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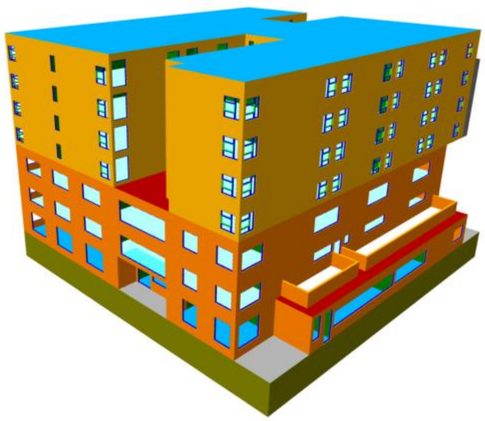
Report #1

Calibrated Energy Savings for Very High Efficiency DOAS in Multi-Family Housing



Final Report

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1. 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, performance can be further optimized if high efficiency HVAC equipment was paired with key design principles. Based on a dozen commercial HVAC projects throughout the Northwest since 2015, NEEA found that this holistic system approach demonstrated an HVAC energy use reduction of 69% on average when compared to a code-minimum system, and a whole-building energy reduction of 48% on average.

Building on this work, NEEA explored how the principles of VHE DOAS could enhance the HVAC performance in multi-family (MF) housing and midrise apartments. Currently, MF housing is a growing sector of the design and construction industry across the Northwest. Best practice in MF housing for energy efficiency already focuses on actively providing ventilation air through dedicated systems, known as balanced ventilation, as opposed to the common practice of exhaust-driven ventilation where outdoor air is pulled through each apartment and exhausted. Balanced ventilation can be configured as large, centralized systems with ventilation air ducted to and from each apartment or, through individual small units, known as a unitized system. This practice of using a dedicated unit or units for ventilation only is not a new concept for MF buildings, however, the potential for energy savings from using high efficiency heat recovery or energy recovery ventilators (HRV/ERVs), efficient controls like ventilation bypass, and efficient fans may provide a way to drive further energy savings.

This report is an initial investigation of the energy benefits of using VHE DOAS in a MF building application to understand the trade-offs in efficiency compared to conventional systems and the impacts of using select options for more significant energy savings potential.

2. Objectives

To estimate the potential of VHE DOAS in MF buildings, the following objectives were defined to guide the investigation:

1. Evaluate the energy benefits of a VHE DOAS configuration in MF buildings compared with conventional balanced ventilation systems (Washington State Energy Code) and exhaust driven systems (code minimum in Oregon, Idaho, Montana).

2. Calculate the impacts of HRV/ERV unit controls for bypass capabilities on energy use and indoor comfort.

3. Methodology

An annual hourly energy model was used as the primary means to evaluate the potential benefits of VHE DOAS in MF buildings. A representative energy model was built based on the Downtown Emergency Service Center (DESC), Hobson Place development, a MF building with central DOAS units and apartment heating-only systems commonly used in the Northwest. The building was built in two phases, each to different energy efficiency standards, which helped inform how centralized balanced ventilation systems would be configured and designed. Operational data was also monitored in both North and South phase HVAC systems and used to calibrate a building energy model to represent system run-time accurately, and the heating energy needs as observed. Trends were not available for a full 12 months though the data gathered could be used to extrapolate the building needs for ventilation and heating. A depiction of the energy model is shown below:

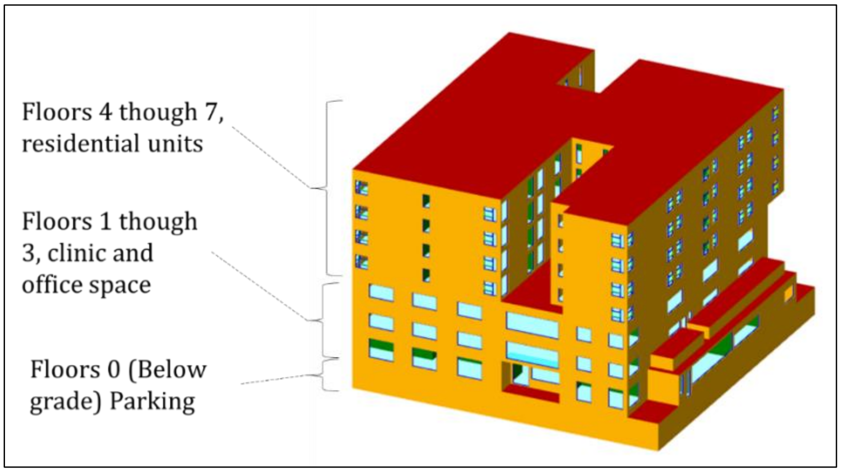


Figure 1: Energy Modeling Massing of the South Phase Building

Hobson Place apartments have individual electric resistance heating systems and manually operable windows for passive cooling; there is no mechanical cooling provided. An initial model with ventilation and a heating only system was built to calibrate the energy model to the observed heating trends from the site and to understand the impacts of simulating a model with and without operable windows and its effect on predicting energy use.

Using the calibrated energy model, a series of additional models were generated to compare three additional MF HVAC systems in different Northwest regions. Each case included apartment air source heat pumps providing heating and cooling with three different types of ventilation configurations:

1. Centralized balanced ventilation with basic efficiencies (meeting the WA 2018 code)
2. Centralized balanced ventilation with very high efficiency components, meeting the VHE DOAS standard
3. Exhaust driven ventilation systems

All energy models were built in Environmental Design Solutions Limited (EDSL) Thermal Analysis Software (TAS), a whole building hourly energy modeling software. This software evaluates building thermal energy performance and systems, including functionalities to define detailed building geometry, natural ventilation, daylighting, and advanced HVAC system configurations. TAS is developed, maintained, and licensed by EDSL. While initially developed for the United Kingdom (UK) market, the software is utilized worldwide and in the United States. It is validated against ASHRAE 140 and other building performance standards worldwide. The software was selected for its quick and effective ability to model a detailed building HVAC system with natural ventilation. EDSL-TAS provides a similar energy modeling environment to the Virtual Environment's (VE) Integrated Environmental Solutions (IES) software in terms of its functionalities for modeling natural ventilation and other elements of building simulation.

4. Background

4.1 About Balanced Ventilation in MF

In most MF buildings, ventilation air is provided by intentional air leakage through fixed ventilation openings in each apartment, moving air with either a local or central exhaust fan. The exhaust driven ventilation system is then coupled with unitized heating (per apartment) and depending on the climate, air conditioning. While this ventilation configuration is low cost to build and maintain, multiple studies have shown how inefficient this can be, resulting in high energy costs, particularly in colder climates. Further, the direct pathway of air into the building can make these types of configurations susceptible to poor indoor air quality, particularly with changes in outdoor air quality like wildfires and inability to add air filtration. The following table of benefits and drawbacks of balanced ventilation systems was provided in a guidelines report (Exemplary Buildings Program (EBP) December 2021) and summarized below.

PLUSES [+]	MINUSES [-]
Ventilation air is pulled in from the outside, not pulled in from your neighbors' homes or from other areas of the building	Increased capital and maintenance costs
Outside air is filtered, which is especially important where outdoor air quality is compromised, as is the case for buildings located near busy roads or ports, or for all buildings during a wildfire smoke event	Takes more effort to design and optimize systems than the previously accepted whole house exhaust fan systems
Ventilation air is not pulled through cracks in the building envelope, thereby reducing the contribution of uncontrolled air leakage to envelope failure	Usually requires more space, whether it be roof or floor area. Some system designs require building height to be increased
When combined with heat recovery, balanced ventilation generally reduces energy consumption, especially if electric resistance is used to heat the dwellings	Efficiency gains can be marginal if fan power is high, sensible heat recovery efficiency is low, or space is conditioned with very efficient heat pumps

Figure 2: Example benefits and drawbacks of balanced ventilation

4.2 About Hobson Place

DESC's Hobson Place is located south of downtown Seattle, Washington. The mixed-use project is owned and developed by DESC and offers supportive housing for disabled and formerly homeless people, and in partnership with Harborview Medical Center, an on-site healthcare clinic. The project was designed with the goal of reducing operational costs and energy consumption while creating healthy living spaces.

Figure 3: Downtown Emergency Center Building

The 2015 Seattle Energy Code (SEC) was the energy code for the entire development, which is 2015 WA State Energy Code (WSEC) with Seattle Amendments. However, because centralized ERVs are used to provide balanced ventilation for apartments, it is a reasonable proxy for a MF project built to 2018 WA State energy code. The construction of Hobson Place was completed in two phases:

Phase 1:

Hobson Place North was completed in October 2020 with 85 affordable studio apartments. This phase was generally built to satisfy the minimum requirements of 2015 Seattle Energy Code and Evergreen Sustainability Development Standard v3.0. However, it did include central energy recover ventilators (ERVs) to provide dwelling unit ventilation, which was not required by code but had become DESC standard practice based on earlier building design and analysis work.

Phase 2:

Hobson Place South is a seven-story building with the first three stories of Type 1 concrete construction for offices and healthcare services and an additional four stories of wood framing for the residential floors of 92 apartments. The project was completed in January 2022. Before breaking ground for Phase 2, the project secured additional funding and technical resources from the State of Washington and Seattle City Light, the local utility provider. With this additional funding, DESC pursued an all-electric Passive House design, leading to the residential floors being pre-certified to PHIUS+2018 standards, and currently awaiting final certification (Bicknell 2022)

The North and South phase HVAC systems differ from one another in four distinct ways:

a. The North ERV-DOAS units were designed with a lower heat recovery effectiveness and higher external static than the South units,

b. The ventilation distribution trunks of the North ERV-DOAS are located above the roof outside the conditioned envelope, exposing them to heat gains and losses,

c. The corridors of the North building are ventilated by a natural gas furnace in a make-up air unit, whereas the South corridors are ventilated by a passive ERV-DOAS units with no mechanical heating, and

d. The kitchen range exhaust hoods for cooking in each apartment in the North are ducted to the exterior and operate intermittently while the South uses locally filtered recirculating range hoods and continuous local kitchen exhaust by the ERV-DOAS.

The building elevation schematic below illustrates three of these key differences between the two building phases.

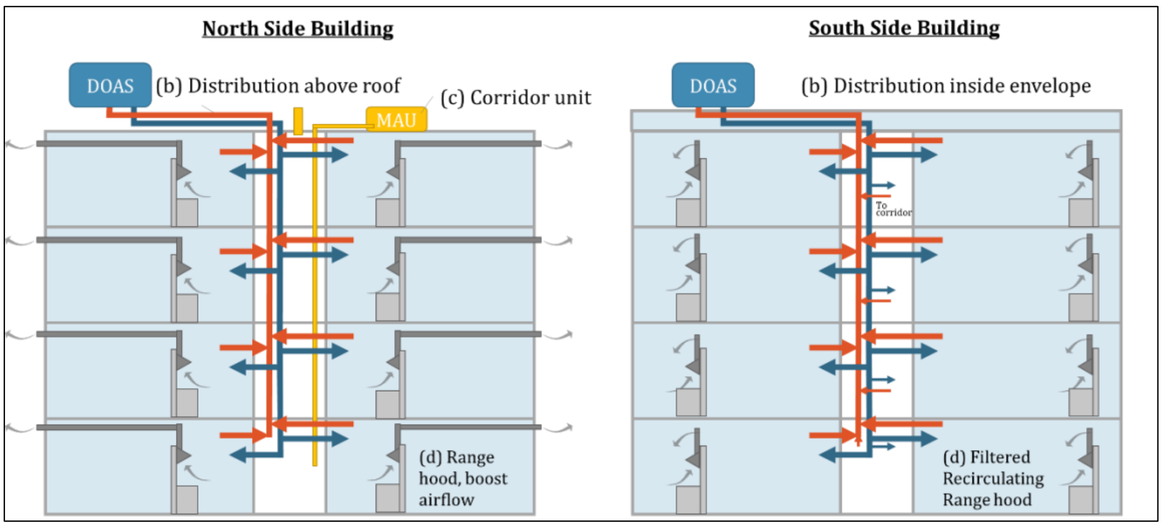


Figure 4: Hobson Place building elevation of HVAC system components for apartments

4.3 Very High Efficiency DOAS Specification

NEEA has developed the very high efficiency dedicated outdoor air system (VHE DOAS) requirements, which outlines how to select efficiency components and provides design recommendations and best practices for implementation (NEEA, Very High Efficiency DOAS Equipment & Design Best Practices for Optimal Efficiency Revised 2022). Research by NEEA has found decoupling the ventilation and using a VHE DOAS design can reduce HVAC energy by over 50% in commercial buildings. To-date, the primary focus has been on small commercial building applications such as offices, schools, and retail. The concept of decoupling the ventilation from space conditioning is captured in the diagram below.

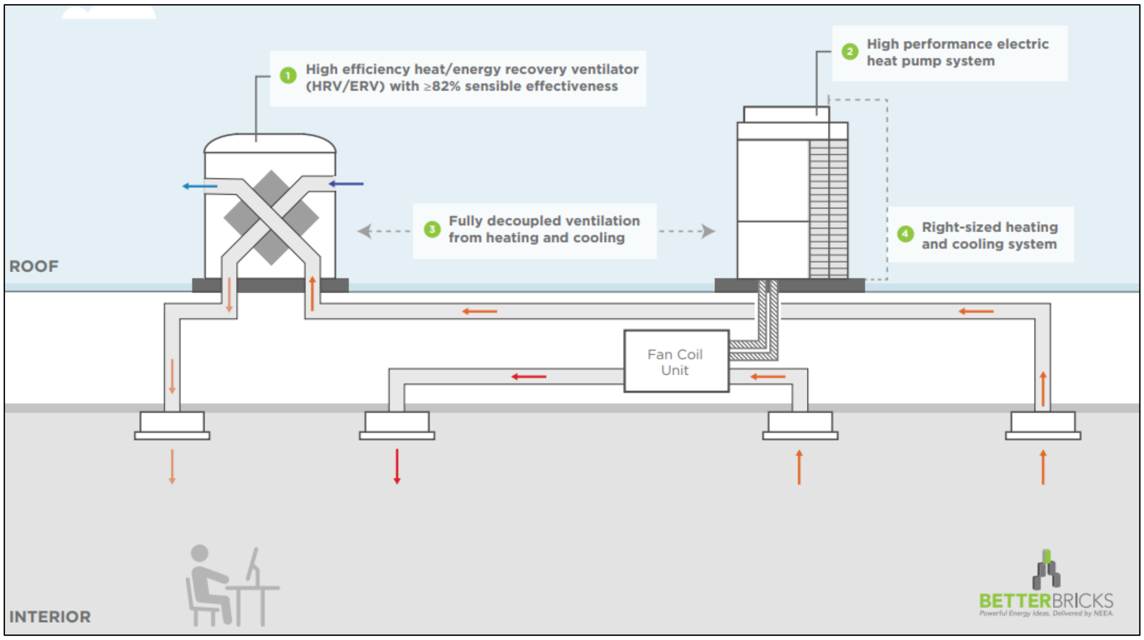


Figure 5: NEEA diagram of commercial building application of VHE DOAS

Additional detail can be found in previous reports by NEEA. The focus of this report will be on the potential benefits of these efficiency strategies in MF buildings.

4.4 Northwest MF Energy Codes

In the Northwest region covered by NEEA, buildings span four unique climate zones over three states. MF buildings greater than three stories are principally governed by three different Commercial energy codes: the 2018 Washington State Energy Code – Commercial (WSEC) in Washington (Washington State Building Code Council 2018 Edition), the ASHRAE 90.1-2019 energy standard in Oregon, and the IECC 2018 standard in Idaho and Montana. Additionally, local jurisdictions such the cities of Seattle, Shoreline and Bellingham have adopted more stringent energy code amendments to further reduce emissions from buildings.

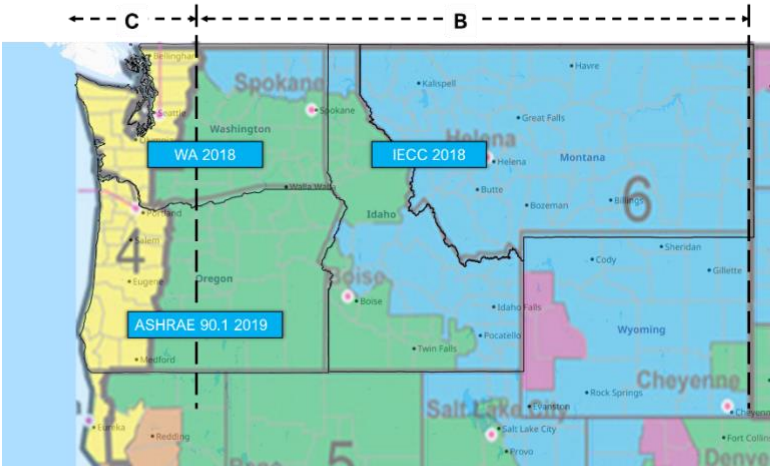


Figure 6: Climate Zones and Building Energy Codes Map of the Northwest

For MF buildings, the minimum efficiencies and systems requirements of the IECC 2019 and ASHRAE 90.1-2019 are nearly identical. These energy codes do not require apartments less than 500 sf in coastal climate zones (4C, 5C) to use balanced ventilation and exhaust air heat recovery, but in all other climate zones and larger sized units, heat recovery for heating is required. In the 2018 WSEC, all MF types are required to include ventilation heat recovery.

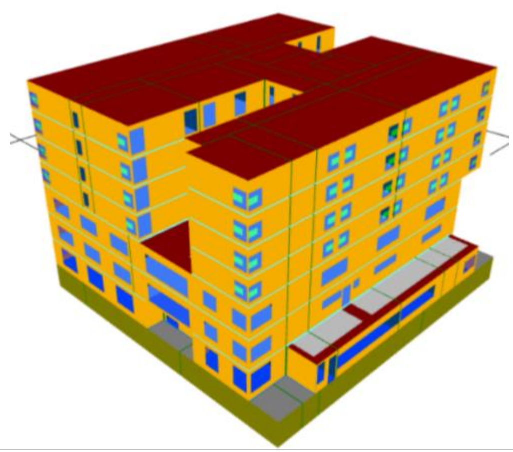
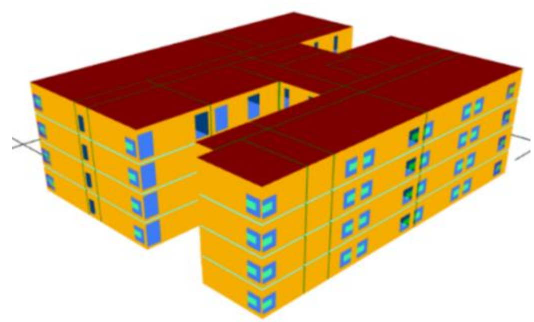
5. Results

5.1 Energy Model Development

5.1.1 Method

An energy model was developed based on the South phase of Hobson Place construction documents and systems as a representative MF apartment building. The building's floor plans, construction assemblies, and HVAC systems were used to construct the energy model. Floors 4 through 7 represent the apartment levels and were the primary focus of the energy model. The South Phase residential floor plan is shaped like an H with interior stairways and elevator shafts. The boundary walls in the garage and clinic spaces were built to meet airtightness and continuous thermal insulation specifications. Ventilation duct work on the south project was enclosed under the roof's air barrier to minimize roof penetrations and reduce the area of ductwork exposed to exterior conditions. The roof assembly included R-50 insulation and vapor barrier, which served as an air control layer.

The exterior wall assembly included 2 x 8 framing with R-30 batt insulation. All windows are triple-glazed with U-values of 0.18 or better, and the interior air seal perimeter was continuous on all four sides.

	
Whole building, apartments, clinic, and parking	Apartment levels only, 4 through 7

Measured data from the apartment levels were used to calibrate the energy model to accurately represent the thermal heating and cooling conditions. Since the apartments had only heating systems and operable windows for passive cooling, the energy model was calibrated to heating energy as a function of the outdoor air temperature and summer indoor temperature conditions as a function of outdoor air temperature.

Trend data for the MF apartments and their HVAC systems were gathered from the North and South phases of the building. The North side provided 15 months of data between May 2021 and July 2022, and the South side collected 7 months of trend data between February 2022 and August 2022. From the data, a calibrated model was developed for the North and the South. Each model was updated to match the construction documentation for the building's envelope and system configuration.

Table 1: Building envelope inputs for North and South phases

		North Phase, Design	South Phase, Design
Exterior Wall			
Construction		Wood Framed Wall, 2x8 with R-30 Blown-In batt	Wood Framed Wall, 2x8 with R-30 Blown-In batt
Overall U-factor	Btu/h-ft2-°F	0.044	0.044
Overall R-factor	h-ft2-°F/Btu	22.9	22.9
Exterior Roof			
Construction		Insulation above deck	Insulation above deck
Overall U-factor	Btu/h-ft2-°F	0.026	0.020
Overall R-factor	h-ft2-°F/Btu	38	50
Fenestration Windows			
Construction		Double Pane, Low-e Vinyl Frames	Triple Pane, Low-e Vinyl Frames
U-COG Glass	Btu/h-ft2-°F	0.26	0.181
U-factor/SHGC/VT		0.27/0.22/0.53	0.18/0.17/0.37
Air Barrier System			
Infiltration at Test	cfm/sf_enclosure	0.25 cfm/sf @ 75 PA	0.08 cfm/sf @ 75 PA
Infiltration Input	ACH	0.170 ACH Apartments	0.054 ACH Apartments

The energy model was configured to allow windows to be opened for cooling from natural ventilation. A moment in time is shown from the energy model below depicting the direction of airflow in and out of windows in the thermal zones.

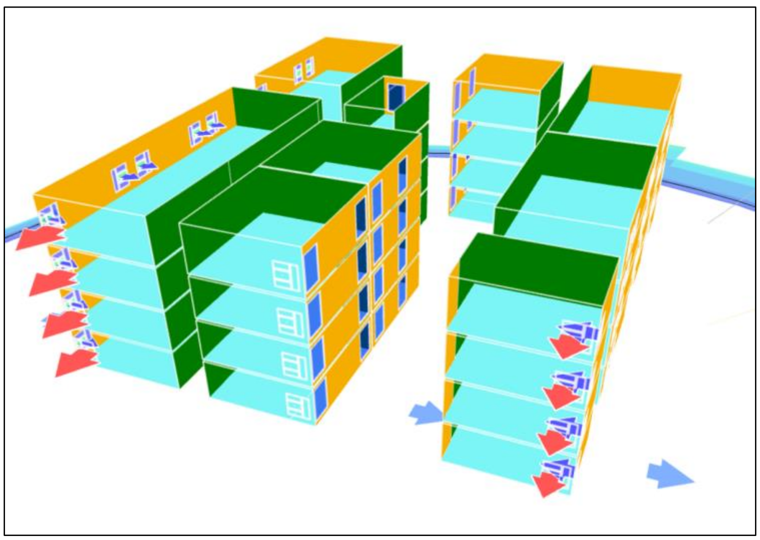


Figure 7: Natural ventilation as configured in the energy model for apartments with operable windows

Only a portion of the windows in each apartment were designed to be manually operable. Those windows, while manual, were controlled in the energy model to automatically open when indoor conditions reach 66F and to fully open at 70F. Windows were only opened to 15% of the free area and shut when outdoor temperatures reached 80F.

The energy models were simulated over a typical year in Seattle, WA with hourly and daily results used to calibrate the models to the measured data. Calibration was done by:

A. Configuring the building thermal envelope as designed

B. Implementing the ERV DOAS system with or without heat recovery bypass for each phase based on field measurements and observations of the controls

C. Configuring the ERV DOAS fan power as measured

D. Adjustments to the operable window control setpoints to tune the heating energy per day and the summer indoor temperature

Results of the calibration for each phase are shown for the heating energy and indoor air temperature compared with the measured performance.

5.1.2 Observations

HVAC System Configurations

The measured field data for the apartment ERV units were consolidated to estimate the operational fan power and heat recovery effectiveness for each system. Fan power directly impacts the net heating energy required by apartment space heaters and the heat recovery device and bypass configuration for both phases.

The table below summarizes the measured ERV-DOAS performance for North and South phase systems as compared to the original design specifications.

Table 2: Apartment HVAC System Efficiency Inputs

System Parameter	Units	North Phase, Design	South Phase, Design	North Phase, Measured	South Phase, Measured
Avg. Fan Efficiency	cfm_supply/Watt	0.442	0.787	0.37	0.94
Avg. Fan Efficiency	W/cfm_supply	2.26	1.27	2.67	1.06
Avg. ERV Sensible Recovery Efficiency (SRE)	%	80%	82%	72.0%	84.5%

The North phase ERV-DOAS units were designed for very high fan power, at 2.26 W/cfm of fan power and were measured at 2.67 W/cfm. These values represent the average power of the units serving the apartments on the North side, measured by the test and balance contractor from 2021. The high fan power is believed to be due to high pressure on the supply and exhaust duct work as well as high internal pressure criteria of the ERV-DOAS units. The South phase ERV-DOAS units were designed at 1.27 W/cfm and were measured on average at 1.06 W/cfm, less than 50% of the fan energy compared with the North.

Both phases were designed to achieve relatively high heat recovery efficiency, 80% and 82% sensible effectiveness for North and South, respectively. Based on the available measured data, the North ERVs underperformed, with the average effectiveness estimated at 72.0%, and the South system over performed, with the average effectiveness of 84.5%. The North phase ERVs included higher exhaust airflow than supply, with several units exhausting air which was supplied by a separate hallway makeup air unit with a dedicated furnace. This configuration of the makeup air unit with heating to the hallways, pressurizing the apartments to the exhaust is believed to be overestimating the North unit measured effectiveness values. This topic of hallway units versus apartment units was flagged as a potential area for further research though was not the primary focus of this report.

Apartment Heating Energy Intensity

Heating energy for mid-level apartments in the South and North were analyzed to develop a trend of daily heating use per apartment as a function of outdoor air temperature. Apartments on the top level with an exposed roof were reviewed as well.

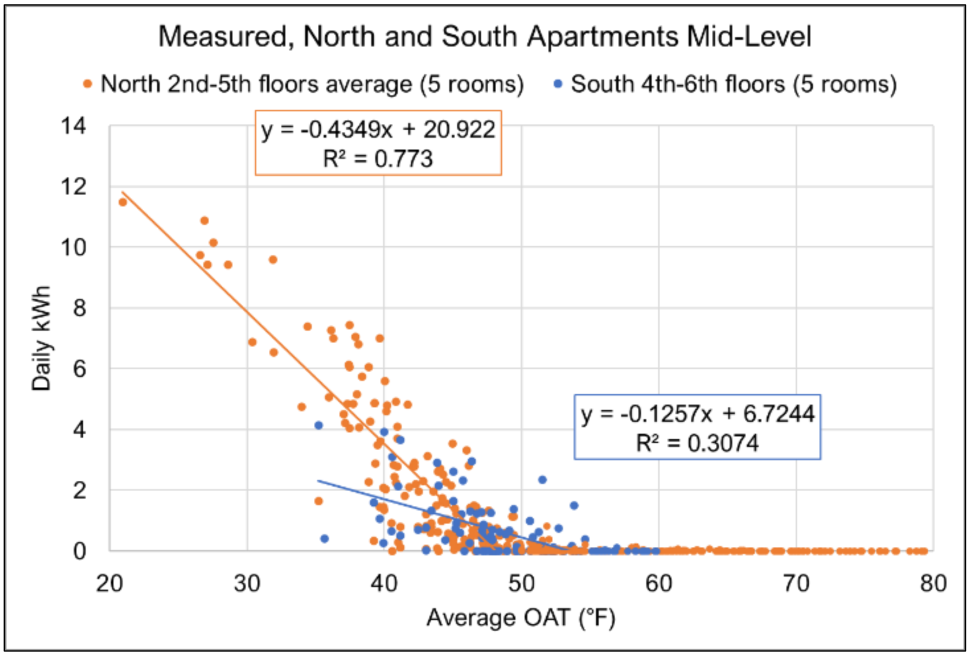


Figure 8: Measured heating energy for mid-level apartments, heating per day at the daily average OA temperature

Measured heating energy for mid-level apartments were aggregated for their daily heating energy and analyzed versus outdoor air dry bulb, as shown in Figure 8. The North phase apartments required approximately 9 kWh a day at 27F and 2.5 kWh a day at 45F. The South phase had fewer data points though was observed to have a lower heating intensity from the improved envelope and ERV DOAS unit. The South apartments required 2.5 kWh a day at 35F, down to 1 kWh at 45F.

The simulated results of the North and South phase are shown below in Figure 9.

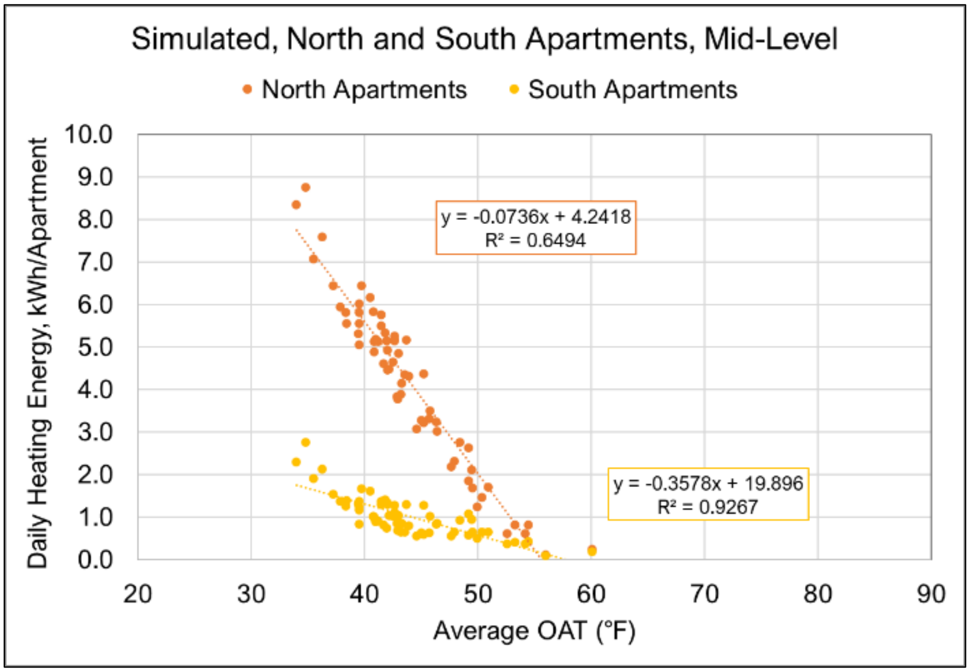


Figure 9: Simulated energy results of heating energy for mid-level apartments, heating per day at the daily average OA temperature

The model of the North was calibrated to require approximately 3 kWh per day at 45F up to 7 kWh a day for days averaging 35F of heating per apartment. The South model calibration required approximately 1 kWh a day at 45F up to 1.8 kWh per day at 35F. Both are considered reasonable approximations for the building given the data observed.

Apartment Indoor Summer Temperature

Neither the North nor South phase use active cooling, so the energy model was calibrated to the indoor temperature versus outdoor temperature for both phases. The average apartment temperature indoors was measured in North and South apartments, with data averaged together to identify the change in indoor temperature with the outdoor air conditions.

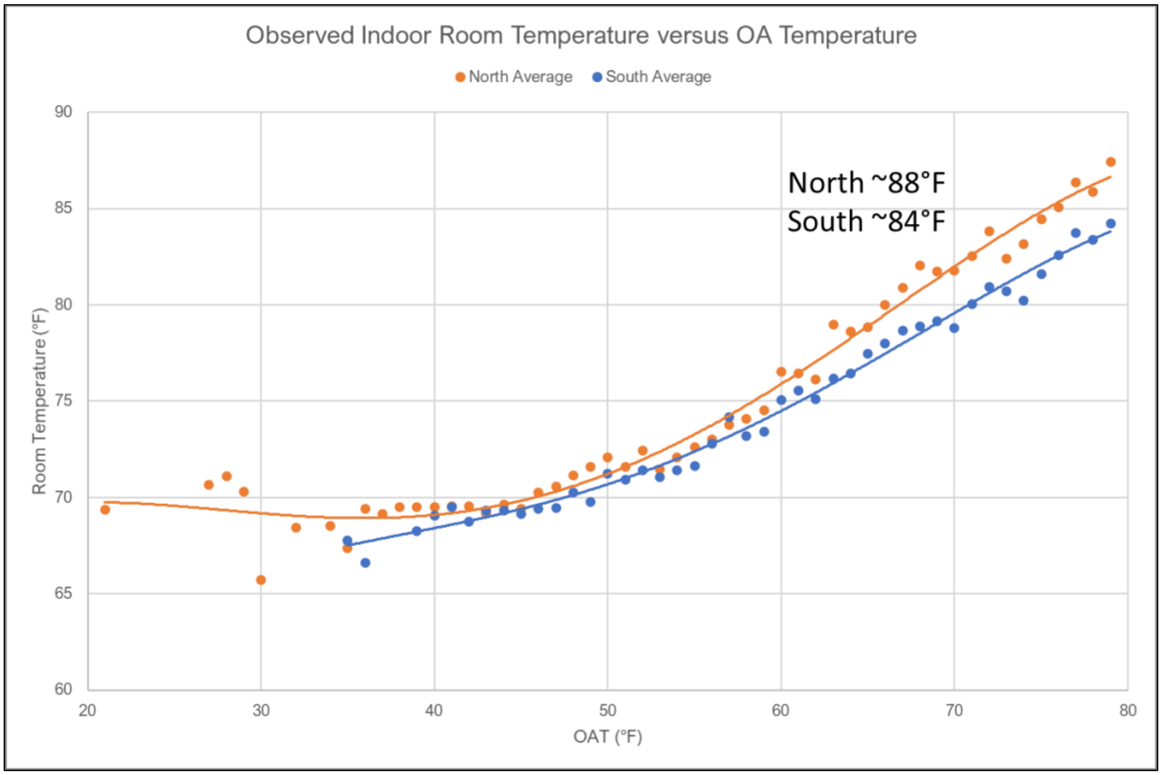


Figure 10: Measured apartment indoor air temperature, averaged daily data versus outside air dry bulb

The measured building found the North side to reach a peak average temperature of 88F and the South side apartments to reach a peak average temperature of 84F.

The same calibration for heating for the North and South resulted in similar trends in indoor temperature during warm months. The North side reached 87F at 80F outdoor air temperature and the South side model reached 82F at 80F outdoor air temperature.

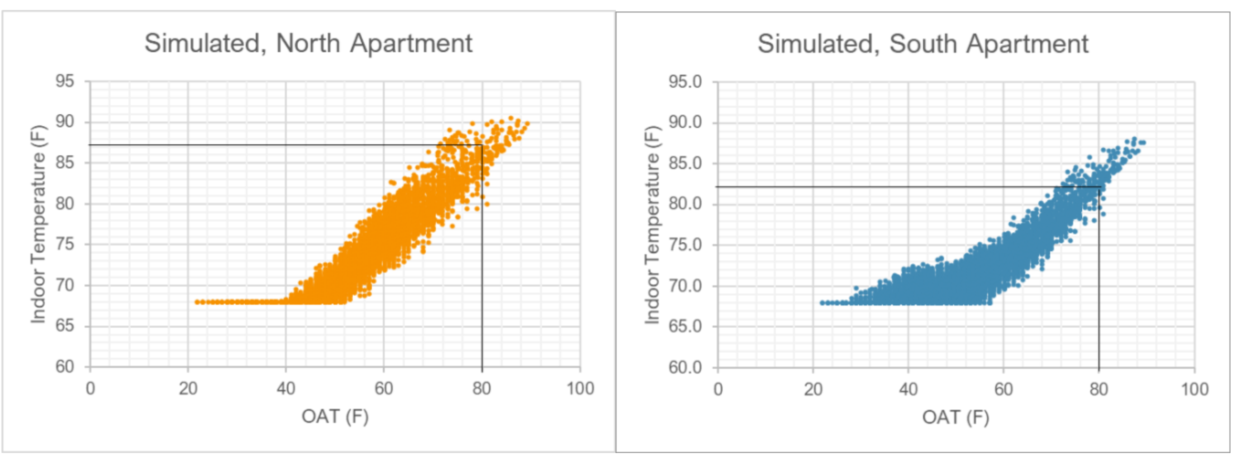


Figure 11: Simulated indoor air temperature for a typical apartment, North and South calibrated model

Additional comparisons from the measured data were completed, comparing the system performance for the North and South HVAC systems to the as-designed systems.

Estimated Energy Use of Calibration

The calibrated models were simulated for a typical year of operations to estimate the potential energy use of the North and South side. Results of the annual energy model for only the apartment levels are shown in the figures below.

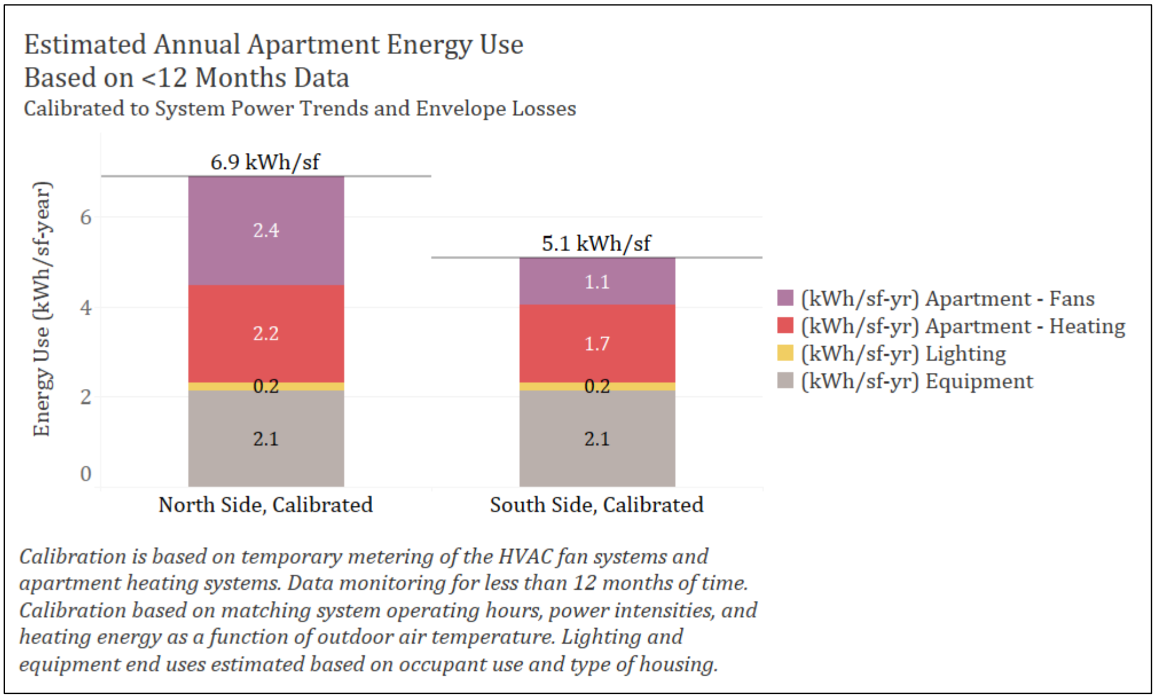


Figure 12: Annual energy use estimated for the North and South apartments, based on partial calibration of electric HVAC end uses. Furnace heat in North MAU not included.

The North side apartments were estimated to use 6.9 kWh/sf of energy for HVAC, lighting, and equipment. Service hot water was not included in the simulated model and would be in addition to these values. The South side was estimated to use 5.1 kWh/sf, 26% less energy than the North.

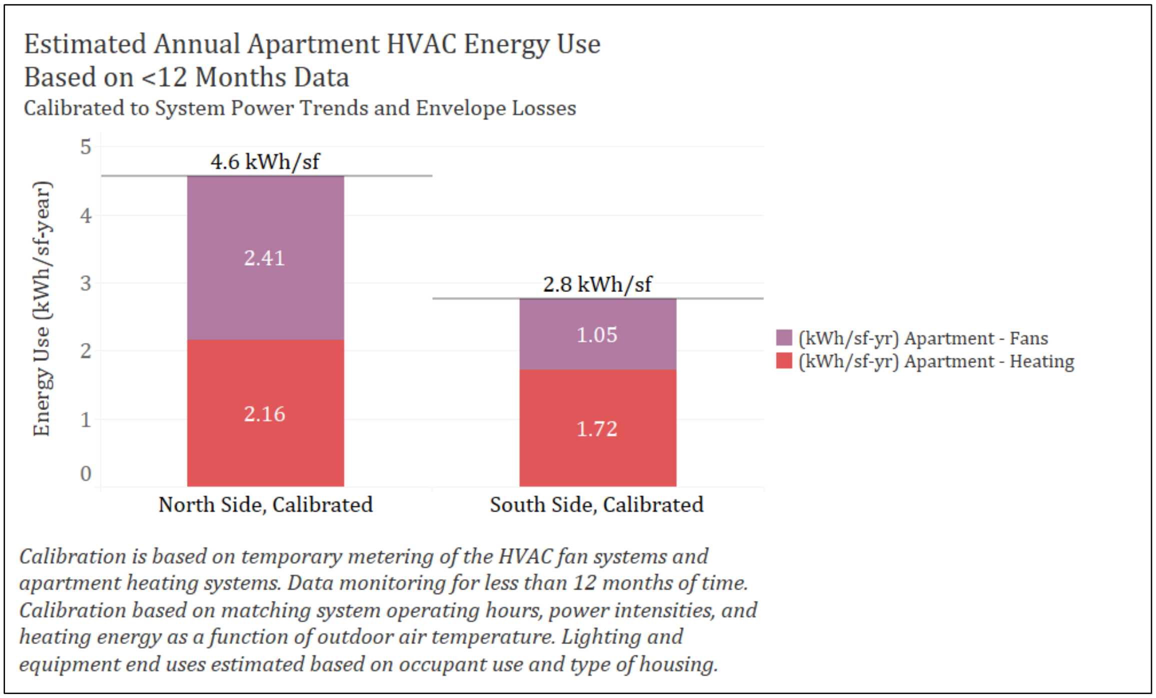


Figure 13: Annual HVAC only energy use estimated for the North and South apartments, based on partial-calibration of HVAC end uses.

Evaluating the HVAC use of the apartments in more detail, Figure 13 shows the energy use for the electric heating elements and the ventilation and exhaust fans. The North apartments use over 2x the fan energy compared with the South. The heating energy use of the North side was estimated to be 25% higher than the South due to differences in the construction envelope and ventilation heat recovery devices. The high fan energy of the North side apartments also contributes heat to the apartments from the fan motors, which are located in the ventilation supply path. If the North had utilized a more efficient fan system, the heating requirement would have been even greater.

5.2 HVAC System Analysis

5.2.1 Methods

Having verified the energy model for heating energy needs and indoor temperature with the field measurements, the model was then used to isolate the energy difference between three HVAC systems for the apartments:

1. Exhaust driven ventilation, as defined by ASHRAE 90.1-2019 and IECC 2018,
2. Balanced ventilation with centralized ERV-DOAS units, as defined by the WA 2018 energy code, and
3. Balanced ventilation with centralized ERV-DOAS units, as defined by the NEEA VHE DOAS system specifications.

Across all simulations, the following assumptions were made:

1. The building envelope was set to WA 2018 code minimum constructions,

2. The operable windows were simulated for manual control as determined in the calibrated modeling phase,
3. Apartments were simulated with unit-by-unit heat pumps, providing heating and cooling,
4. Corridor spaces were assumed to be on a dedicated DOAS unit and heat pump with the same efficiencies as the apartment systems, and

The three HVAC configurations evaluated are shown in a schematic diagram of the building elevation in Figure 14.

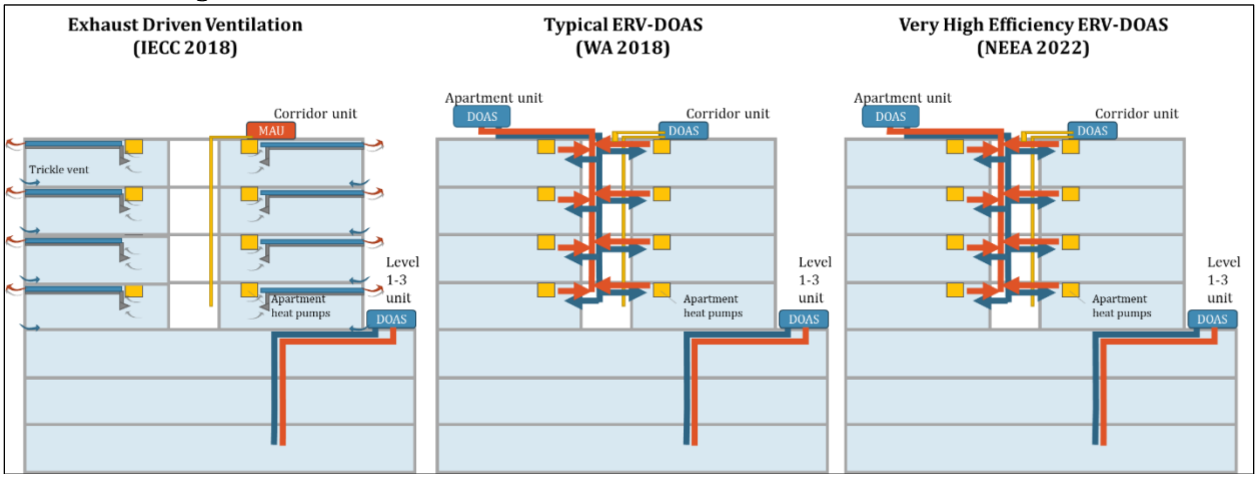


Figure 14: Regional HVAC energy efficiency configurations evaluated. WA 2018 and NEEA 2022 have identical system configurations with different efficiencies.

While the design of the building utilized natural ventilation along with electric heating, the research team choose to select a system with active air conditioning to make the comparison more holistic in comparing cooling energy differences.

The models were simulated in four locations, representing three climate regions:

1. Seattle, Washington (CZ 4C)
2. Boise, Idaho (CZ 5B)
3. Helena, Montana (CZ 6B)

Key inputs from each HVAC system are summarized below in Table 3.

Table 3: Regional efficiency analysis key HVAC system inputs

Property	Units	IECC 2018 Apartment Levels	WA-DOAS Apartment Levels	VHE-DOAS Apartment Levels
Ventilation / Exhaust Fans	w/cfm	0.35	1.00	0.56
Zone HP Fan	w/cfm	0.35	0.35	0.35
Ventilation Routing	desc.	n/a	To HP	To HP
Heat Pump Fan Control	desc.	On/Off	On/Off	On/Off

Ventilation Heat Recovery	% sens	none	60%	82%
Bypass Control	yes/no	None	None	Yes
Economizer	desc.	None	None	Ventilation
Rated Cooling	#	14 SEER	14 SEER	16 SEER
Rated Heating	rating	8 HSPF	8 HSPF	9.5 HSPF
Compressor Cooling	COP	3.84	3.84	4.13
Compressor Heating	COP	3.81	3.81	4.11

Results were evaluated in energy use and energy cost, assuming a flat energy rate across the region of $0.08/kWh. Domestic hot water (DHW) was not the primary focus of this evaluation, and all DHW systems were modeled as electric resistance.

5.2.2 Observations

The results of the energy analysis of the MF building with three different HVAC systems are shown below for Seattle, WA (climate zone 4C).

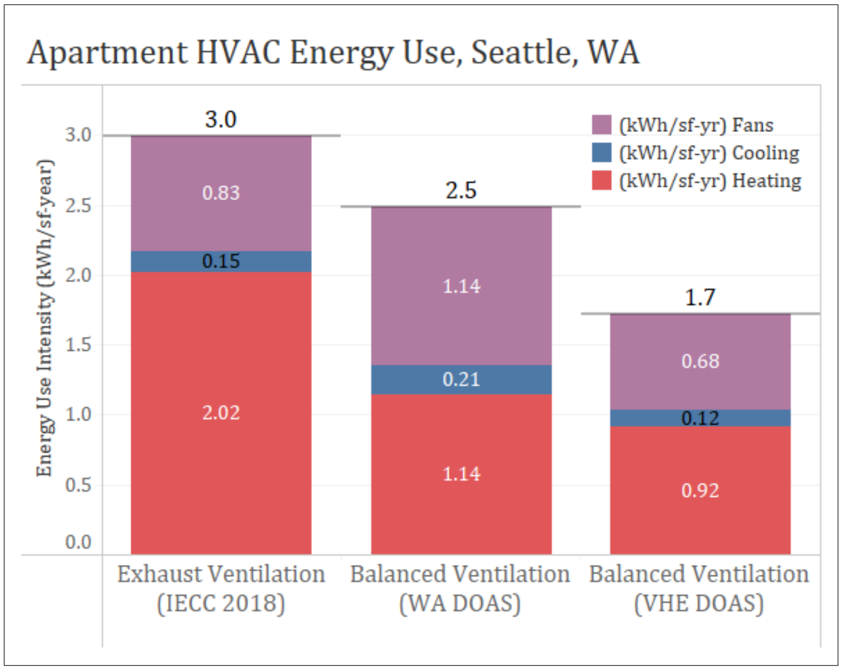


Figure 15: Apartment HVAC energy use of three HVAC systems, Exhaust ventilation, WA DOAS, and VHE DOAS, Seattle, WA

The VHE DOAS system reduces HVAC energy use by 43% compared with the exhaust ventilation system and by 32% compared with the code minimum balanced ventilation system.

The primary reduction in HVAC energy is in space heating and fan energy. In both balanced ventilation systems, shown as the WA DOAS and VHE DOAS, fan energy increases from adding the supply fan and exhaust duct work otherwise not used in an exhaust only ventilation system. In the VHE DOAS system, fan energy is then reduced by designing the system with high efficiency fans and motors, low pressure components, and low-pressure ventilation air delivery duct work. Cooling energy is reduced in the VHE DOAS system by utilizing an ERV unit with bypass capabilities, allowing the ventilation air to provide free cooling when outdoor conditions allow. The model is configured with a bypass controller to enable full bypass at 65F outdoor air to 75F.

HVAC only energy use is shown in Figure 16 for all climate zones simulated to better compare the energy savings of each system.

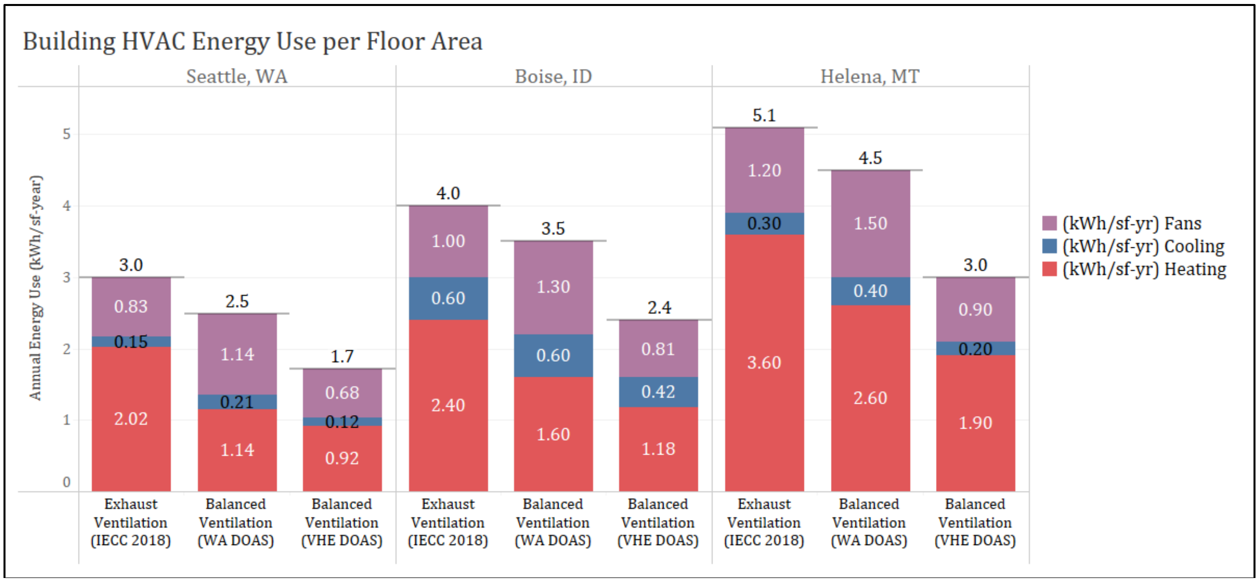


Figure 16: HVAC end use estimates of three HVAC systems, Exhaust ventilation, WA DOAS, and VHE DOAS, all climate zones

HVAC energy use is shown for the clinic areas and the apartment areas in fan energy and heat pump energy. Heat pump energy accounts for the heating and cooling energy. Fan energy includes all fans in each respective system. For balanced ventilation scenarios, this includes the DOAS supply and exhaust fan, and the fan energy of each heat pump. Comparing the exhaust ventilation scenario to the WA DOAS balanced ventilation, fan energy increases from adding dedicated ventilation supply fan though the net HVAC energy is reduced from the ventilation heat recovery device. In the VHE DOAS balanced ventilation, utilize overall less fan energy by reducing thermal loads from a very high efficiency heat recovery device and minimizing the amount of time a heat pump fan is running.

The relative HVAC energy use in percent HVAC energy savings to exhaust ventilation and WA DOAS balanced ventilation are shown for he apartment only in Table 4.

Table 4: Relative HVAC energy savings of VHE DOAS to the Exhaust Ventilation and WA DOAS systems for all climate zones

HVAC Energy Savings Relative to IECC and WA DOAS Systems

	HVAC Scenarios	Seattle, WA	Boise, ID	Helena, MT
(%)MF HVAC Savings, IECC	Exhaust Ventilation (IECC 2018)	0%	0%	0%
	Balanced Ventilation (WA DOAS)	17%	13%	13%
	Balanced Ventilation (VHE DOAS)	43%	40%	39%
(%) MF HVAC Savings, WA Code	Exhaust Ventilation (IECC 2018)	-20%	-14%	-14%
	Balanced Ventilation (WA DOAS)	0%	0%	0%
	Balanced Ventilation (VHE DOAS)	31%	32%	30%

From the apartment HVAC energy use only, the WA DOAS configuration saves 14% HVAC energy on average compared with traditional exhaust driven ventilation systems across the four cities evaluated. The VHE DOAS configuration reduced HVAC energy use by 41% on average compared with the exhaust driven ventilation system.

5.2.2.1 Daily Energy Use

Energy use for fans, cooling, and heating were plotted for daily energy use per apartment versus the average daily outdoor air temperature. Reviewing the trends of each of the three HVAC systems shows how different systems save or use more energy seasonally.

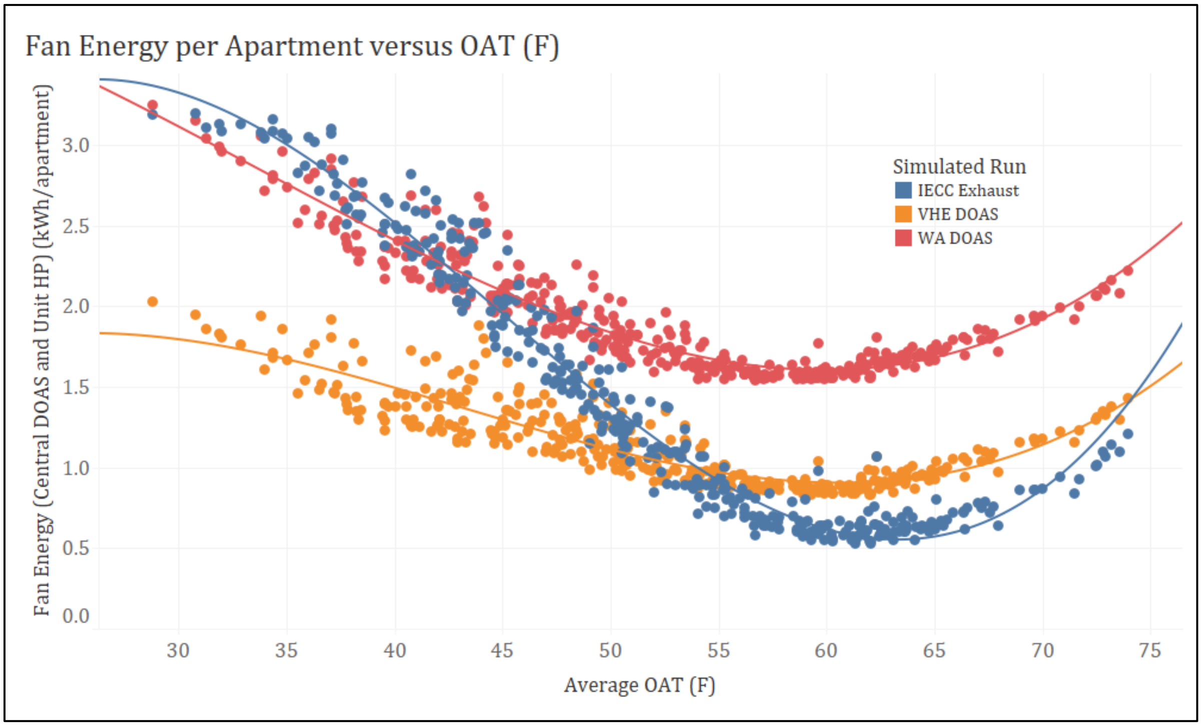


Figure 17: Daily fan energy per apartment versus outdoor air dry bulb, Seattle, WA

Figure 17 shows fan energy per apartment per day for each system. On cold days, the exhaust drive ventilation system and the WA DOAS use nearly the same fan energy per day. The exhaust driven system fans are a result of using a heat pump with a fan to move heat, while the WA DOAS system is the combined ERV fan and a heat pump fan. The VHE DOAS on the other hand is able to reduce the heating load from a high efficiency ERV and use less fan energy. VHE DOAS uses approximately 2 kWh/day per apartment at 30F while both of the other systems use nearly 3.2 kWh/day per apartment. On warm days, the exhaust driven ventilation system uses the least energy as a result of only having a heat pump fan and a single exhaust fan and no supply fan. While the VHE DOAS system uses more fan energy on warm days, 1.4 kWh/day versus 1.1 kWh/day, the net savings annually from VHE DOAS fans results in lower fan energy.

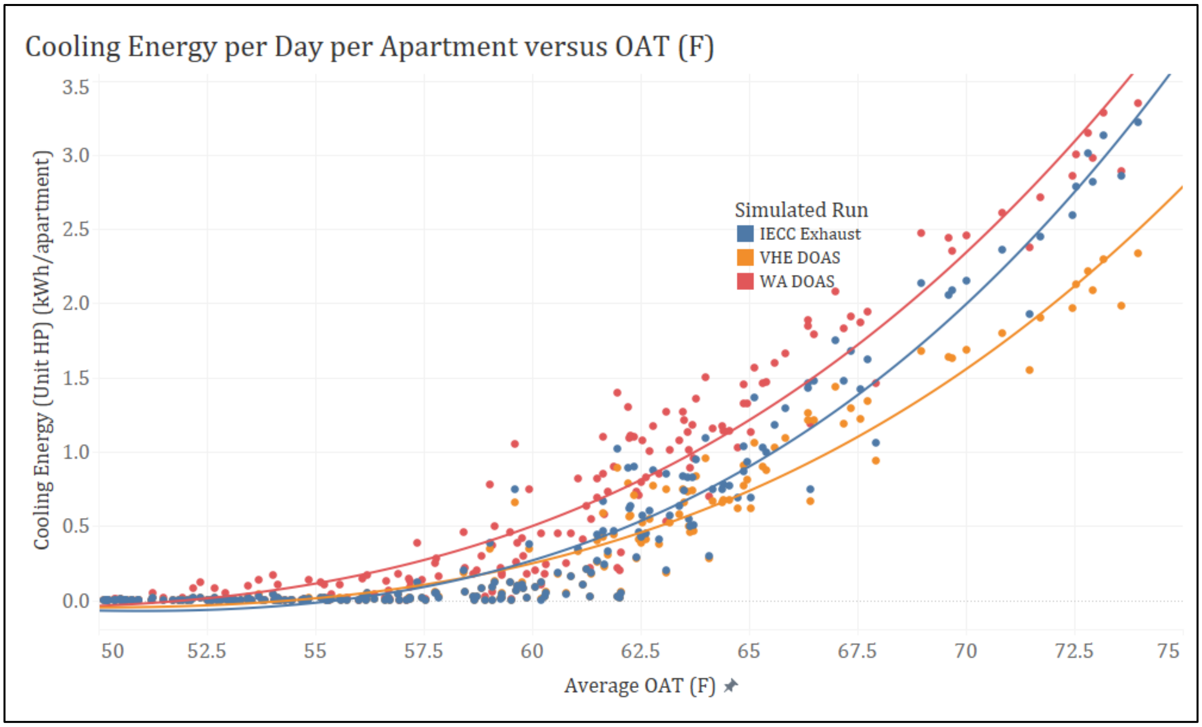


Figure 18: Daily cooling energy per apartment versus outdoor air dry bulb, Seattle, WA

Figure 18 shows the daily cooling energy per apartment for the three systems. All systems show an increase in cooling energy at 60F outdoor air. At warmer temperatures, the VHE DOAS system uses less energy than the other two due to the very high effectiveness of the ERV system and with integrated bypass control allowing the ERV to not recover heat during optimal conditions for free cooling. The IECC Exhaust energy model uses less cooling energy than the WA DOAS in this analysis due to ventilation air being drawn in by an exhaust-only system, where the WA DOAS uses a supply fan which introduces fan heat into the apartments and can increase cooling loads.

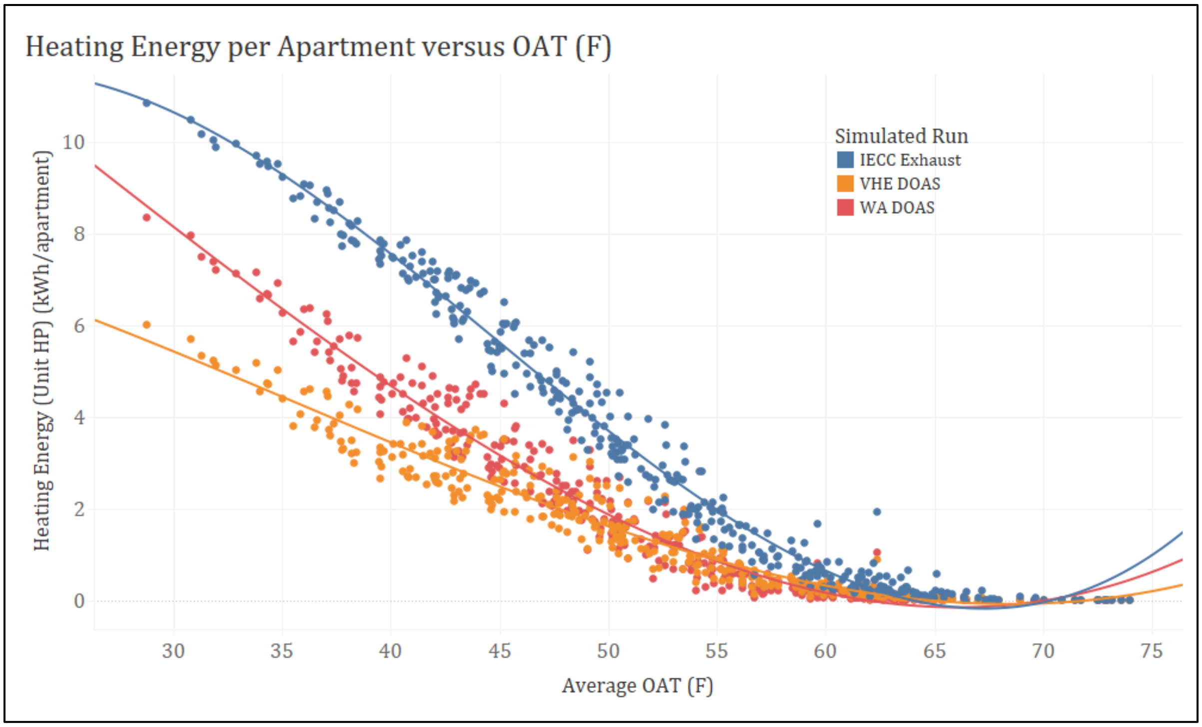


Figure 19: Daily heating energy per apartment versus outdoor air dry bulb, Seattle, WA

Figure 19 shows the daily heating energy per apartment for each HVAC option. Heating energy in MF buildings in the northwest is the largest portion of HVAC energy. At 30F outdoor air temperature, the exhaust driven ventilation system uses nearly 5.7 kWh/day per apartment, while the WA DOAS system uses 4.2 kWh/day per apartment (26% reduction) and VHE DOAS uses 3.2 kWh/day per apartment (44% reduction). Both systems with an ERV for ventilation track similar levels of heating requirements between 60F and 45F outdoor air temperature, though in colder conditions the VHE DOAS outperforms the WA DOAS.

5.2.2.2 Whole Building Monthly HVAC Energy

The monthly HVAC energy use and cost were evaluated for each HVAC system to understand the seasonal variation in energy use and how ventilation heat recovery reduces energy use in the extreme parts of winter and summer. Results are presented for Seattle, WA for the three systems in Figure 20 to Figure 22.

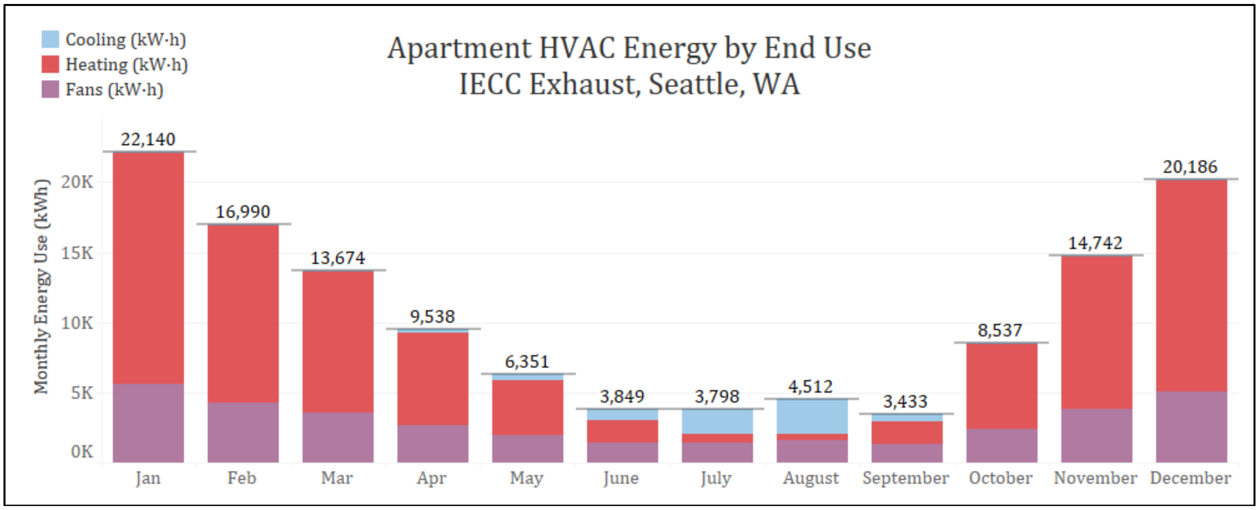


Figure 20: Monthly HVAC energy use, Exhaust Ventilation, Seattle, WA

From the exhaust ventilation system, the winter months show the highest energy use, 20,000 kWh a month in December and January, from heating and an increase in fan energy to provide the heat. HVAC energy in summer months drops signficantly, to 3,400 to 4,500 kWh per month in June through September.

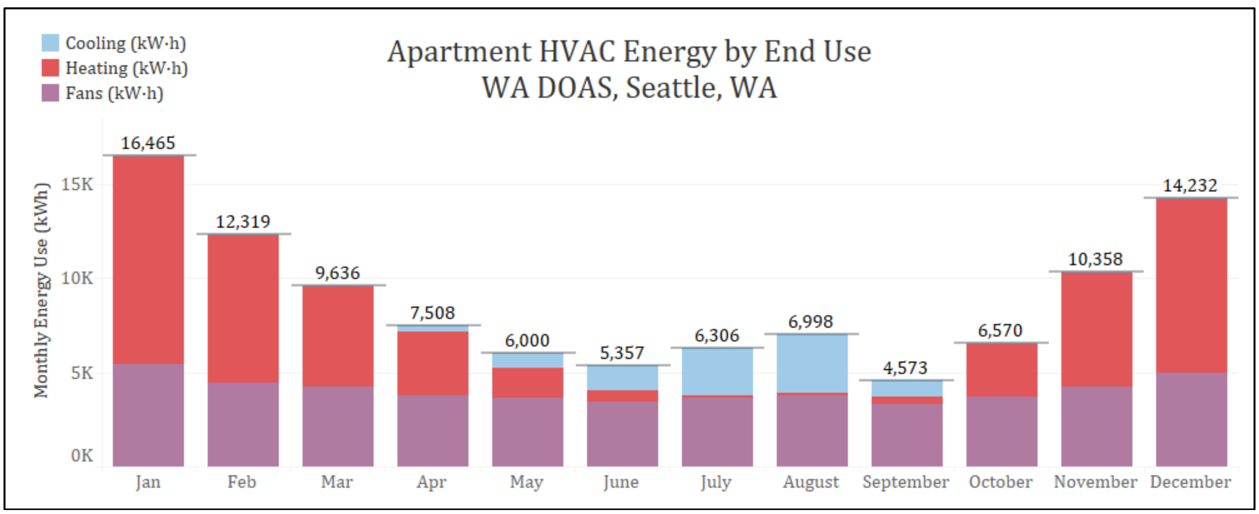


Figure 21: Monthly HVAC energy use, WA DOAS System, Seattle, WA

With a heat recovery ventilator built to the WA DOAS energy code, the winter energy is reduced, 14,000 kWh in Decemeber and 16,000 kWh in January, though summer energy increases, 5,000 to 7,000 kWh. The increase in summer energy is due to continual heat recovery without bypass capabilities and higher fan energy from utilizing a supply and exhaust fan for ventilation.

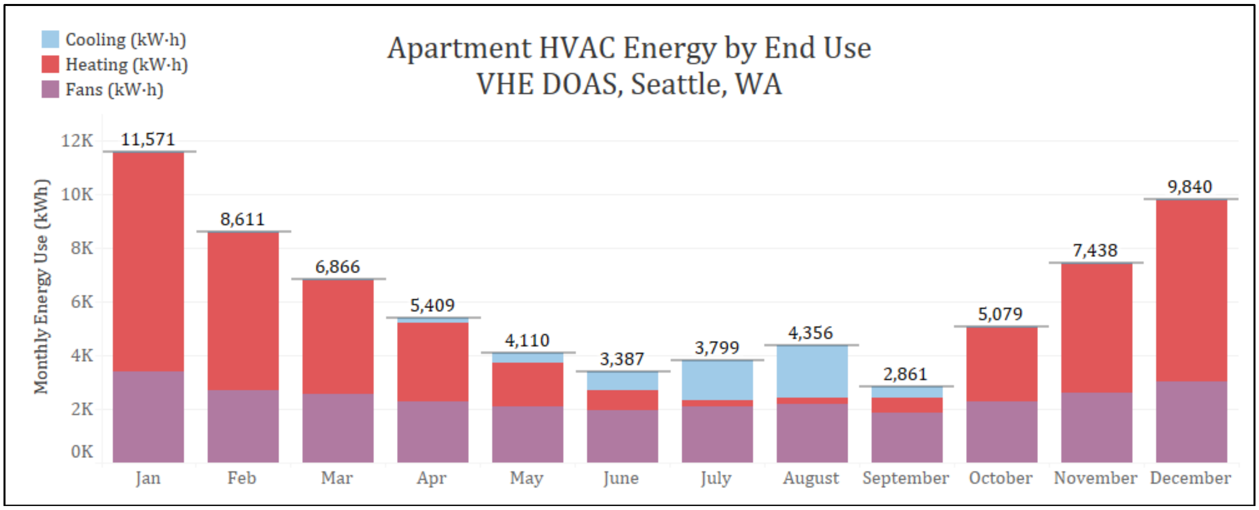


Figure 22: Monthly HVAC energy use, VHE DOAS System, Seattle, WA

With a very high efficiency heat recovery ventilator built to the VHE DOAS requirements, the winter energy is reduced to 10,000 to 11,500 kWh in December and January, and summer energy is maintained between 3,000 and 4,300 kWh a month. While the HRV unit includes bypass capabilities the slight increase is due to the unit being controlled in a basic configuration based on outdoor air temperatures to approxmiate building cooling or heating.

5.3 Assessment of VHE DOAS Bypass Controls

5.3.1 Method

Bypass capability and controls for an HRV/ERV unit can allow for free cooling from ventilation air during warmer seasons when the outdoor air is mild. Different systems provide bypass capabilities in different ways, either through a dedicated bypass air pathway or in many rotary wheel devices, stopping or slowing the wheel from spinning to disable or reduce heat recovery. In all configurations, the setpoints that enable and disable the bypass are typically configured when the system is installed, setting them once. Determining the most efficient setpoints for a building depends on the building's type and construction. MF buildings tend to have lower internal heat gains compared with offices or schools, which can result in a need for higher heating energy.

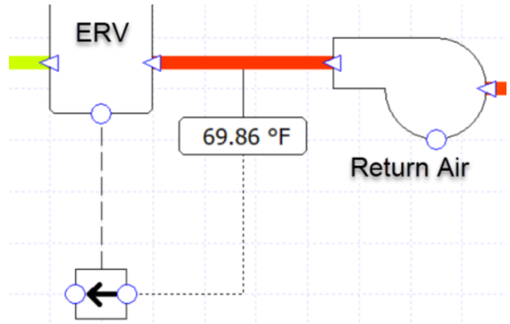
For the Hobson place building, the North phase systems were configured without bypass controls, recovering heat at all conditions. The South phase utilized an outdoor air setpoint to enable and disable bypass at set temperatures. These two configurations, along with two additional setpoint limit configurations, one alternative integrated bypass biased for heating, one non-integrated bypass, were simulated using the market analysis energy model with the VHE DOAS configuration. This model includes apartment heat pumps and provides results of each control sequence for heating and cooling thermal load needs. Models were evaluated in Seattle, WA climate only to understand the impact of these control configurations.

Control Configurations

The four configurations simulated include a base reference with no bypass, and three configurations where the temperature setpoints when bypass starts and stops. For each instance, four setpoints were defined: when bypass starts, when the bypass is fully enabled and heat recovery is fully disabled, when the bypass starts to close, and when the bypass is fully closed. Each configuration setpoints are described and shown below.

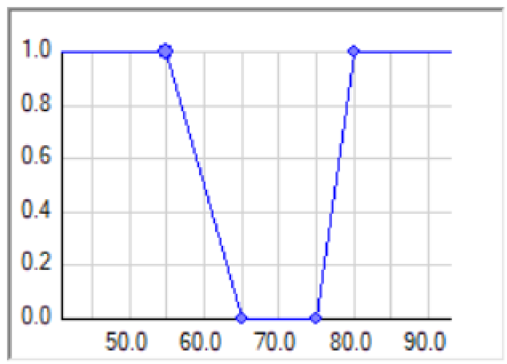
Without Bypass

The model was configured to control the heat recovery device to maintain the return air temperature, which enables the heat recovery device to run at 100% at all times. The diagram shows a portion of an ERV system, where the ERV is controlled to track the return air setpoint and never bypass.



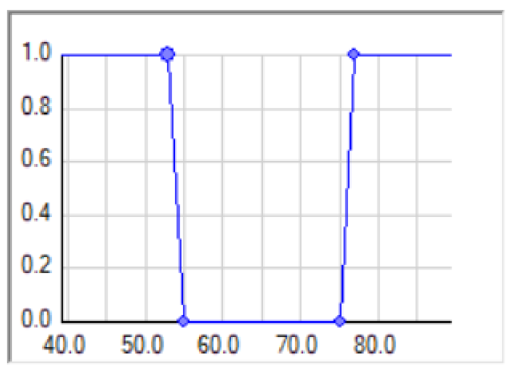
Integrated bypass at 55F to 75F, 65F-75F at 100% bypass

This configuration was created to reflect control points which are biased to reduce heating energy. This configuration enables bypass starting at 55F outdoor air and is fully bypassed at 65F. The systems then directly economize until outdoor air temperatures reach 75F and the bypass will start to close, fully closing by 80F



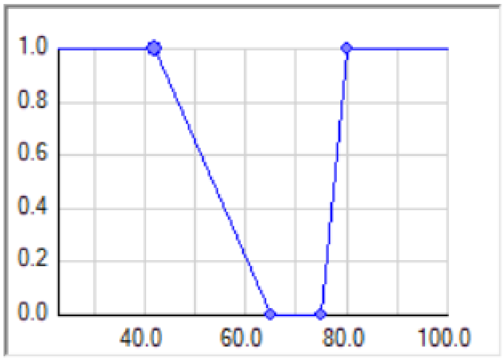
Non-integrated bypass 55F to 75F

This configuration enables full bypass at 55F outdoor air until 75F. The system includes a minimum ramp (2F) to enable stable simulation of the non-integrated control, in reality this is a simple on/off control.



Integrated bypass at 42F to 75F, 65F-75F at 100% bypass

This configuration matches how the South phase ERV units were configured and enables bypass starting at 42F outdoor air and is fully bypassed at 65F. The systems then directly economize until outdoor air temperatures reach 75F and the bypass will start to close, fully closing by 80F



5.3.2 Observations

The annual energy model results of each bypass configuration is presented below in Figure 23 for the VHE DOAS system, simulated in Seattle, WA.

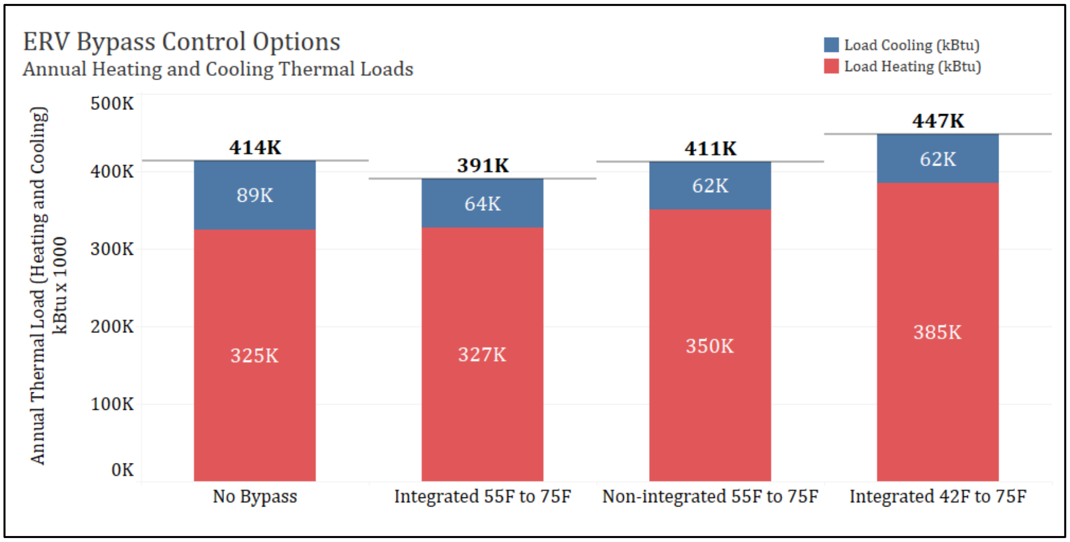


Figure 23: ERV Bypass Control Impact on Annual Heating and Cooling Loads

These numbers represent the thermal load for apartment heat pumps and excludes the load recovered by the ERV unit. No Bypass resulted in the lowest heating loads and the highest cooling loads. The Bypass 55F to 65F configuration resulted in the lowest thermal load, resulting in a 6% reduction in net thermal load and a 28% reduction in cooling load. Both Bypass configurations which started at 42F and 45F show a similar level of cooling load reduction, however, the heating load in both increases substantially, with the Bypass 45F to 55F increasing the total annual thermal load by 14% compared to No Bypass.

A diagram of the Bypass 55F to 65F control is shown in Figure 24 when the system is in partial bypass, operating at 70.8% of heat recovery and 30.2% of the air being bypassed.

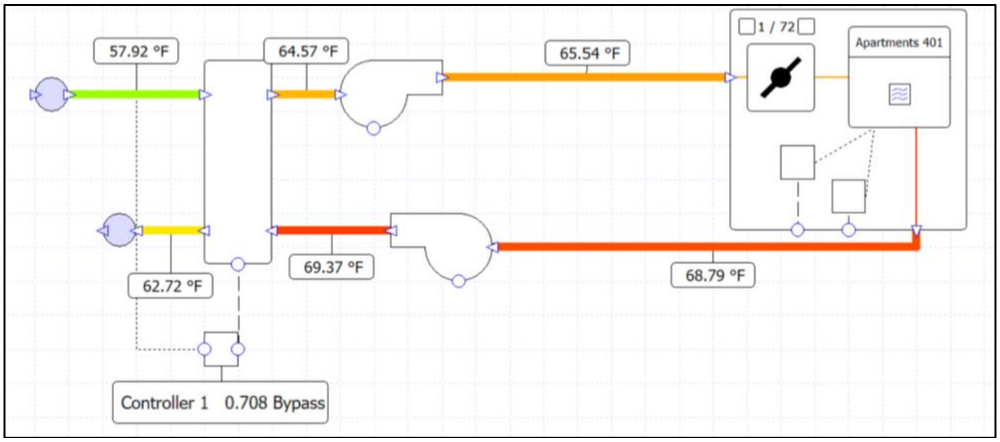


Figure 24: ERV System Diagram of Bypass Control, integrated 55F to 75 in bypass mode

For each simulated configuration, the supply air temperature of the ERV before the supply fan was plotted versus the outdoor air temperature. All four configurations are shown below.

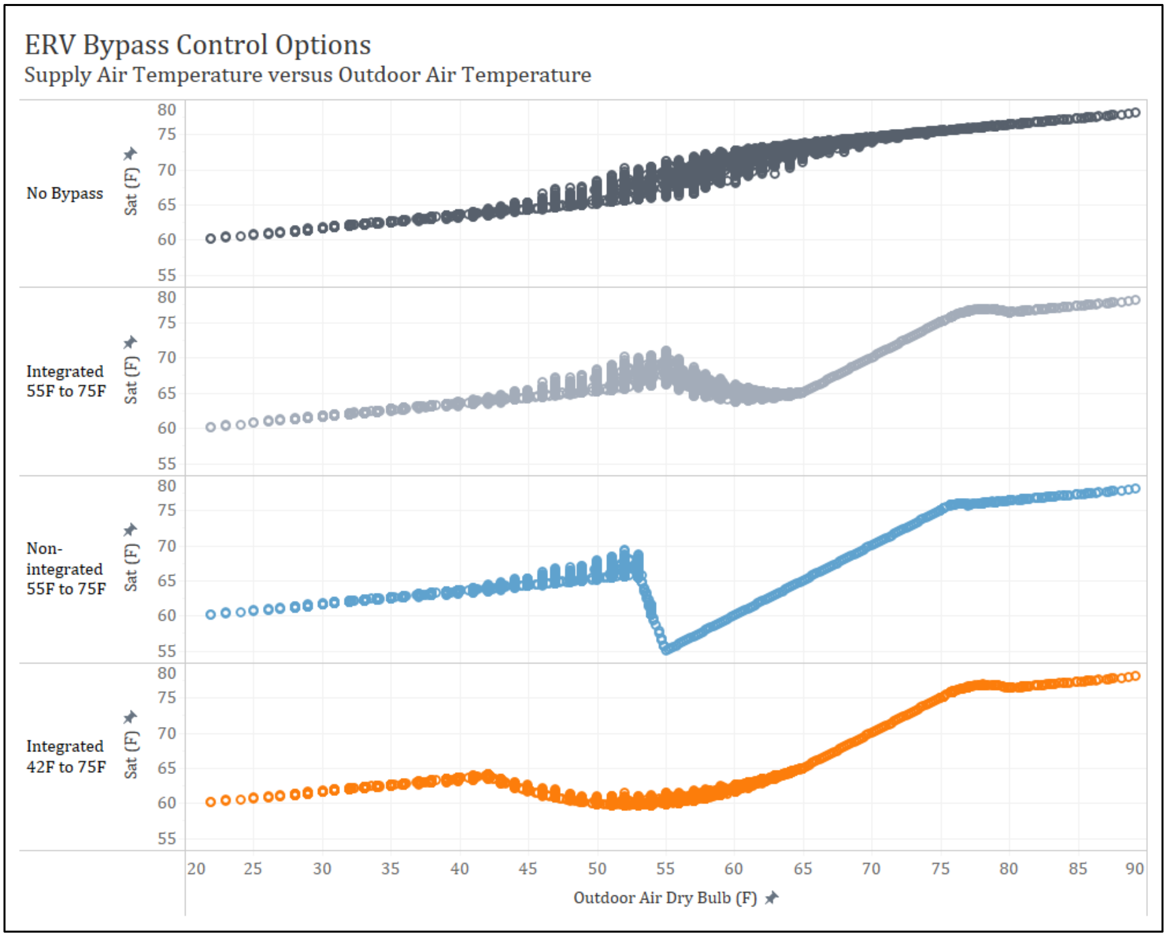


Figure 25: ERV Bypass configuration supply air temperature versus outdoor air temperature

For each configuration, the lower limit where bypass is enabled is visible as the supply air temperature drops after this point until the unit is fully bypassed. The supply air in each control then follows the outdoor air until the unit is fully shut at 80F in all configurations.

With No Bypass, the first thermal load profile shows the lowest heating energy and the highest cooling energy. The greatest difference in cooling energy between the configurations can be observed at outdoor air bins of 62.5F to 70F. In the last two bypass configurations, shown in blue and orange, the heating energy increases as the bypass starts to be enabled, with the greatest difference in heating energy at the outdoor air bin of 50F.

6. Conclusions

The VHE DOAS system was evaluated for HVAC energy savings in multi-family (MF) buildings in the Northwest and compared with a code minimum balanced ventilation system, built to WA 2018 code, and exhaust driven ventilation, code minimum in OR, ID, and MT. The energy analysis evaluated a MF building assuming each unit included operable windows and individual heat pumps for heating and cooling. The code minimum balanced ventilation system reduced HVAC energy by 14% on average and the VHE DOAS balanced ventilation system reduced HVAC energy by 41%, an increase of 27% HVAC energy savings compared with exhaust driven ventilation systems. Based on these findings, the research team believes the principles of VHE DOAS are applicable for MF buildings and can provide a structure for defining best practices in high efficiency components, configurations, and controls.

Cooling Energy Benefits

Cooling energy only accounts for 4% to 7% of the total HVAC energy use. Though cooling is a small portion of annual energy, the VHE DOAS configuration reduced cooling by 43% compared with a code minimum balanced ventilation system by utilizing an ERV unit with bypass control capabilities and a high sensible heat recovery ratio.

ERV/HRV bypass controls can provide a source of free cooling in buildings without active air conditioning. As observed in the field monitoring results for Hobson place, the South phase utilized a heat recovery bypass and a high-performance envelope. It maintained an indoor temperature of 4 deg F lower than the North phase during warm summer days.

Heating Energy Benefits

Most HVAC energy savings were attributed to heating and fan energy. In heating dominated climates such as the Northwest, fan energy can be a form of unintended heat, with the heat from the supply fan motor entering the ventilation air stream. While beneficial in the winter, this additional fan heat can result in warmer supply air in summer conditions, which can be problematic, either negatively impacting thermal comfort in buildings without active cooling or, increasing energy in buildings with cooling. As observed in the VHE DOAS system, using an HRV/ERV device with high efficiency heat recovery and efficient fans can be a winning strategy to maintain low heating energy while avoiding fan heat when not desired.

Ventilation Air Quality Benefits

Using balanced ventilation, either centralized or unitized, can provide an increased level of air quality for MF buildings by controlling and filtering outdoor air. In many exhaust driven ventilation systems, outdoor air is directly introduced, often in an open vent incorporated into a window, without the ability to filter the air. With wildfires occurring more frequently or, for any buildings within proximity of major roadways, air quality can fluctuate throughout the year. Using balanced ventilation, either from a VHE DOAS system or others can provide increased resilience to tenants.

Monthly Energy Costs

As shown in the regional assessment of VHE DOAS in the MF building, using this configuration, compared with exhaust driven ventilation and lower efficiency balanced ventilation systems (WA 2018 code), can reduce the swing in energy costs from shoulder seasons to peak winter and summer seasons. Minimizing the change in monthly energy costs can create stability and predictability for tenants living in low-income housing. A study by Fisher Sheehan & Colton found that low-income households pay proportionally more than the average household for energy costs (Fisher 2003). Further, research conducted by ACEEE found that families who face higher energy burdens experience many negative long-term effects on their health and well-being (Drehobl and Ross 2016).

Optimized HRV/ERV Bypass Control

Bypass control of an HRV/ERV can be used to provide free cooling during mild weather conditions by directly introducing outdoor air without recovering the heat from air being exhausted out of the space. When this occurs is typically controlled by the outdoor air temperature directly or by setting a supply air temperature setpoint. The analysis found that for MF buildings in the Northwest, using a control which is biased towards heating savings, bypassing fully from 65F to 75F, can be the most advantageous for energy efficiency and still achieve free-cooling savings. Scenarios analyzed at lower temperatures, bypassing fully at 55F, found that heating energy dramatically increases with little to no additional cooling benefits.

7. Future Research Recommendations

Throughout evaluating the Hobson place and developing the analysis of VHE DOAS, the research team discovered areas that could potentially enhance energy efficiency in MF buildings. Several items presented in the paper touch on these areas, such as the analysis of HRV/ERV bypass controls, though not all ideas were thoroughly evaluated. The items identified for future evaluation include:

1. Exploring what unitized products exist for ERV/HRV units which may be able to meet the VHE DOAS criteria and a comprehensive energy analysis and life-cycle cost evaluation of unitized vs centralized ventilation systems for MF buildings.
2. An assessment of duct sealing and test and balance (TAB) methods for central MF DOAS. Given the very low individual apartment airflows, and extensive duct systems, poor airflow measurement accuracy and duct leakage could result in needing much higher system airflow setpoints, which has significant impact on design fan power and heat recovery effectiveness.
3. The impact of hallway/corridor ventilation and conditioning systems on apartment HVAC systems overall. Several buildings still utilize makeup air-only units or DOAS units with heat pumps and no heat recovery.
4. In centralized balanced ventilation systems, where the outdoor air ERV unit is located on the roof and serves apartments through vertical shafts, evaluate the impact of insulating the portion of the duct work outside the thermal envelope on heating and cooling.
5. In heating only buildings, during warm and hot weather, how could passive cooling or small active cooling elements be introduced into the HVAC design to reduce thermal discomfort and heat stress? Strategies for consideration:
    a. In central DOAS, temper DOAS air using a heat pump to provide partial cooling in the summer, and offset a portion of electric resistance heating energy in the winter
    b. Room by room ceiling fans integrated into the room thermostat controls to expand thermal comfort based on research at the Center for the Built Environment[1] at University of California, Berkeley
6. In HRV/ERV units, what functionalities exist for bypass control in unitized systems as well as centralized? What level of energy savings can be achieved by utilizing bypass control that utilizes partial bypass versus fully on/off?

[1] https://cbe.berkeley.edu/research/advanced-ceiling-fan-design-tool/

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Appendix 1 Energy Model Input Assumptions

Building Constructions

		Market Assessment Assumptions
Exterior Wall		
Construction		Wood Framed and Other Walls
Overall U-factor	Btu/h-ft2-°F	0.040
Overall R-factor	h-ft2-°F/Btu	25
Exterior Roof		
Construction		Insulation above deck
Overall U-factor	Btu/h-ft2-°F	0.026
Overall R-factor	h-ft2-°F/Btu	38
Fenestration Windows		
Construction		Double, Low-e Vinyl Frames
U-COG Glass	Btu/h-ft2-°F	0.38
U-factor/SHGC/VT		0.38/0.38/0.53
Air Barrier System		
Infiltration at Test	cfm/sf_wall	0.25 cfm/sf @ 50 PA
Infiltration Input	ACH	0.170 ACH Apartments

Building Internal Gains

Primary Space Type Assumptions for Equipment, People, DHW

Space Type Name	People Density [sf/per]	Occupant Density [People/sf]	Equipment & Lighting Power Density [W/sf]
Health Care Clinic	200	0.01	0.70
Apartments	348	0.00	1.00
Stairways	10000	0.00	0.00
Storage, Inactive	10000	0.00	0.20
Corridors Level 1-3	5000	0.00	0.00
Corridors Level 4-7	5000	0.00	0.00
Electrical/Mechanical	0	0.00	0.40
Waiting Area (lobby)	33	0.03	0.20
Restrooms	0	0.00	0.2
Parking Garage	33	0.03	0.70
IDF/MDF	0	0.00	2.00

Lighting Power Assumptions

Space Type Name	Design: Lighting Power Density [W/sf]	source design
Health Care Clinic	0.50	*RCA*
Apartments	0.00	in equipment
Stairways	0.40	*equest south*
Storage, Inactive	0.35	*equest south*
Corridors Level 1-3	0.26	*equest south*
Corridors Level 4-7	0.26	*equest south*
Electrical/Mechanical	0.20	*RCA*
Waiting Area (lobby)	0.72	*WA 2015*
Restrooms	0.78	*WA 2015*
Parking Garage	0.15	*WA 2015*
IDF/MDF	0.50	*RCA*

HVAC Systems

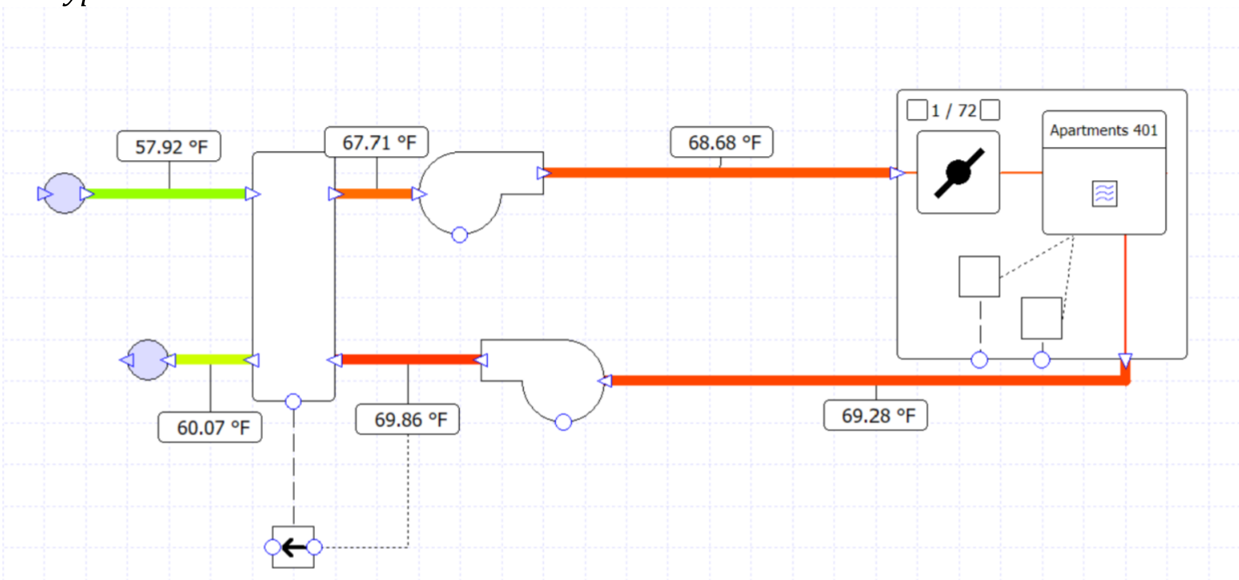
Detailed HVAC inputs for the regional energy analysis for fan and heat pump systems in the clinic offices and apartments.

Apartment Levels		IECC 2021	WA-DOAS	VHE-DOAS
Ventilation		Exhaust Ventilation with Trickle Vents	ERV-DOAS Central	ERV-DOAS Central
Heating/Cooling		Heat Pump Units	Heat Pump Units	Heat Pump Units
Ventilation Exhaust Fans				
Fan Efficiency Ventilation & Exhaust	W/cfm	0.35	1.00	0.56
Supply Fan	W/cfm	0.00	0.60	0.34
Exhaust Fan	W/cfm	0.35	0.40	0.22
Heat Recovery Effectiveness	%	-	0.60	0.82
Heat Recovery Supply Air Control		-	SAT 65F Constant, No bypass	Bypass, starting at 42F to 65F fully open
Heat Pumps				
Supply Fan	W/cfm	0.35	0.35	0.35
Unit Capacity Range	Btu/hr	<65,000 Btu/hr	<65,000 Btu/hr	<65,000 Btu/hr
Cooling Rated System Efficiency	EER	14 SEER	14 SEER	16 SEER
Heating Rated System Efficiency	HSPF	8.0 HSPF	8.0 HSPF	9.5 HSPF
Modeled Cooling Efficiency	COP	3.84	3.84	4.13
Modeled Heating Efficiency	COP	3.81	3.81	4.11

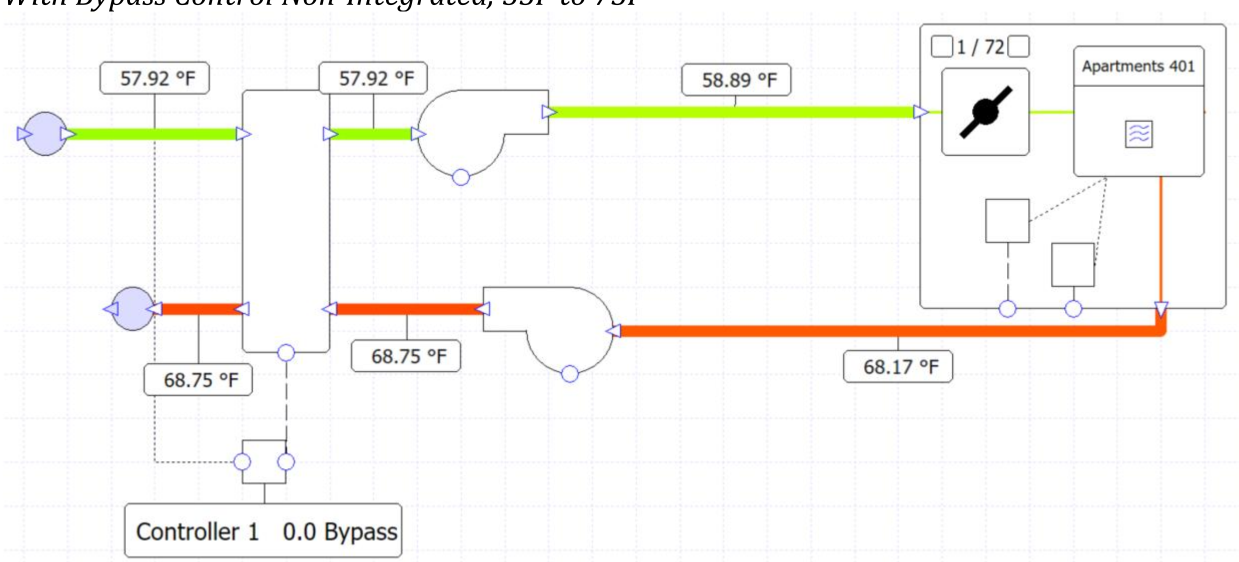
Bypass Configuration Diagrams

The following are system configurations of each of the four bypass controls evaluated in the report. The system diagrams show the same instance in time, taken at 2pm on the 11th day of the year for each system to show the state of the bypass.

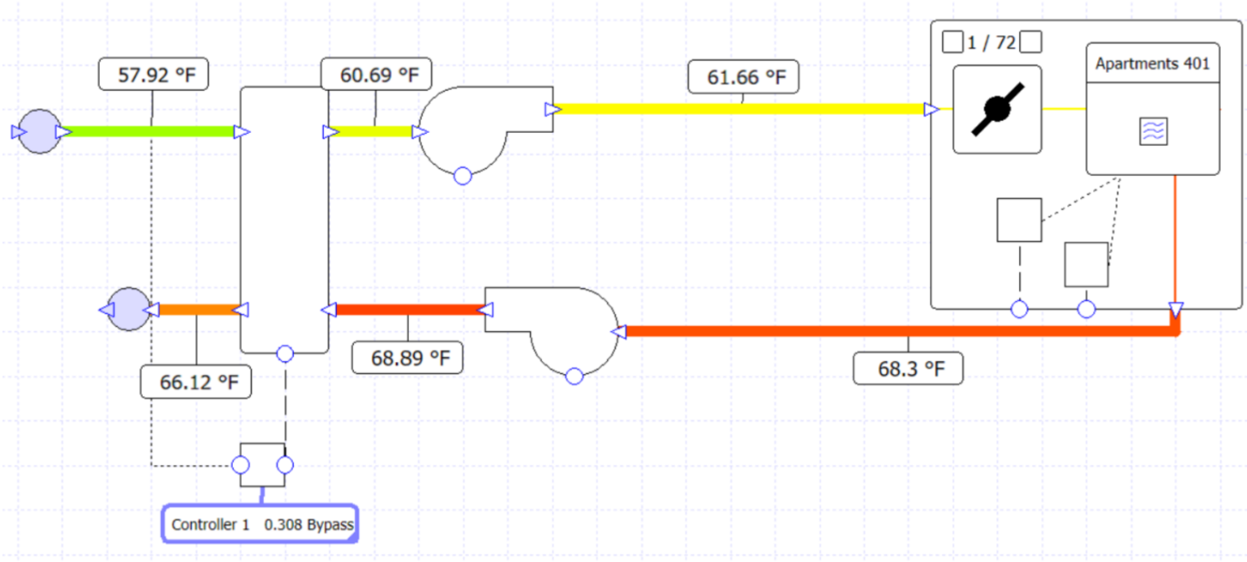
No Bypass Control



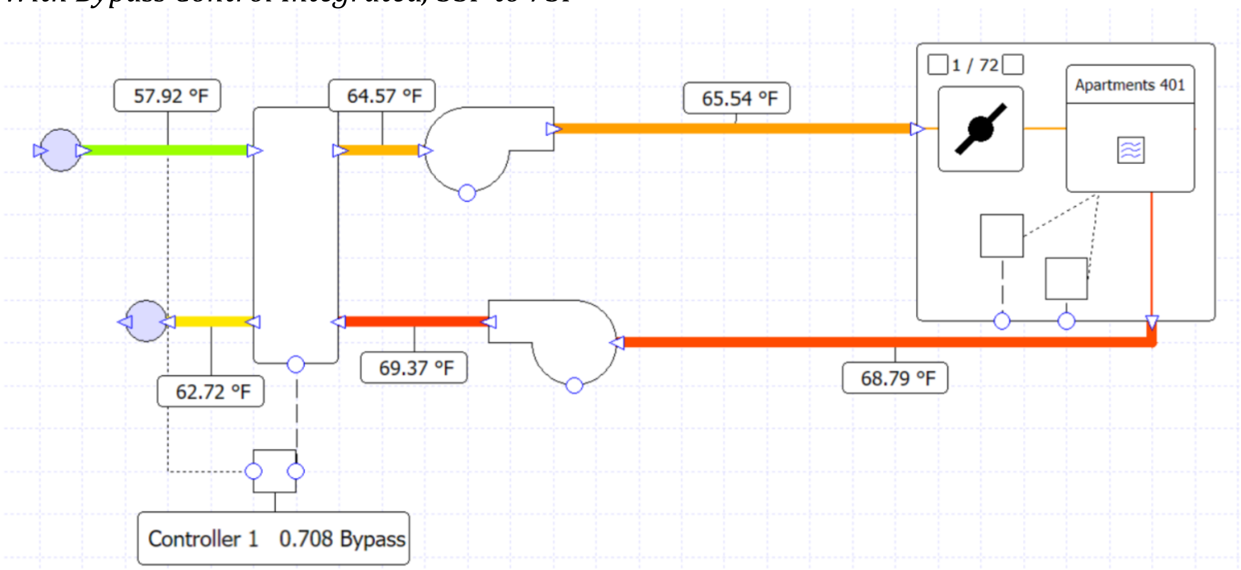
With Bypass Control Non-Integrated, 55F to 75F



With Bypass Control Integrated, 42F to 75F



With Bypass Control Integrated, 55F to 75F



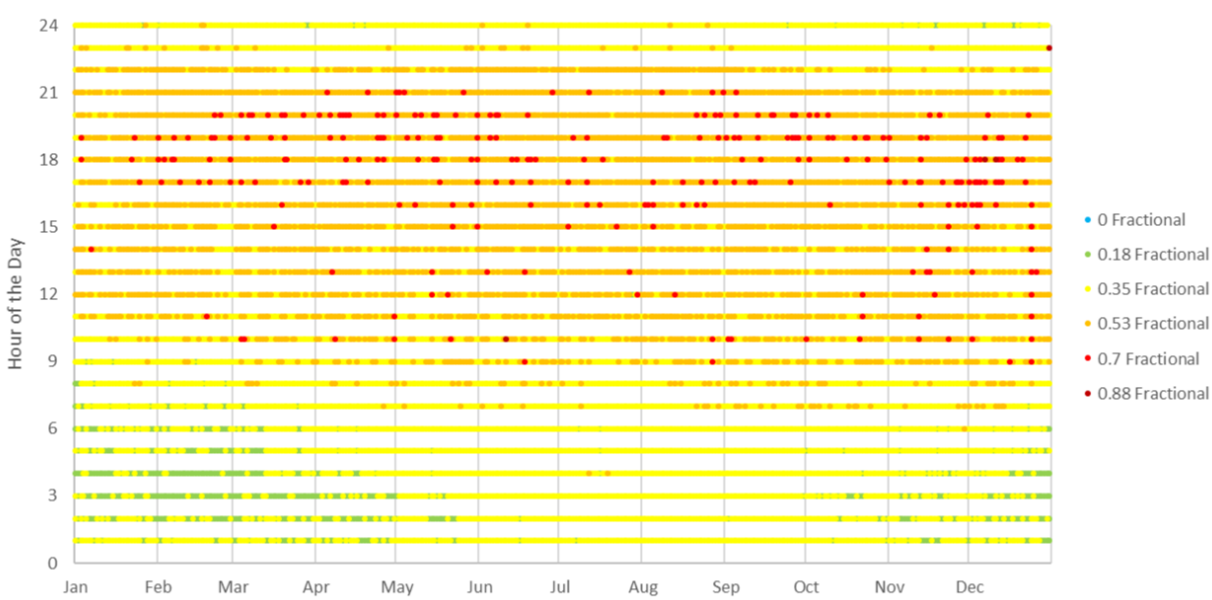
Apartment End Uses for Plug Loads

These apartments serve as temporary housing primarily and apartments tend to have low internal use for equipment and lighting energy. Modelers should use bottom-up approach to estimate the end use equipment needs and wherever possible, leverage existing equipment load shapes for apartments to give the best indication of time of use, anticipated primarily in the mornings and evenings. The following estimates were made to arrive at a peak equipment and lighting power for each apartment unit.

Load Source	Avg Dwelling Size (sf)	Hrs of Operation/yr	Electrical Energy kWh/unit	W/sf
Refrigerator	675	2,894	529	0.27
Cooking (electric stove/range)	675	2,894	600	0.31
Miscellaneous Dwelling unit Plug Loads & Lights	650	2,894	800	0.43

Fractional Schedule of Internal Loads

The following schedule was utilized from existing apartment buildings for a detailed hourly schedule for a year. This data was measured from several existing building sites for low income housing tenants at sub-hourly intervals for over 12 months. Data was normalized by Red Car Analytics and provides a much more accurate estimate of plug load and lighting energy use than default schedules.

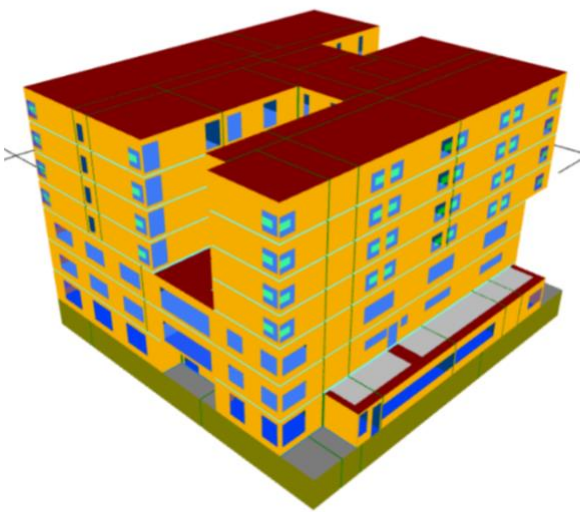
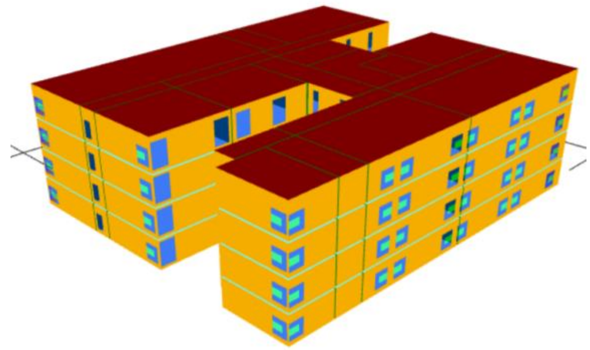
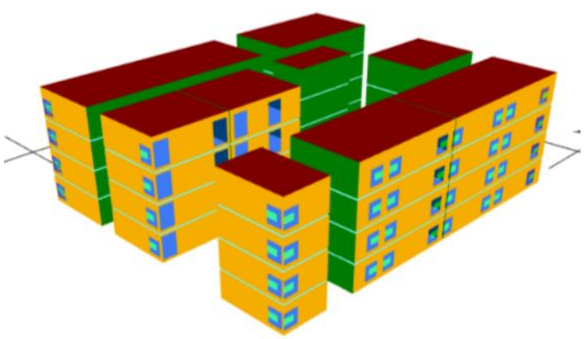
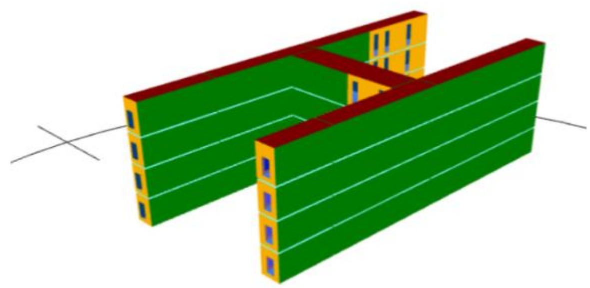


Outdoor Air Assumptions

Space Type Name	Outdoor Air Area [cfm/sf]	Outdoor Air Person [cfm/person]	Airflow Exhaust [cfm/sf]	Outdoor Air Total [cfm/sf]	OA source design
Health Care Clinic	0.06	5.0	0.0	0.09	*62.1 2019*
Apartments	0.00	50.0	0.0	0.14	
Stairways	0.00	0.00	0.0	0.00	*no air*
Storage, Inactive	0.06	5.0	0.0	0.06	*62.1 2019*
Corridors Level 1-3	0.06	0.0	0.0	0.06	*62.1 2019*
Corridors Level 4-7	0.06	0.0	0.0	0.06	*62.1 2019*
Electrical/Mechanical	0.00	0.00	0.0	0.00	*no air*
Waiting Area (lobby)	0.06	5.0	0.0	0.21	*62.1 2019*
Restrooms	0.00	0.00	0.10	0.10	estimated
Parking Garage	0.00	0.00	0.00	0.00	*no air*
IDF/MDF	0.00	0.00	0.0	0.00	*no air*

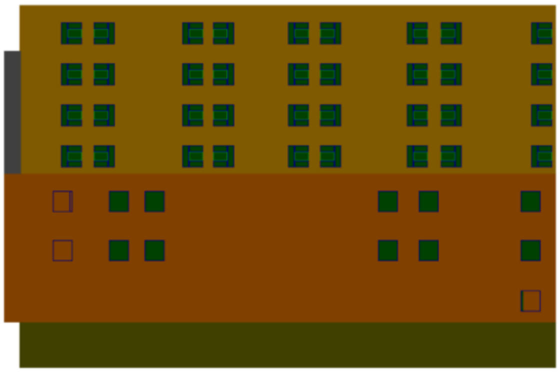
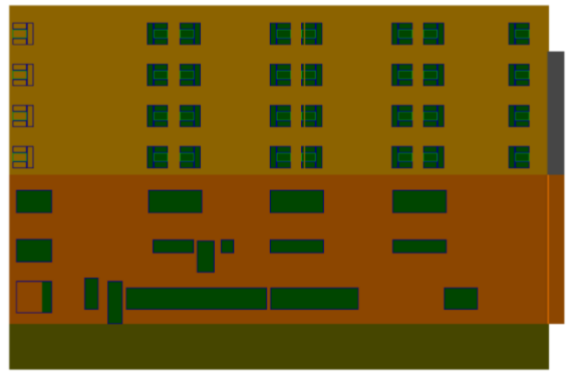
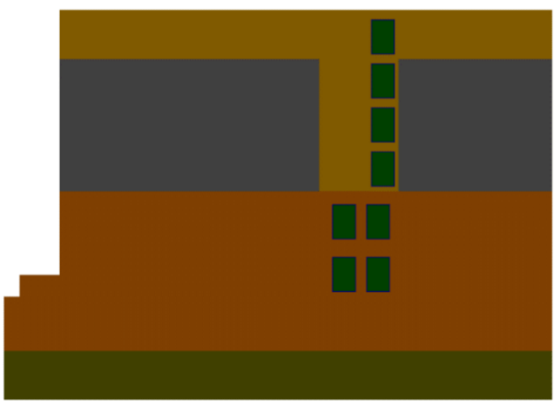
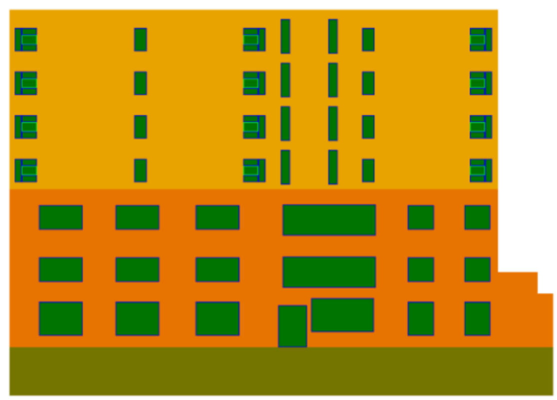
Appendix 2 Energy Model 3d Model and Floor Plans

3d Building Models

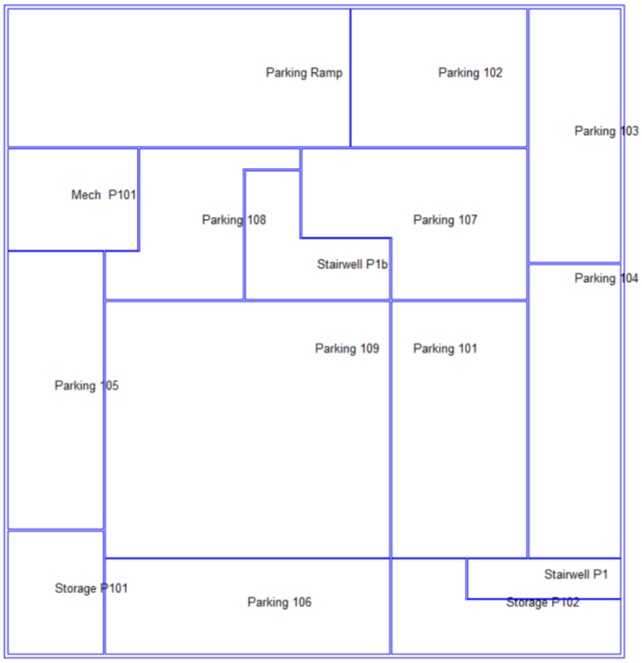
	
Whole model of the apartments on levels 4-7, clinic on levels 1-3, and parking below ground.	Apartment levels only, 4 through 7
	
Apartments only in levels 4 through 7	The Corridors in the apartment levels 4 though 7

Building Elevations

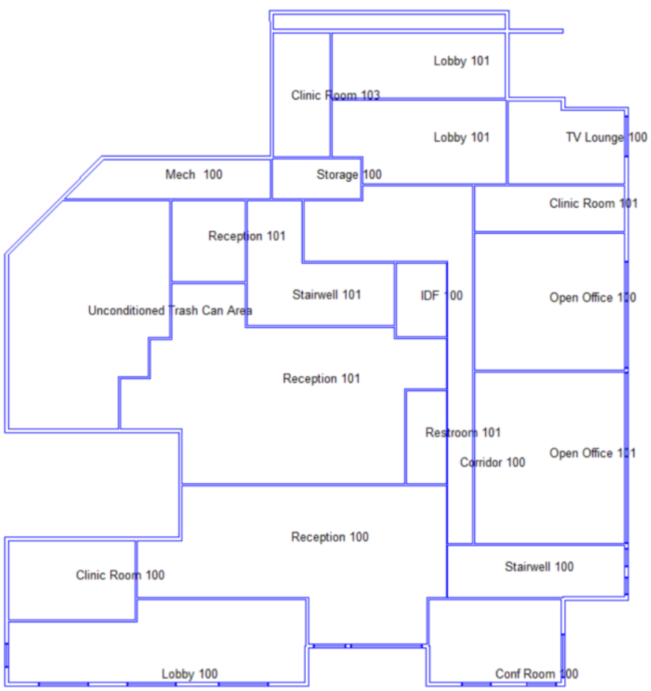
Note the same building was utilized at the same rotation for all simulated cases. While the North building is slightly different in shape and orientation the primary objective of this report was to understand the impacts to building systems. The model was not rotated to minimize differences between the analysis.

	
East Elevation (South Building)	West Elevation (South Building)
	
North Elevation (showing walls which connect with adjacent building phase) (South Building)	South Elevation (South Building)

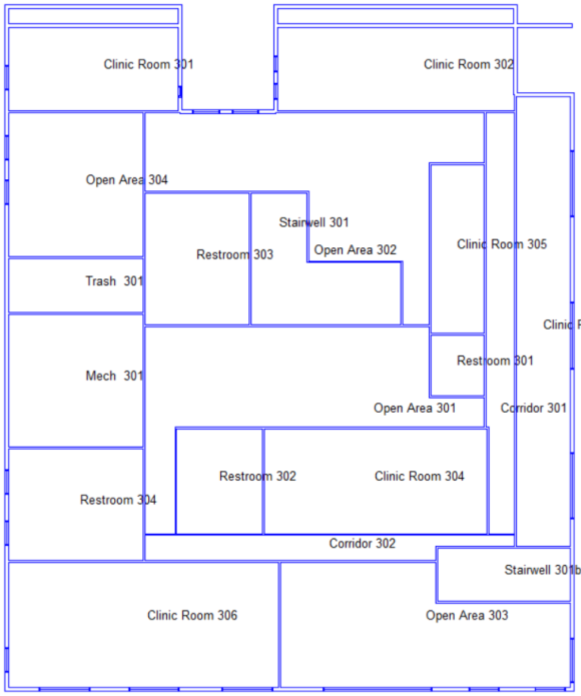
Building Floor Plans



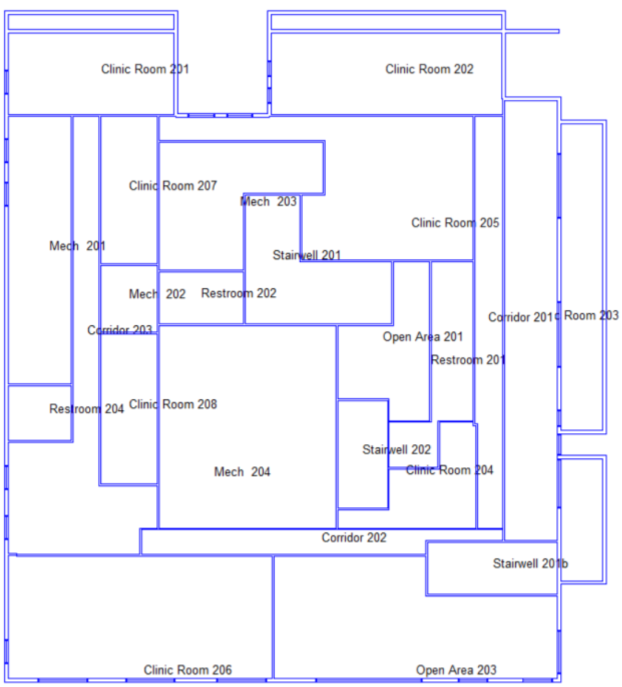
Level 0, Parking



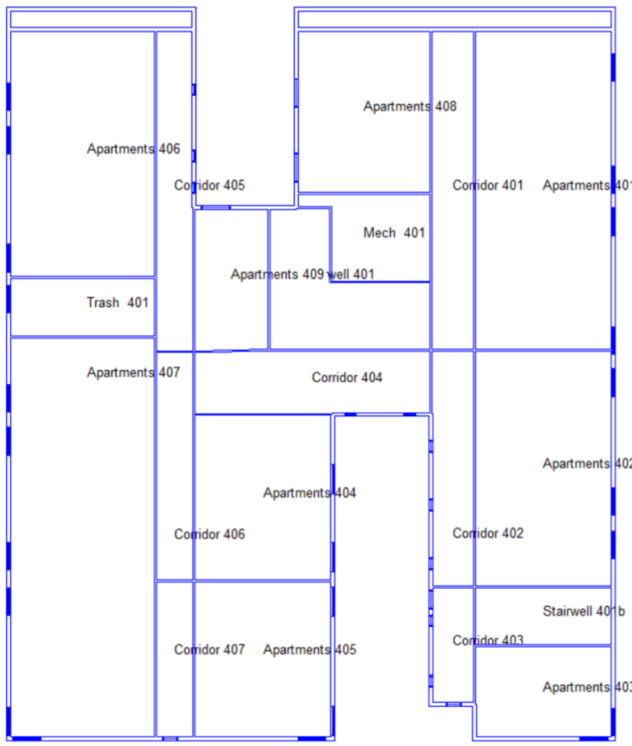
Level 1, Clinic Offices



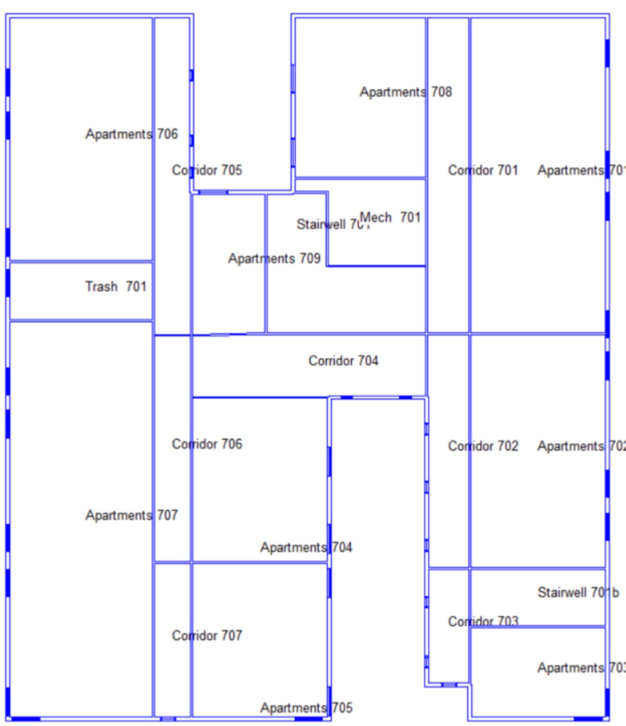
Level 2, Clinic Offices



Level 3, Clinic Offices



Level 4-6 Apartments (same layout)

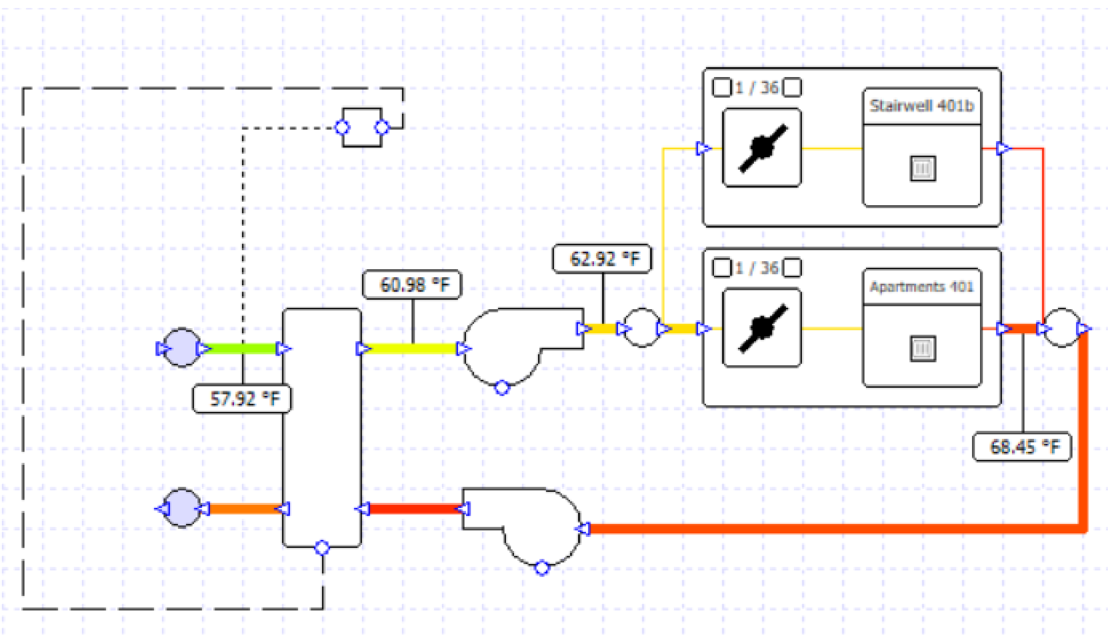


Level 7 Apartments

Appendix 3 Hobson Place Calibrated Model Assumptions

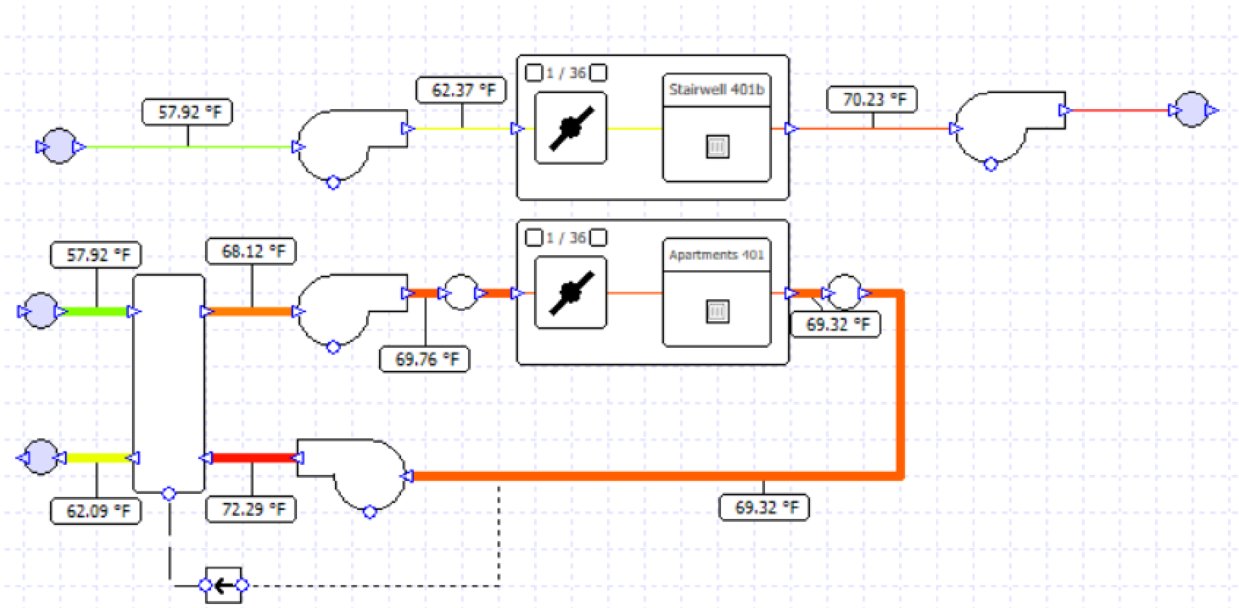
Property	Calibrated Models
Run Period	2022
Weather File	Seattle, Boeing Field
Balanced Ventilation, Central ERV-DOAS	ERV-DOAS field measured
Electric cove heaters + natural ventilation	100% efficient, field calibrated to sample room
HVAC Performance	as-designed
Schedules	Field measured usage patterns from past MF housing projects (Red Car Analytics)
Equipment Loads	By equipment estimates
Lighting Loads	as-designed
Domestic HW Loads	as-designed
Building Envelope	calibrated leakage based on heating measurements
Building Envelope Assemblies	
Floors 1 through 3	All based on the North phase design
Floors 4 through 7	
Walls / Roof	specific North or South
Glazing	specific North or South
Air Leakage	specific North or South

HVAC system diagrams from the North and South side apartment systems are shown below. Apartment units are modeled with a dedicated supply and exhaust fan and the ventilation energy recovery device.



Apartment HVAC diagram of South side systems

The South side supplies ventilation to apartments and corridors from central ERV units located on the roof. The ERV bypass controller is based on the outdoor air entering the unit, bypassing when within economizer conditions. Bypass starts at 42F outdoor air, is fully open at 65F, remains open up to 75F, and is fully shut at 80F.



Apartment HVAC diagram of South side systems

The North side systems include stairwells, corridors and support spaces on floors 4 through 7 on a ventilation only, makeup air unit without ventilation energy recovery. The ERV unit is configured to track the return air temperature setpoint and effectively never bypasses the heat recovery device.