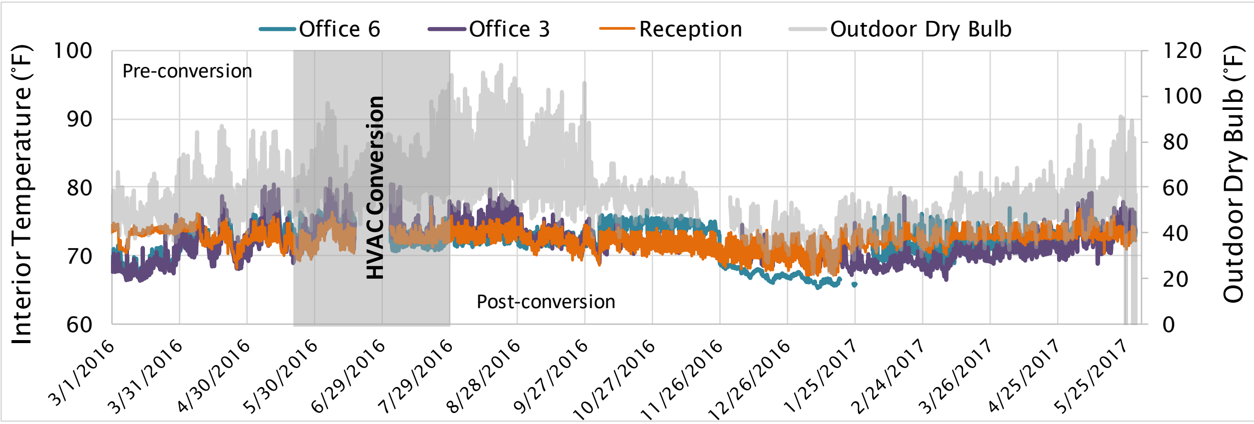
The measurements from post-conversion result are typically close to those from the pre-conversion testing. The most significant decrease (51%) in air leakage was measured in Building #4. This conversion included removal of two swamp coolers used to ventilate and cool the garage section of the building and reuse of the penetrations for supply and extract air from the HRV. A significant amount of airflow was observed through these opening in the pre-conversion test but this was eliminated in the post-conversion due to the increased tightness of the damper on the HRV ductwork which prevented leakage. The only building with a significant increase (23%) in air leakage after the conversion was Building #6. The increase in air leakage was attributed to difficulty sealing ductwork from the pre-conversion HVAC system that was disconnected but remained in place.

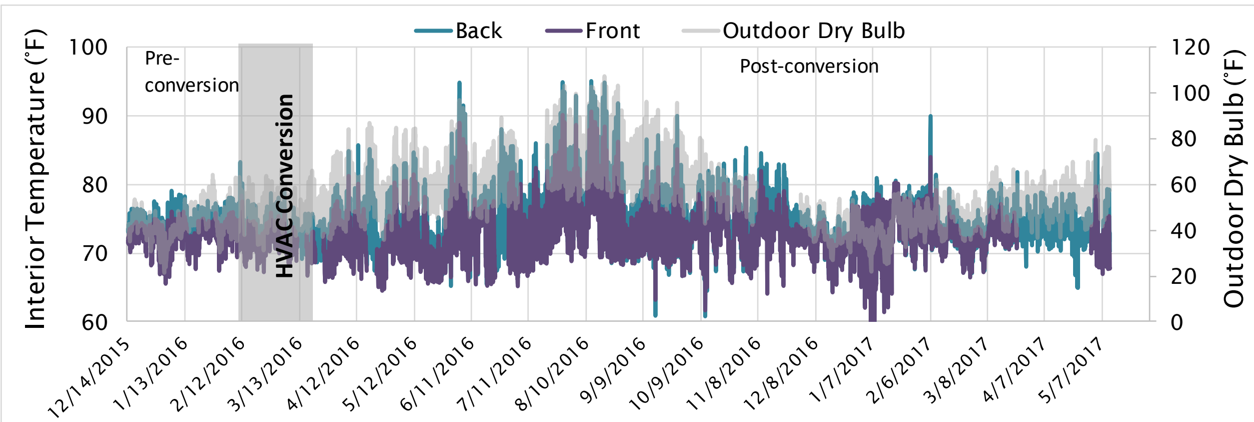
Indoor Environmental Quality

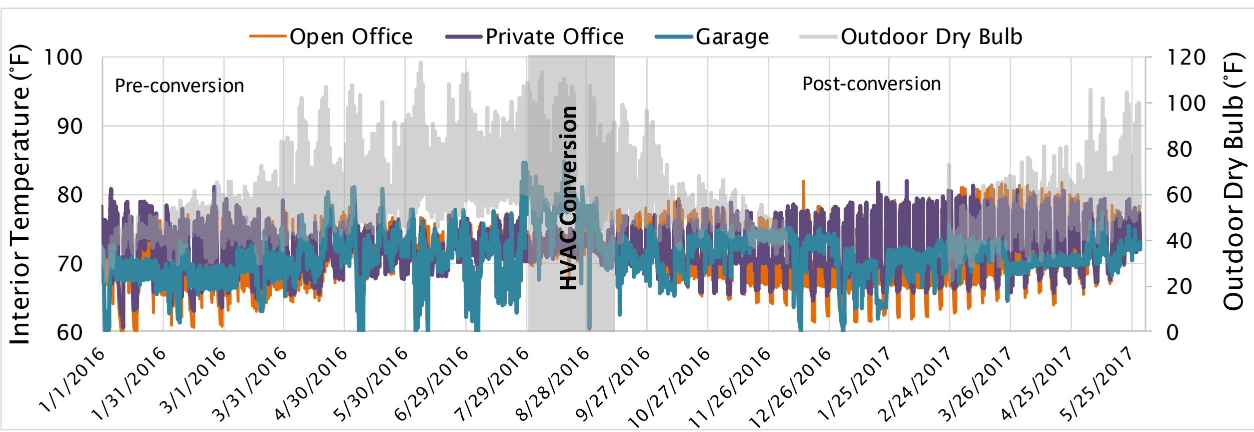
Indoor environmental quality sensors installed within the buildings during pre-conversion and post-conversion monitoring allow for troubleshooting of the system operation and confirmation that the HVAC equipment is maintaining the desired space conditions. The IEQ parameters in the buildings will be discussed in terms of both CO_2 concentrations and space temperature. Relative humidity was monitored in the spaces but was not found to be a primary concern in the commercial buildings and has not been included in this analysis.

Indoor Drybulb Temperature

The primary purpose of the temperature monitoring was to confirm the building setpoint and setback temperatures, as well as for use in troubleshooting and optimizing operations. Figure 5 shows examples of hourly temperature data collected for four of the study buildings to illustrate typical trends. The greyed-out section of data collection refers to the construction period, which typically included a commissioning phase. Building #1 and Building #6 do not have any pre-conversion data as they were empty prior to the renovation. Setpoint and setback temperatures varied with each building and were often adjusted by occupants after initial setup. They were typically in the range of 65°F to 75°F (18°C to 24°C).







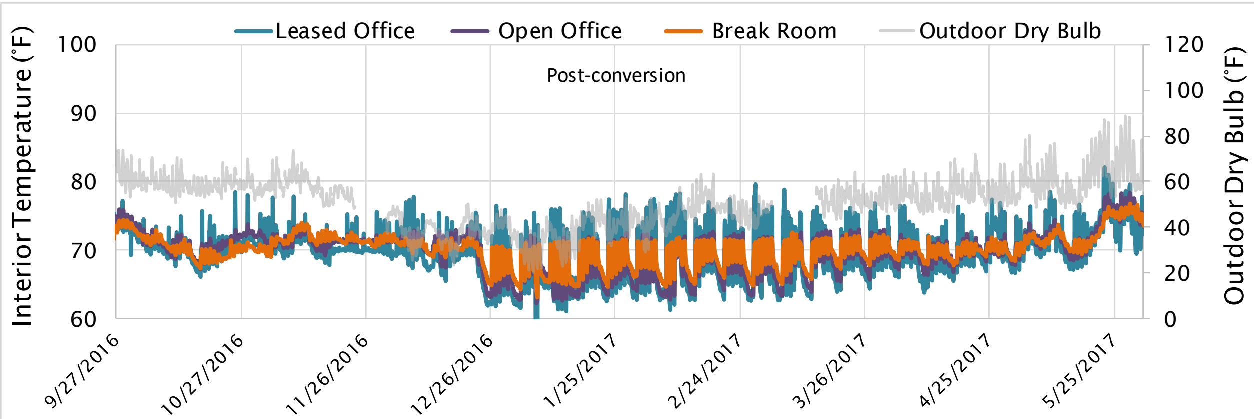


Figure 5: Examples of indoor temperature measurements in Building #2 (top), Building #3 (middle-top), Building #4 (middle-bottom) and Building #6 (bottom).

The general temperature readings for the office buildings show reasonable control of the space conditions with both the pre-conversion and the post-conversion systems. There is some indication that the post-conversion scenario provides tighter control of the space temperature, which could possibly be due to a combination of the improved system as well as re-adjustment of the settings. The data shows a trend of all spaces in each building having a similar temperature profile immediately following the conversion with subsequent deviation as the occupants acclimate to the new system and make adjustments.

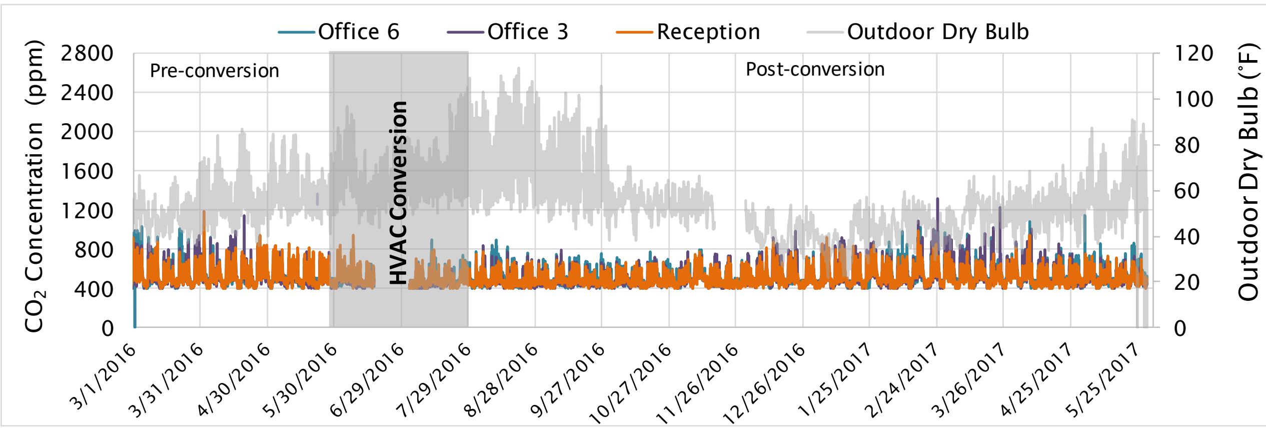
The data for Building #6 provides a good example of the impact of occupant adjustments to the system. The HP was originally set to hold the setpoint temperature at all times of the day and allow for the occupants to make manual adjustments. The control method was in place until the end of December 2016 at which point the HP controls were modified to allow for lower overnight setback temperatures (~63°F (17°C)). This was then found to require too long a time to heat the space in the morning due to the thermal mass of the enclosure (masonry) and a gradual increase in setback temperature can be seen in the adjustments from March 2017 to May 2017.

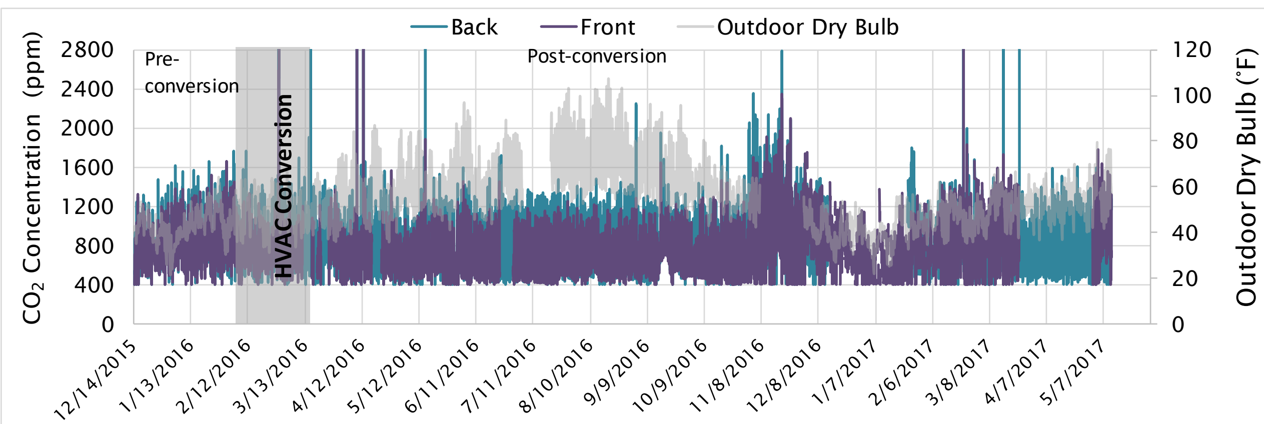
In the case of Building #4 the legacy electric boiler and hydronic baseboard heating loop was retained to provide backup during peak heating demand. In practice, it was found that the boiler was operating during periods of non-peak demand. This was determined to be a result of two factors of building operation. The setpoint on thermostats controlling boiler operation were raised above the threshold that would allow for the new heat pump system alone to meet demand which activated the boiler more frequently than anticipated. It was also found that the boiler demand was increased during the snowy winter season by manual increases in the thermostat setpoints in the garage area to heat the indoor space temperature and transfer heat through the roof insulation and act as a snow melting system. The impact of these adjustments can be seen in the high indoor temperatures throughout the winter months post-conversion.

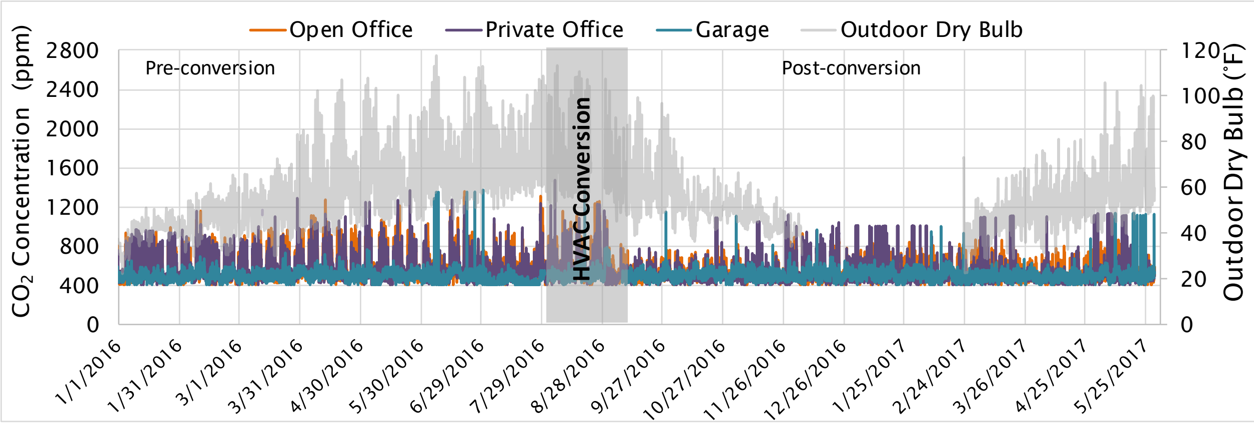
The data from Building #3 (a restaurant) shows significantly greater variation in the space temperature in a given day as well as throughout the year. This is a result of the high process loads from the kitchen equipment which is open to the dining area. Given that the restaurant provides both take-out and delivery service, the front and rear delivery doors are frequently opened. The Front and Back measurements are similar though the Back sensor is closer to the kitchen area resulting in typically higher temperature readings. As the outdoor temperature rises above ~70°F (21°C) the indoor space temperature also rises indicating that the air conditioning system cannot keep up with the cooling loads in the space.

Carbon Dioxide Concentrations

Examples of the hourly CO_2 concentration data are shown in Figure 6. All buildings were monitored but data is shown for only a sample of the buildings for brevity. The greyed-out section of data collection refers to the construction/commissioning period. Building #1 and Building #6 do not have any pre-conversion data as they were empty prior to the renovation. The CO_2 concentrations follow typical profiles for all buildings in the study both pre- and post-conversion. The office buildings have low overnight concentrations that increase throughout the day when occupant density is highest. The CO_2 measurements in the restaurant (Building #3) show higher concentrations than the office buildings due to higher occupancy densities during peak operation and potential impact of gas cooking equipment. CO_2 concentrations in all buildings are maintained below levels of concern with no measurements above 4,000ppm.







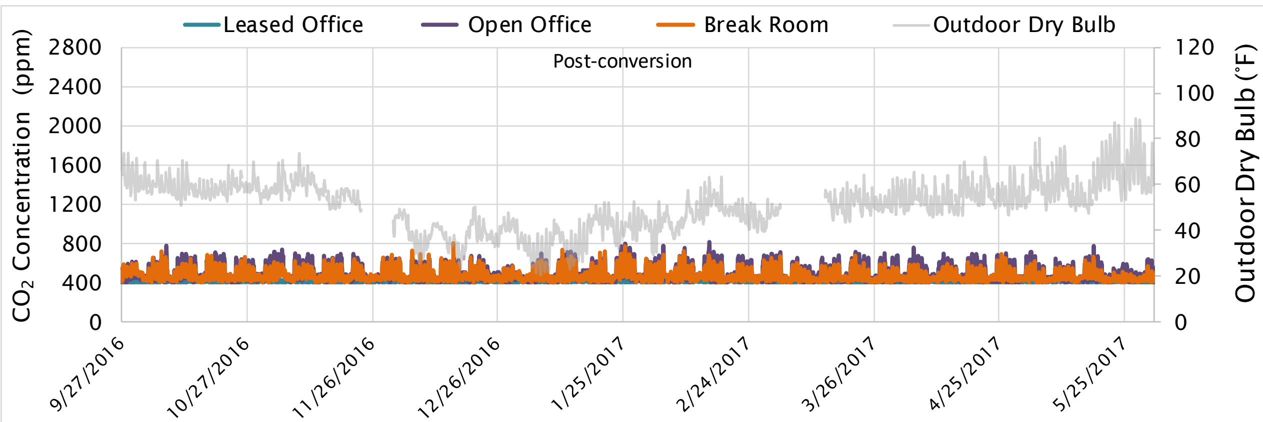


Figure 6: Examples of indoor carbon dioxide measurements in Building #2 (top), Building #3 (middle-top), Building #4 (middle-bottom) and Building #6 (bottom).

Building #2 is operating at constant air volume during occupied hours whereas Building #6 operates with variable flow rate to control to return duct CO_2 concentration. A comparison of the post-conversion CO_2 readings in Building #2 and Building #6 shows that the ventilation system can effectively control CO_2 concentration with either control strategy if programmed correctly.

The CO_2 concentrations within the buildings were compared to determine the relative performance of the pre-conversion and post-conversion ventilation system. The metrics used for comparison were the frequency of readings above 1,000ppm, representing high concentration, and the average CO_2 concentration during occupied hours, representing the typical system effectiveness. Results are shown in Table 4. Entries with N/A indicate that no data was available for that time period.

Table 4: Comparison of pre-conversion and post-conversion CO_2 concentrations (during operating hours)

Project Number	Building Type	Frequency above 1000ppm Pre-conversion	Frequency above 1000ppm Post-conversion	Average Occupied Concentration Pre-conversion (ppm)	Average Occupied Concentration Post-conversion (ppm)
1	Office	N/A	0.2%	N/A	500
2	Office	0.7%	0.1%	615	565

3	Restaurant	23%	15%	900	740
4	Office w Garage	2.6%	0.1%	620	545
5	Restaurant	7.2%	N/A	760	N/A
6	Office	N/A	0.0%	N/A	500
7	Office	0.0%	2.7%	480	560

The average occupied CO_2 concentrations in the pre-conversion data varied between 480ppm to 900ppm. These readings are typically lower in the post-conversion data with a range between 500ppm and 740ppm. These concentrations are generally considered low and are indicative of effective ventilation. The frequency of readings above 1,000ppm (the threshold for ventilation design) was found to be between 0.0% and 23% in the buildings pre-conversion. This changed to 0.0% to 15% for readings post-conversion. The most significant improvement in the CO_2 readings was found in Building #3 which lowered the average CO_2 concentration from 900ppm to 740ppm and the frequency above 1,000ppm from 26% to 15%.

Only one building (Building #7) was found to have higher concentrations of CO_2 after the conversion. The average CO_2 concentration in Building #7 rose from 480ppm pre-conversion to 560ppm post-conversion. Because the post-conversion levels are still well within acceptable limits, this indicates that the space was likely overventilated prior to the conversion. Delving further into the hourly CO_2 data for Building #7 (Figure 6) shows that the instances of elevated CO_2 concentration typically occur in the conference room which uses a CO_2 sensor to open a damper to start providing ventilation when CO_2 concentrations in the space reach 1000ppm (indicating occupancy). The largest spikes in CO_2 concentration also occur after occupied hours when the HRV would be scheduled off. This type of reactionary system control allows for reduced ventilation in the space when unoccupied but inevitably results in high CO_2 concentrations when in use because it waits until the 1000ppm limit is reached prior to starting the space ventilation during occupied hours and has no ventilation when the space is used during unoccupied hours.

The CO_2 concentration measurements collected in this work indicate that most of the HVAC systems pre-conversion were providing adequate ventilation to the spaces. The conversion typically improved CO_2 concentration metrics indicating that the ventilation was improved in conjunction with significant reductions in energy consumption for all buildings.

CONCLUSIONS AND LESSONS LEARNED

The high efficiency DOAS and heat pump conversion has been successfully performed in six of the buildings discussed in this work. One building (#5) is under construction at the time of writing. The conversion of existing RTU HVAC systems to DOAS with heat pump conditioning was successfully demonstrated as a feasible approach for small commercial buildings. Calibrated whole building energy modeling was used to predict energy savings. Models will be calibrated again using post-conversion utility bills and actual weather data once an entire year has passed. The predicted energy savings varied by application but was found to be in the range of 13% to 54% with HVAC energy savings from 22% to 71%. Monitoring of indoor environmental conditions was used to confirm proper system operation and identify any trends in building performance. The indoor space temperature was found to be well controlled both pre-conversion and post-conversion, provided the occupants selected appropriate operating settings. Comparison of CO_2 metrics identified an improvement in air quality for most buildings with the new ventilation system. Given that the buildings did not have significant ventilation issues prior to conversion, the indoor environmental data primarily shows that significant energy reductions can be achieved while *also* maintaining or improving air quality and comfort metrics.

The project team interacted with contractors, owners, and occupants throughout the project to identify any challenges with integration and assist in troubleshooting the system where required. This has led to the identification of key lessons learned from the project that will assist with future installations as well as broader scale adoption of this system. Four key lessons can be categorized as follows:

1) **Air leakage:** During the commissioning process airflow rates were measured at the HRV supply diffuser outlets. In most installations, the supply airflow at the outlets was found to be lower than the design conditions by up to 25%. The initial solution from contractors was to increase the airflow rate at the HRV by adjusting the flow setting until space supply flowrates were met. Although this could correct for the undersupply of ventilation air, it increased the energy consumption of the system. Further investigation into the root cause identified a number of locations where air leakage could be felt from the ductwork at fittings. Efforts to improve duct seals reduced the amount of leakage into unwanted space. The work identified challenges with repurposing existing ductwork due to the potential leakage and the added importance of preventing duct leaks in the low airflow DOAS designs compared to standard recirculating air systems.

2) **Contractor education:** In several of the pilots, the initial bids assumed the same capacities as the old equipment. They also tended to rely heavily on design assistance from heat pump equipment suppliers, typically leading to more zones and extra features that added cost, such as a simultaneous heating and cooling option for the VRF system. For effective broad scale implementation of this type of program, contractors will need independent, easy-to-use tools and/or technical support for right-sizing and selecting equipment.

3) **Specification and procurement:** The pilot relied on a single HRV model as it was the only unit available with sufficiently high heat recovery effectiveness, controllability, and very low fan power. In effect, the pilot included a specification that only one equipment manufacturer could meet. This proved a challenge for government owners with procurement policies to obtain three quotes.

4) **Occupant education:** Another key to achieving significant energy reductions was the proper commissioning and operation of the new system. Building owners/operators were required to change operation of the building system to account for the separation of the ventilation from the air conditioning systems, which increased the number of control panels within the building. Initial feedback from some building occupants identified hesitation to adjust setpoint temperature despite dissatisfaction with the indoor temperature. Others made changes without understanding the impact, or expressed confusion about which controls to adjust to solve a particular comfort issue. Proper instruction around the intended system operation, as well as periodic follow-up (for example, part-way through each season for the first year) is required to ensure both comfort and energy goals are achieved.

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