DO AS We Say (and As We Do): Maximizing HVAC Efficiency, Flexibility, and Resiliency with High Efficiency Dedicated Outdoor Air Systems

Jordan Pratt, Energy 350
Maria Murphy, NEEA
Nick O'Neil, Energy 350

ABSTRACT

With the ever-increasing environmental impacts of local pollution and global climate change, there is a necessity for resilient, flexible, and extremely efficient HVAC systems. While HVAC systems are critical to our comfort and well-being, conventional systems are costly to operate and contribute to over 40% of commercial building energy usage. Dedicated outdoor air systems (DOAS) are a proven solution for reducing energy consumption as they optimize the control and functionality of ventilation and thermal comfort independently. A very high efficiency approach to DOAS pairs a high efficiency heat/energy recovery ventilator (HRV/ERV) with a high efficiency heat pump, while following design principles that optimize performance. This allows for many benefits, including:

- Demonstrated HVAC energy use reduction by an average of 69% over conventional systems (48% of building energy)
- Excellent indoor air quality (IAQ) and thermal comfort
- Proven adaptability to changing occupant densities and ventilation requirements as well as resiliency in extreme weather events
- Significant carbon emission reduction with minimal peak electric demand increase in gas conversion projects

This paper builds on a 2018 Summer Study paper (Love et al. 2018) that presented initial results from three demonstration projects. The expanded data set discussed herein includes results from the energy monitoring of 14 demonstration projects, including eight pilots completed between 2015-2018, and six additional sites supported by NEEA since 2019. These combined results, along with five years of market and technical analysis, have enabled NEEA to develop a market transformation program in support of this high-performance HVAC strategy.

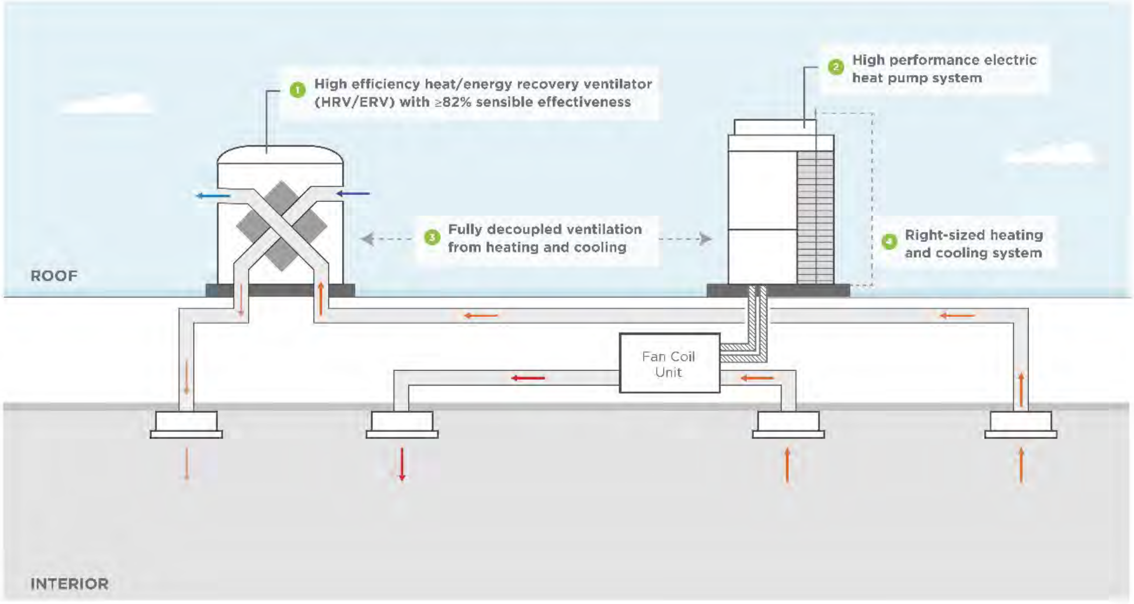
Introduction

In 2014, Northwest Energy Efficiency Alliance (NEEA) identified dedicated outdoor air systems (DOAS) as an HVAC system approach with significant energy savings potential in the commercial building sector. While energy consumption can be reduced in both fan energy and conditioning of ventilation air simply by decoupling these two functions, savings could be substantially increased if high efficiency equipment paired with key design principles are applied. HVAC typically accounts for 30-50% of all energy use in commercial buildings (CBECS 2012), skewing more toward the higher end of that estimate for small to medium-sized buildings (<50,000 ft^2). These buildings are estimated to make up 40-50% of commercial building square footage in the Northwest (NEEA 2014) and are prime targets for HVAC system conversions. For buildings in that size range, a common feature is an existing gas, heat pump, or electric resistance packaged rooftop unit (RTU) that handle both space conditioning and ventilation air in a single packaged unit.

System Overview

The very high efficiency DOAS approach is comprised of four key elements, listed below and depicted in Figure 1. While there are varying levels of “good”, “better”, and “best” practices associated with each of these individually, addressing them all and applying design “best” practices on a project-by-project basis enables maximum performance and the substantial energy savings seen in the demonstration projects.

1. **High efficiency HRV/ERV** with ≥82% sensible recovery effectiveness[1] (SRE) that enables a fully decoupled approach while delivering tempered air with little-to-no post-heating or cooling in many Northwest climates and applications.
2. **High performance electric heat pump system** that meets or exceeds current ENERGY STAR minimum efficiency requirements[2].
3. **Fully decoupled ventilation** that delivers outdoor air directly to the indoor spaces so that the primary heating and cooling system can cycle off when space conditions allow. This also ensures that ventilation air is effectively distributed to all spaces regardless of the operation of the primary heating and cooling system.
4. **Right-sized heating and cooling system** supported by peak load analysis that considers the HRV/ERV’s reduction of ventilation load and includes reasonable assumptions and safety factors.



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[1] HRV/ERV must also meet a minimum total fan efficacy of 1.3 cfm/Watt at 0.5% w.g. external static pressure at 75% of rated air flow and have variable speed supply and exhaust fans to be a compliant product.

[2] For equipment where ENERGY STAR does not apply, minimum efficiency requirements are included in NEEA’s “Equipment and Design Best Practices for Optimal Efficiency” summary document (NEEA 2022).

Figure 1. Very high efficiency DOAS diagram with key elements (NEEA 2022).

The initial eight pilot demonstration projects were used to hone a detailed, prescriptive set of guidelines that included stringent requirements for the four core elements, as well as several other best practices and sub-requirements for how to design and install this system approach. Full compliance was elusive and difficult to verify. Because of this, the HVAC upgrade done at the Energy 350 office (Building #13) was the only demonstration project that could be confirmed as ‘fully compliant’. That said, all 14 of the demonstration projects included the four core elements with good to best design practices, and all demonstrated significant energy savings. Based on these findings, NEEA commissioned extensive energy modeling[3] on the detailed, prescriptive set of guidelines to investigate thousands of permutations of system configurations. In reviewing both real-world demonstration projects and modeled results, combined with market experience and feedback, NEEA generated a streamlined, more flexible set of very high efficiency system requirements that was published in February of 2022 (NEEA 2022).

Market Context

Commercial HVAC is a relationship-based industry with costly, complex equipment and long project timelines. Based on NEEA’s work over the last five years, a $1.5 million dollar project is not uncommon between equipment and installation costs, even in relatively small renovation projects that include an HVAC system conversion. These projects could take 1-3 years to design and execute, while new construction could take 3-5 years. Further, the customization of the system components and variability of HVAC systems for each application creates further complication as every building is unique and presents unique design challenges.

With regard to product availability, the market for high efficiency commercial heat pump systems, like Variable Refrigerant Flow (VRF), has grown tremendously since the first demonstration projects began in 2015. At that time, the market for these systems was still relatively small and incremental pricing for the highest efficiency units was substantial. As such, several of the early pilot demonstrations used heat pump technologies with lower seasonal efficiency than was desired, especially in rural projects with limited distribution channels. High efficiency heat pumps are now widely available and commonly selected in commercial HVAC projects. That said, increasing availability of a very high efficiency HRV/ERV is still a main point of focus for the program. There are only a handful of HRV/ERV manufacturers who have a majority of the market share, and it is difficult for new firms to enter the market due to high costs of entry and established market relationships. Nonetheless, there has been HRV/ERV market growth since 2015, when NEEA supported the first manufacturer who brought a product line that met the efficiency requirements for this DOAS approach to the U.S. from the Czech Republic. As of January 2022, there are five manufacturers with over 40 compliant HRV/ERVs. However, there is still substantial progress to be made before a very high efficiency HRV/ERV is commonly selected in HVAC design. Finally, equipment and installation pricing practices are opaque and variable due to the relationship-based nature of the industry. Equipment list price is

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[3] NEEA commissioned two reports to refine the system approach. The first included analysis to understand the cost benefit of converting an existing commercial building’s HVAC system to three configurations of a DOAS with each one increasing in energy efficiency (Red Car Analytics 2019). The second was in 2021 (Red Car Analytics 2022).

often a starting point for negotiations and markups occur at every step of the supply chain in an inconsistent manner. On top of that, the breakdown of HVAC project costs is not always communicated clearly with the decision makers, and pricing is often given as lump sum. These factors have made it difficult for utility programs and the energy efficiency industry as a whole to make strides in influencing commercial HVAC equipment and design practices.

Despite numerous market challenges, there are some key trends that could shift the inertia of the commercial HVAC industry. Firstly, DOAS, a familiar concept to commercial HVAC market actors, has grown in popularity with the rise of high efficiency zonal heat pumps in the last decade. Beyond energy savings and zoning flexibility, DOAS can also provide enhanced filtration and better humidity control[4]. Further, because the comfort heating and cooling system is separated from the ventilation in DOAS, market awareness of ventilation practices has increased, and more attention than ever is being given to ventilation and indoor air quality (IAQ) in the HVAC design industry. This presents an opportunity for change in deeply rooted design practices which have primarily focused on the sizing of the heating and cooling system, with ventilation as an afterthought, even though it often accounts for 10-30% of the peak loads and annual HVAC energy consumption in small to medium-sized buildings. Secondly, the increased emphasis on IAQ due to a rise of wildfires and the COVID-19 pandemic over the last 2-5 years have brought ventilation and filtration to the forefront of commercial HVAC discussions, and extreme weather has necessitated a need for flexible, resilient HVAC systems.

Finally, policy trends are shifting to address climate change throughout the region, country, and world. Legislation mandating decarbonization is being included in local, state, and national policy in the U.S., prompting a growing number of end-users to demand more from their HVAC systems, which typically account for 30-50% of energy use in commercial buildings (CBECS 2012). Codes and standards are another policy avenue where change is occurring. Elements of the very high efficiency DOAS approach have already been adopted in the 2015 and 2018 Washington State Energy Code (WSEC), as well as California’s Title 24. This activity has resulted in increased adoption of the key design principles and extremely efficient HRV/ERVs required by very high efficiency DOAS designs.

NEEA’s Market Transformation Effort

Since 2015, this system approach has been progressing through NEEA’s stage-gate process for vetting potential market transformation programs. Demonstration projects, market research, and technical research have been underway since that time in an effort to confirm both technical and market feasibility of a transformation initiative. The High-Performance HVAC team at NEEA anticipates ramping up program activities in August 2022 to generate the momentum needed to drive broad adoption of this very high efficiency DOAS approach through the following strategies:

1. Building supply chain awareness and capability, especially in HVAC designers and manufacturer representatives, who both influence equipment selection and design.

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[4] Unlike other parts of the U.S., humidity is rarely actively controlled in commercial buildings in the Northwest. However, DOAS utilizing air-to-air exhaust energy recovery can provide quite stable indoor humidity year-round.

2. Defraying the incremental cost of very high efficiency HRV/ERVs with potential incentives and promotions between NEEA, utility partners, and manufacturers.
3. Leveraging the air quality, comfort, sustainability, and net operating income benefits of the system approach in value proposition communications for owners and their design teams.
4. Supporting inclusion of system equipment and design elements in local, state, and national codes and standard development.

Project Descriptions

While the more recent demonstration projects were recruited through a variety of industry and NEEA utility partners, the buildings shared similar characteristics that make them ideal for conversion using the very high efficiency DOAS approach. Many projects considering DOAS are smaller office buildings or schools (often < 25,000 ft^2 but in general up to 50,000 ft^2) with existing gas, heat pump, or electric resistance packaged rooftop units (RTU). The six recent demonstration projects included four offices and two schools and are positioned across three locations and two climate zones: Portland, OR and Tacoma, WA (urban, climate zone 4C), and Monument, OR (rural, climate zone 5B). A map showing the locations of the 14 demonstration projects is shown in Figure 2.

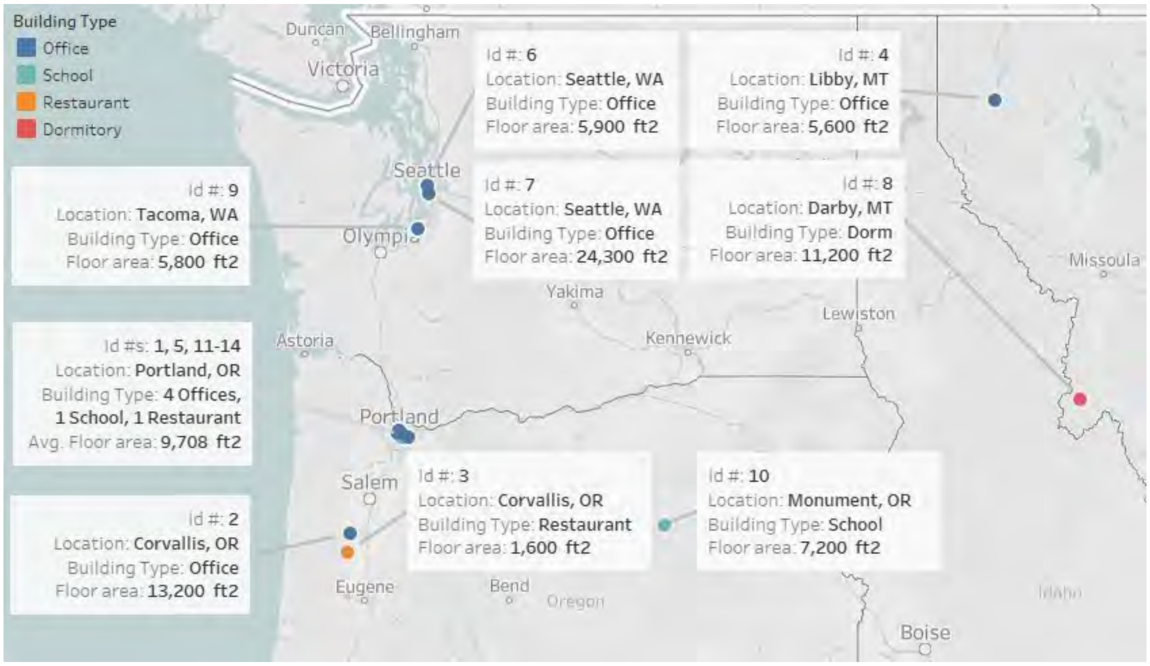

Figure 2. Project map with building type, location, and conditioned floor area of all 14 demonstration sites.

Building Characteristics

Two of the offices (#9 and #14) and one of the schools (#11) were undergoing major renovations and elected to convert their end-of-life conventional HVAC systems to very high efficiency DOAS rather than replacing with similar equipment. The other school (#10) and two offices (#12 and #13) elected to only convert their existing HVAC systems primarily to improve energy efficiency and indoor air quality.

In all six of the more recent demonstration projects (#9-14), either the owner or project architect learned of the very high efficiency DOAS approach from the research and findings that came out of the original eight pilot projects, and they approached the NEEA team for technical support and guidance. Descriptions of each of the 14 demonstration project buildings and existing HVAC systems are provided in Table 1. This paper will present the high-level findings from all projects but will focus on the findings from the six more recent demonstration projects.

Table 1. Project building and HVAC system characteristics

ID #	Location	Building Type	Conditioned floor area, ft^2	Existing HVAC System Type	Building Description
1	Portland, OR	Office	11,600	Gas Packaged RTUs	Second story of a historical, urban office.
2	Corvallis, OR	Office	13,200	Gas Packaged RTUs	Single story government office building.
3	Corvallis, OR	Restaurant	1,600	Gas Packaged RTUs	Single story pizza restaurant with office, seating area, and take out counter.
4	Libby, MT	Office w/ Garage	5,600	Electric Boiler and Heat Pump RTU mix	Single story office with attached truck garage in a rural town center.
5	Portland, OR	Restaurant	1,150	Gas Packaged RTUs	Single story restaurant with seating area.
6	Seattle, WA	Office	5,900	Electric Resistance Packaged RTUs	Third story of a 3.5 story mixed-use office and retail building in downtown Seattle.
7	Seattle, WA	Office w/ Assembly	24,300	Gas Packaged RTUs (Dual Duct)	Two story combined office and airport terminal building.
8	Darby, MT	Dormitory	11,200 (ea.)	Electric Resistance Furnaces	Single story dormitory with 4 wings.
9	Tacoma, WA	Office	5,800	Heat Pump Packaged RTUs	Single-story office building in urban setting.
10	Monument, OR	Primary School	7,200	Unitary Heat Pumps	Rural elementary school.
11	Portland, OR	Preschool	2,900	Gas Packaged RTUs	Net zero energy preschool in urban neighborhood.
12	Portland, OR	Office	20,000	Ductless Heat Pumps w/ Gas Boiler	Single story office converted from elementary school.
13	Portland, OR	Office	7,600	Gas Packaged RTUs	Single story office with common work area and café.

14	Portland, OR	Office	15,000	Packaged VAV w/ Gas Hydronic Reheat	Three story historic office building in downtown Portland.

Pre- and Post-Conversion HVAC Systems

While the very high efficiency DOAS approach has been refined over time based on industry feedback, product availability, and lessons learned from the pilot and additional demonstration projects, all 14 projects contain the four key elements of the system approach that achieve high performance and resulting energy savings. Each project and design are unique, but generally include a decoupled system comprised of an HRV/ERV with ≥82% SRE and a highperformance electric heat pump system (VRF or mini-split heat pumps).

Eight of the 14 pre-conversion systems (#s 1, 2, 3, 5, 6, 9, 11, and 13) were variations of a constant volume packaged RTU system and 12 of the 14 systems served non-restaurant loads. Of those 12, an average system capacity reduction of 40% was enabled by both utilizing HRV/ERVs with ≥82% SRE and by performing peak load-calculations to support right-sizing of the heating and cooling system.

Energy Modeling and Data Collection

Energy savings were calculated for each of the 14 projects by developing custom energy models and calibrating those models with at least one year of monthly utility billing data. The models were calibrated according to ASHRAE Guideline 14 standards with CVRMSE < 15% and NMBE within ±5% (ASHRAE 2014). In most cases, both the pre- and post-conversion models were calibrated within acceptable values using actual meteorological year (AMY) weather files to match a one-year period before and after the system conversion. In some cases, this was not practical, as was the case when the building had been unoccupied for more than three years before conversion (#1 and #14) and/or the use of the building and HVAC system operation changed significantly as a part of a major renovation (#1 and #11). In these situations, only the post-conversion system model was calibrated. Sub-metered HVAC electric data was also collected and used to improve the model inputs so that the end-use HVAC results (heating, cooling, fans) were also in line with the actual annual consumption[5]. Figure 3 shows an example of both the monthly calibration results and sub-metered HVAC calibration results.

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[5] HVAC end-uses were not formally calibrated to ASHRAE Guideline 14 standard as was the case with monthly utility data.

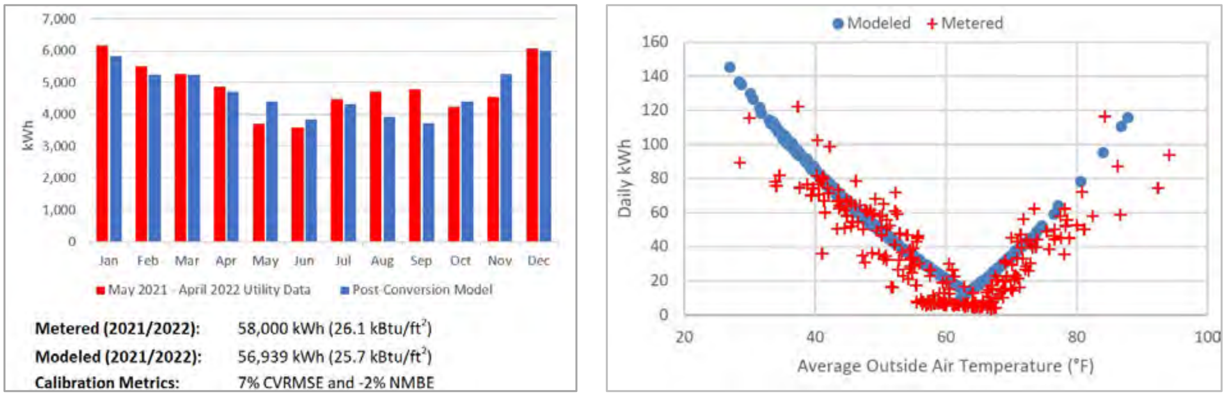

Figure 3. Building #13 calibrated AMY post-conversion model results compared to monthly utility billing data (left) and daily sub-metered heating and cooling electricity consumption used to calibrate the heating and cooling outputs of the model (right).

After calibration, the pre- and post-conversion models were modified with typical meteorological year (TMY) weather data to compare the energy use consumption of the two systems in a typical weather year. All results shown in this paper are based on the TMY models rather than the AMY models. While similar in their approach and modeling goals, the pilot and additional demonstration projects were analyzed with different modeling methodologies as follows:

- **Pilot demonstration projects (#1-8).** The eight pilot project energy models were developed using the DesignBuilder user interface for the EnergyPlus simulation tool. In addition to the energy models, sub-metered HVAC data, IEQ measurements (CO_2, temperature, and relative humidity in a sub-set of rooms), and informal occupant surveys were collected.
- **Additional demonstration projects (#9-14).** The energy savings for the six additional demonstration projects were calculated using custom spreadsheet-based hourly energy models. Sub-metered HVAC electric data was collected, as well as IEQ measurements (CO_2, temperature, and relative humidity in a sub-set of rooms), and informal occupant surveys.

Results

Energy Savings

Energy savings results from the 12 non-restaurant projects[6] are shown in Figure 4[7], which are normalized by conditioned floor area and broken out by end-use for each project. All pre-conversion energy results shown in this report are based on the pre-conversion system with code-minimum equipment. On average, the non-restaurant system conversions reduced the total

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[6] Average EUI and savings results are presented excluding the two restaurant projects due to their high non-HVAC loads. See Table 2 for EUI results for Buildings #3 and #5.

[7] Figure 4 excludes the two restaurant projects (#3 and #5) because of their relatively high EUIs compared to the other building types. See Table 3 for the EUI breakdowns of the two restaurants.

building energy usage by 48% (69% reduction in HVAC energy). The average pre-conversion building energy use intensity (EUI) of 65.3 kBtu/ft^2-yr (range of 25.7 to 122.0) was reduced to an average post-conversion EUI of 34.2 (range of 12.9 to 70.0).

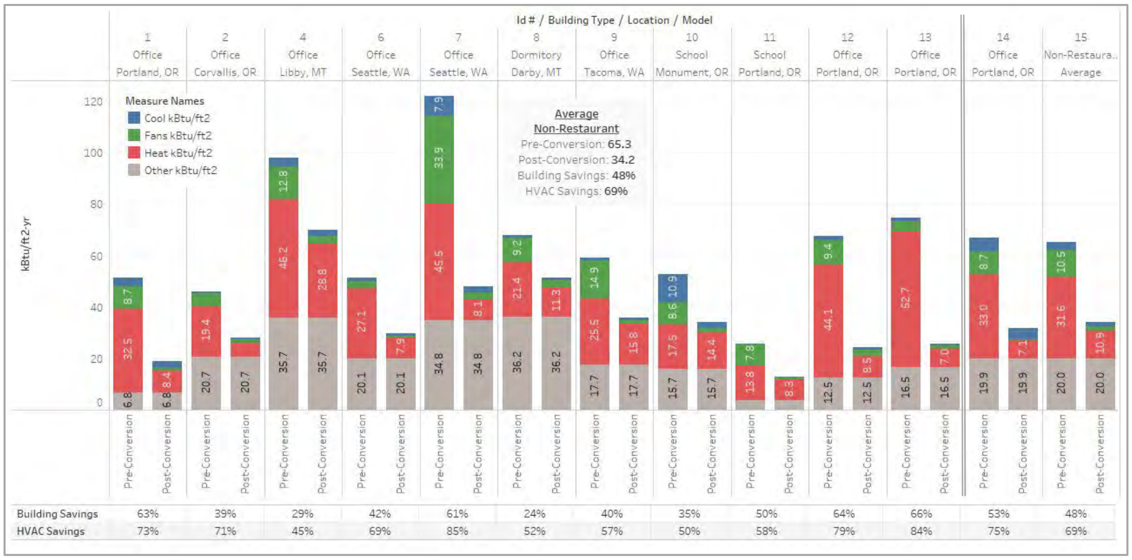

Figure 4. Annual energy use intensity by end-use pre- and post-conversion. Average non-restaurant project savings are 48% of total building energy use and 69% of HVAC energy use.

Tabulated EUI data for the pre- and post-conversion systems for all 14 projects, including the restaurants, are shown in Table 2. Across the 12 non-restaurant projects, an average annual EUI reduction of 31.1 kBtu/ft^2-yr was found due to an 84% reduction in fan energy, 65% reduction in heating energy, and 48% reduction in cooling energy.

Table 2. Annual energy use intensity comparison of pre- and post-conversion systems

ID #	Description	Model	Other kBtu/ft^2	Fans kBtu/ft^2	Heat kBtu/ft^2	Cool kBtu/ft^2	Total kBtu/ft^2	Total Savings kBtu/ft^2	HVAC Savings %
1	Portland law office #1	Pre-conv.	6.8	8.7	32.5	3.4	51.4	32.3 (63%)	73%
		Post-conv.	6.8	1.0	8.4	2.8	19.1		
2	Corvallis office	Pre-conv.	20.7	5.1	19.4	0.7	45.9	17.9 (39%)	71%
		Post-conv.	20.7	1.3	5.3	0.7	28.0		
3	Corvallis restaurant	Pre-conv.	1,193	80.1	174.1	23.1	1,470	118.9 (8%)	43%
		Post-conv.	1,193	65.6	59.7	33.3	1,352		

4	Montana office	Pre-conv.	35.7	12.8	46.2	3.3	98.0	28.0 (29%)	45%
		Post-conv.	35.7	3.2	28.8	2.3	70.0		
5	Portland restaurant	Pre-conv.	635.7	49.6	181.0	8.2	874.5	173.5 (20%)	73%
		Post-conv.	635.7	32.8	25.9	6.7	701.0		
6	Seattle office	Pre-conv.	20.1	2.9	27.1	1.2	51.3	21.6 (42%)	69%
		Post-conv.	20.1	0.9	7.9	0.8	29.7		
7	Seattle airport/office	Pre-conv.	34.8	33.9	45.5	7.9	122.0	73.9 (61%)	85%
		Post-conv.	34.8	2.8	8.1	2.4	48.1		
8	Montana dorms	Pre-conv.	36.2	9.2	21.4	1.1	67.9	16.4 (24%)	52%
		Post-conv.	36.2	2.9	11.3	1.1	51.5		
9	Tacoma office	Pre-conv.	17.7	14.9	25.5	1.2	59.3	23.6 (40%)	57%
		Post-conv.	17.7	1.4	15.8	0.9	35.7		
10	Rural school	Pre-conv.	15.7	8.6	17.5	10.9	52.7	18.6 (35%)	50%
		Post-conv.	15.7	1.7	14.4	2.3	34.2		
11	Net zero preschool	Pre-conv.	3.6	7.8	13.8	0.5	25.7	12.8 (50%)	58%
		Post-conv.	3.6	0.8	8.3	0.2	12.9		
12	Portland office	Pre-conv.	12.5	9.4	44.1	1.5	67.5	43.3 (64%)	79%
		Post-conv.	12.5	2.2	8.5	1.0	24.2		
13	Energy 350 office	Pre-conv.	16.5	4.2	52.7	1.3	74.7	49.0 (66%)	84%
		Post-conv.	16.5	1.4	7.0	0.8	25.7		
14	Portland law office #2	Pre-conv.	19.9	8.7	33.0	5.4	66.9	35.3 (53%)	75%
		Post-conv.	19.9	0.3	7.1	4.4	31.7		
Average (12 nonrestaurants)[8]		Pre-conv.	20.0	10.5	31.6	3.2	65.3	31.1 (48%)	69%
		Post-conv.	20.0	1.7	10.9	1.6	34.2		
		% Savings	--	84%	65%	48%	48%		

Peak Demand Impacts

In addition to impressive energy savings, the six projects that converted from an electrically heated baseline significantly reduced their building peak demands. Table 3 shows the

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[8] Average savings are weighted on a total savings basis rather than per project. On a per project weighted basis, building and HVAC savings are 47% and 66% respectively.

modeled pre- and post-conversion peak demands for both winter and summer[9]. On average, the projects with electric pre-conversion heating systems resulted in a 24 kW winter peak demand reduction (40%) and an 8 kW summer peak demand savings (31%).

Table 3. Winter and summer peak demand impacts pre- and post-conversion (electric)

	Winter peak demand				Summer peak demand			
ID #	Preconv., kW	Postconv., kW	Conversion impact, kW	%	Preconv., kW	Postconv., kW	Conversion impact, kW	%
4	104	74	↓30	↓29%	30	27	↓3	↓8%
6	56	26	↓30	↓54%	16	10	↓6	↓34%
8	84	65	↓19	↓22%	46	43	↓3	↓7%
9	63	16	↓47	↓75%	15	8	↓7	↓48%
10	41	35	↓6	↓13%	47	21	↓26	↓56%
11	18	4	↓14	↓80%	6	2	↓4	↓66%
Avg.	61	37	↓24	↓40%	27	19	↓8	↓31%

Gas conversion projects. The 5 non-restaurant projects that converted from gas to electric heat resulted in significant gas savings, CO2 emissions reductions, and relatively small peak winter electric demand increases. Table 4 shows the peak winter and summer electric demand of the 5 systems with gas heat pre-conversion systems. On average, the system conversion resulted in a 9 kW winter demand increase (↑25%) while the summer demand was decreased by 25 kW (↓44%).

Table 4. Winter and summer peak demand impacts pre- and post-conversion (gas)[10]

	Winter peak demand				Summer peak demand			
ID #	Preconv., kW	Postconv., kW	Conversion impact, kW	%	Preconv., kW	Postconv., kW	Conversion impact, kW	%
1	13	27	↑14	↑114%	35	22	↓13	↓37%
2	30	30	↓0.6	↓2%	39	33	↓6	↓16%
7	71	84	↑13	↑18%	136	57	↓79	↓58%
12	51	54	↑4	↑8%	54	30	↓24	↓44%
13	8	21	↑13	↑161%	26	21	↓4	↓17%

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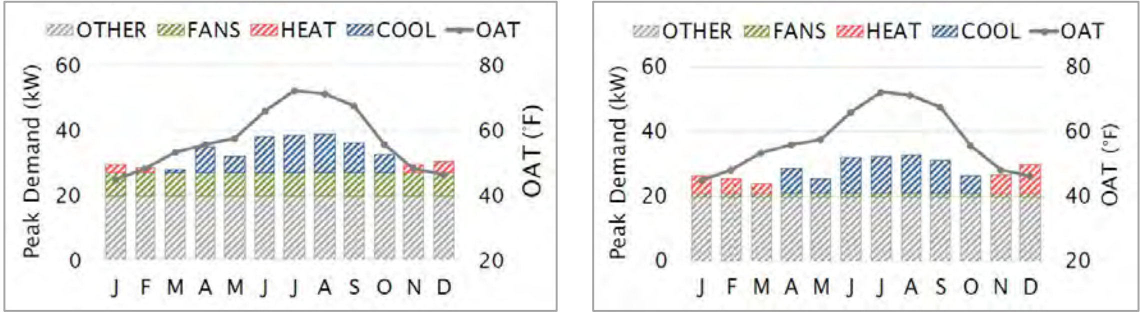
[9] Peak demand savings are modeled only and not based on a utility billing analysis.

[10] Peak demand analysis for Building #14 has not yet been completed.

Avg.	35	43	↑9	↑25%	58	33	↓25	↓44%

Figure 5 shows the modeled pre- and post-conversion monthly peak electric demand of two example buildings (#2 and #13). Despite converting from gas as the primary heating fuel to electric, Building #2 resulted in a small decrease in winter peak demand. The gas conversion in Building #13 on the other hand, resulted in a significant modeled peak electric demand increase of 13 kW (↑161%).

Building #2 – 0.6 kW Winter Decrease, 6 kW Summer Decrease



Building #13 – 13 kW Winter Increase, 4 kW Summer Decrease

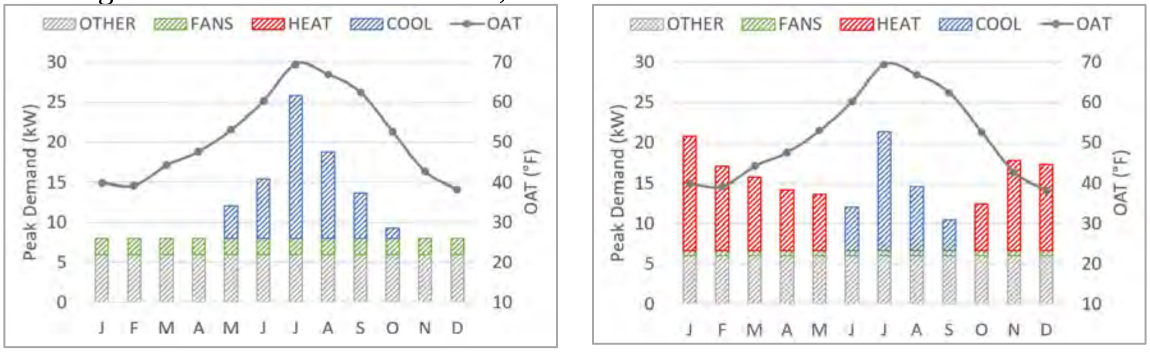


Figure 5. Monthly peak electric demand of two example buildings (#2 and #13) with gas as the primary heating source for the pre-conversion system. Pre-conversion demand is shown on the left and post-conversion on the right.

Indoor Environmental Quality

Very high efficiency DOAS delivers excellent IEQ. To assess the post-conversion IEQ of the demonstration projects, temperature, relative humidity, and CO_2 sensors were installed in a minimum of three rooms for each project. Additionally, occupancy surveys were completed to receive anecdotal evidence of the IEQ in the buildings and, whenever possible, compare the pre- and post-conversion conditions. In every room that was monitored across the demonstration projects, the CO_2 levels, room temperature, and relative humidity remained within acceptable levels. Figure 6 shows an example week in one of the metered rooms of Building #9, postconversion, where temperatures stayed within 2°F of setpoint, relative humidity stayed between 50-62%, and CO_2 concentrations always stayed below 700 ppm. Post-conversion occupant satisfaction levels were reported as extremely high across all buildings as well.

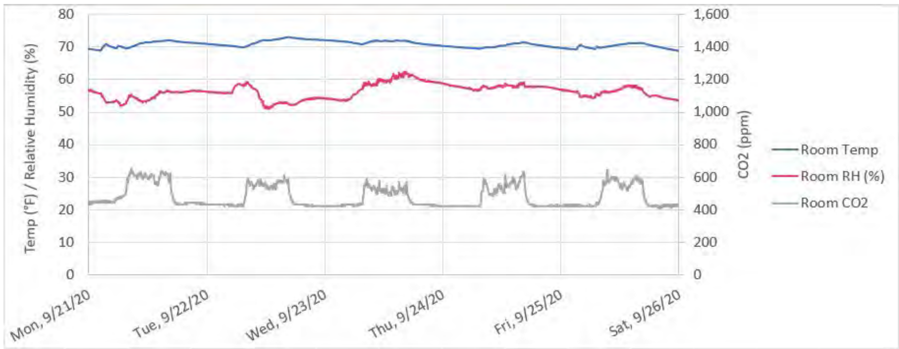


Figure 6. Typical week showing CO_2 concentrations, temperature, and relative humidity levels.

Partially coupled DOAS can cause poor IAQ. A typical industry approach to DOAS is delivering ventilation air from the HRV/ERV into the return side of the primary heating and cooling fan coil units (FCUs). This method saves cost on ductwork, supply diffusers, and can avoid thermal comfort issues when selecting a less efficient HRV/ERV which may deliver hot or cold air in extreme conditions. In some cases, this can be an effective strategy, especially in designs with a single fan coil unit in each room like in typical school DOAS designs. An example schematic utilizing this strategy is shown in Figure 7.

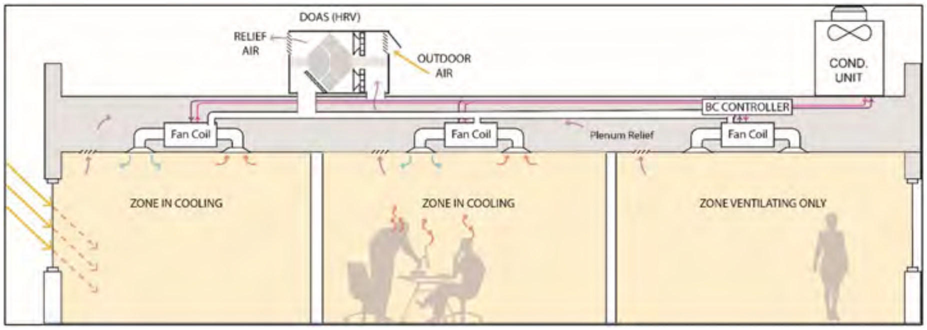


Figure 7. Partially coupled HRV DOAS with VRF fan coil units (Red Car 2021).

In most other cases this partially decoupled strategy is applied when FCUs serve many offices with similar heating and cooling profiles instead of serving a single room. This strategy is shown in an example office floor plan in Figure 8 where a single FCU serves eight offices.

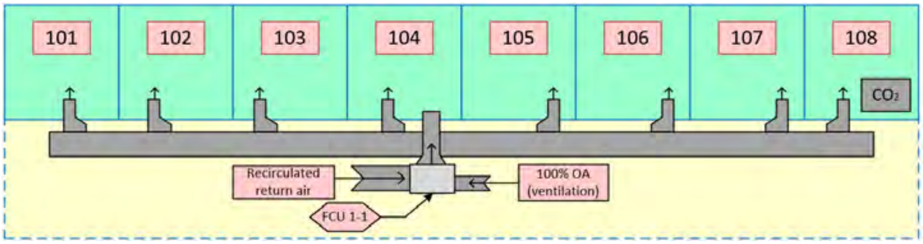


Figure 8. Partially coupled DOAS with ventilation air ducted into a fan coil unit.

Though this partially decoupled method often saves on cost, the rooms farthest from the FCU can be deprived of ventilation air, especially when there are no calls for heating or cooling during mild weather conditions. For a real-world example, refer to Figure 9 which shows the

CO_2 concentrations of the corner office shown in Figure 8 (office 108) on a mild fall day with outside air temperatures between 50-55°F. The fan coil unit serving these eight north facing offices did not receive a call for heating or cooling for over four hours in the afternoon. While ventilation air was still being delivered directly to the FCU, it appears that it was not effectively being delivered to the rooms furthest from the FCU while the rooms closer to the FCU were being over-ventilated. Several other CO_2 spikes were seen in the first few months of the data collection period, typically occurring after extended periods with no FCU power being drawn. One such event saw CO_2 concentrations reach 2,381 ppm. These issues have now been observed in multiple partially coupled designs and are a primary reason why NEEA continues to recommend a fully decoupled system approach.

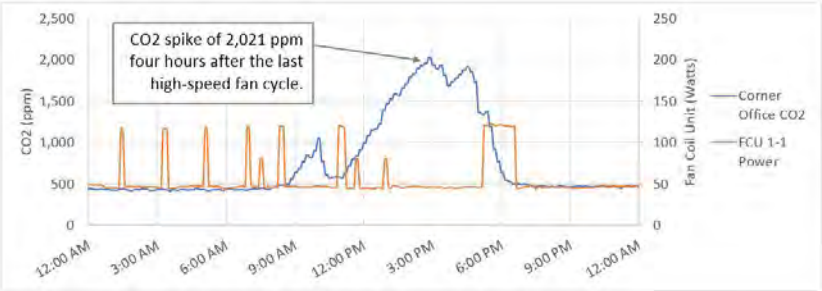


Figure 9. CO_2 concentrations from corner office furthest from fan coil unit.

Right Sizing, Flexibility, and Resiliency

In mid-2020, Energy 350 management became interested in upgrading their office HVAC system with the following goals: (1) improving indoor air quality and ventilation flexibility, (2) reducing their building energy consumption and carbon footprint, and (3) increasing the thermal comfort of their office which was previously a single-zone system serving a diverse set of heating and cooling needs. After two years of providing technical consultation to NEEA for their high-performance HVAC initiative, Energy 350 was in a unique position to work closely with NEEA and use the concepts and lessons learned from their experiences to design, implement, and monitor the performance of a very high efficiency DOAS in their own office. In early 2021, Energy 350 worked with a preferred HVAC contractor and manufacturer representative to convert their gas heated packaged RTU system. The design team incorporated the very high efficiency DOAS approach and applied the best practices developed over the previous 4 years from market research and pilot demonstration project monitoring efforts.

As in many of the demonstration projects, the project engineers were able to significantly reduce the heating and cooling system size due to high efficiency heat recovery/rejection, nearly eliminating the ventilation load, avoiding excessive safety factors, and using accurate values for internal and envelope heat gains. The end result was that the HVAC system cooling capacity of Building #13 was reduced by 41% (17-tons down to 10-tons)[10]. Figure 10 shows the results from the peak cooling analysis of the post conversion system compared to the assumed load analysis the pre-conversion system was sized for.[11]

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[10] The system peak heating capacity was also reduced even more (by 54% from 296 to 135 MBH).

[11] No load analysis was found on the pre-conversion system mechanical permit, so the project engineers completed a load analysis exercise for the pre-conversion equipment (RTU with no heat recovery).

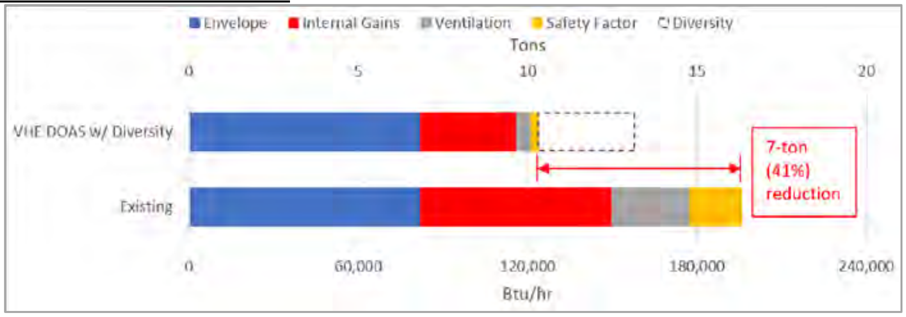

Figure 10. Peak cooling loads from Building #13 resulting in a system downsizing of 41%.

Within nine months of installation, the right-sized system was put to the test experiencing both an extreme cold event where sub-freezing temperatures were reached every day for a week straight[12] and an extreme heat event where the temperature reached 108°F, 112°F, and 115°F on consecutive days, all of which were hotter than the 50-year extreme temperature. The last two days of this event saw temperatures hotter than had ever been recorded in Portland and over 20°F warmer than the design cooling temperature (91.7°F) for which the peak cooling load analysis used. Impressively, during both the extreme cold and hot events, the HVAC system kept the office environment comfortable even with the system being downsized by 41% compared to the pre-conversion system. Figure 11 shows the indoor temperature measured in the office over the two days that reached 108°F and 112°F[14]. During occupied hours, the office temperature was maintained within 2°F of the 75°F setpoint throughout the day, even with the outdoor temperature being 35°F warmer than the indoor temperature.

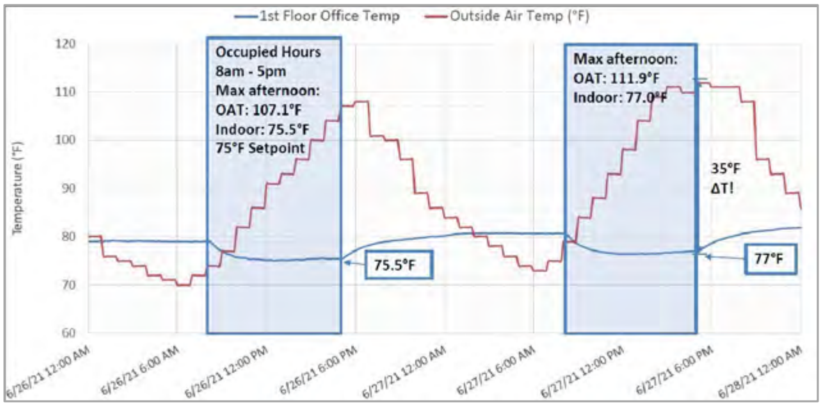

Figure 11. Indoor temperature during an extreme heat event in June 2021.

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[12] The daily minimum temperature fell below freezing for eight consecutive days from 12/26/21 through 1/2/22 and the ASHRAE 99% Heating DB (29°F) was reached on four consecutive days from 12/29/21 through 1/1/22.

[14] Temperatures at the Portland airport were recorded as high as 115°F.

Lessons Learned and Conclusions

A tremendous amount of learning has taken place regarding both this very high efficiency DOAS approach and the commercial HVAC market since work began on the initial pilot demonstrations in 2015. While the overall market transformation goals have remained unchanged, these lessons, along with extensive market research, have enabled NEEA to hone intervention strategies and target good applications for very high efficiency DOAS. In an effort to minimize redundancy, the following list expands on the 2018 paper's lessons learned[13] to help inform others interested in pursuing this system approach:

- **It takes a village.** Consistent buy-in is required throughout the project identification, design, procurement, and installation process for this system approach to be successful. There were a myriad of influencers and decision-makers within both the supply chain and commercial buildings sector on each of the demonstration projects, and many points at which value engineering, pricing, and even brand preference could change the course of a project. Maintaining buy-in from everyone involved from project sales through value engineering and install was a significant challenge.
- **Design is key.** Each of the four core elements that contribute to optimal performance and energy savings in this very high efficiency DOAS approach are addressed during system design. If an HVAC design can survive value engineering, permitting, and approved construction documents, it will remain unchanged, and the contractor will install as designed. For instance, many system designers and contractors were reluctant to stray far from conservative rules of thumb, such as 400 sf/ton to size a heating/cooling system, regardless of the application. This issue was seen on every demonstration project.
- **Perfect is the enemy of the good.** As discussed in the 'System Overview' section, the initial very high efficiency DOAS system approach was outlined in a detailed, extensive, and prescriptive set of guidelines that were difficult to meet completely. Through experience and research, NEEA concluded that a level of flexibility was both necessary and achievable with this system approach without significantly impacting energy savings, IEQ, or thermal comfort. For that reason, NEEA has expanded and streamlined the very high efficiency DOAS approach, putting emphasis on those elements that contribute the most to high performance and substantial energy savings, and recommending other best practices with value propositions to support them (e.g. thoughtful decoupling for improved IAQ).
- **DOAS means different things to different people.** Based on experiences over the last several years, there is a substantial lack of clarity around the definition of DOAS. DOAS can be defined as a concept, where the heating and cooling system is decoupled from the ventilation component. ASHRAE's definition of DOAS speaks to this: "A dedicated outdoor air system (DOAS) uses separate equipment to condition

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[13] Previous lessons learned that still apply include energy modeling limitations, market resistance to heating/cooling system right-sizing, lack of high efficiency HRV/ERV availability, air leakage challenges when repurposing duct work, and occupant education (Love et al. 2018).

> all of the outdoor air brought into a building for ventilation, and delivers it to each occupied space, either directly or in conjunction with local or central HVAC units…used to maintain space temperature.” (ASHRAE 2017). However, discussions with HVAC market actors generally revolve around ‘a DOAS’ [unit], which could include energy or heat recovery, also known as an energy or heat recovery ventilator. Context is sometimes the only way to determine whether DOAS is being referred to as a concept or a piece of equipment, which can cause confusion.

Though this very high efficiency DOAS approach is not without challenges- a design that pairs two pieces of equipment made by different manufacturers, along with key design practices, in an entrenched industry very resistant to change- if ever there were a time to embrace a challenge, it’s now. The combination of once-in-a-lifetime weather events, the growing number of wildfires, and a pandemic are encouraging changes in paradigm, and this system approach has been proven as an effective and timely solution to address the evolving climate and policy landscape in the under-served small to medium-sized commercial building market segment.

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